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An Overview of Aircraft Noise Reduction Technologies

The aim of this article is to provide a broad overview of current and future noise reduction technologies used in aircraft industries. It starts by recalling the regulation framework and the European incentives that have triggered efforts in this domain, as well as the major dedicated EU research programs. Then, technologies are introduced in four parts: engine nacelle, fan, jet and exhaust technologies and finally the airframe noise. The article concludes by giving some indications about the present capacity of these technologies to meet the noise reduction requirements and future trends to improve them.

Introduction

This paper is aimed at providing an updated outlook on aircraft noise reduction technologies. However, these technologies are not to be considered alone. They are not add-ons or gadgets that can be plugged into given aircraft architectures irrespective of any regulation context. On the contrary, they have arisen as output from a continuous effort intended to give the most suitable response to a vast regulation framework and high community expectations.

In this paper, we will first provide an outlook on the existing regulations and recommendations, focusing on the International Civil Aircraft Organization's (ICAO) balanced approach. Therefore, we will explain how industrial countries or regional blocks, such as the European Union, initiated comprehensive programs that encourage aerospace industries and related research centers to develop innovative parts or subsets leading to low noise aircraft. Then, we will detail these technologies, starting by the engine and nacelles – which have traditionally been associated with noise issues in people's mind – and ending with the airframe, which up until recently was not thought to be a major noise source, though it is the case in modern aircraft. The paper concludes by giving some clues about future trends, such as open rotors or/and flying wings and their expected performances with regard to these very significant noise issues.

Contextual regulations and recommendations

Aircraft noise has become, at least in Europe, a major concern for communities around airports. This concern has led to great societal pressure on policy-makers, thus giving rise to stacked legislations and regulations at various levels. In Europe, two directives address noise issues, the first from a general standpoint [1] and the second one specifically in regard to noise-related operating restrictions at community airports [2].

Both of these EC directives refer to notions that are now commonly handled by the aerospace industries – such as noise mapping, L_{den} or dose-response curves [3] – but they are also based on the famous "balanced approach" popularized in the fall of 2001 by the 33rd General Assembly of the ICAO [4]. This so-called balanced approach establishes that the reduction of perceived noise and of the subsequent annoyance should stem from advances in Air Traffic Management and land-use policies around airports, but also on technologies aimed at lowering the noise at the source, i.e., on aircraft. This incentive came with more mandatory policies – such as the progressive hardening of certification procedures – the famous successive "chapters" of Appendix 16 to the Convention on International Civil Aviation [5].

ICAO's regulations and local policies

As a matter of fact, "Chapter 2" of ICAO's Annex 16 was superseded by Chapter 3, which became mandatory for new design in 1978 and by Chapter 4, which became mandatory for new design in 2006. As an outcome, "Chapter 2" aircraft were completely phased-out in developed countries as early as April 2002, but some Chapter 3 aircraft are still in operation. Currently, Chapter 3 defines the maximum effectively-perceived noise levels (in EPNdB) for approach, take-off / sideline and take-off / cutback depending on the maximum take-off weight of airplanes. Basically, Chapter 4 has implemented the additional requirement of achieving a 10 dB cumulative margin – i.e., on the sum of the three certification measurements – compared to Chapter 3. This provision associates to the increased stringency some flexibility in the way to achieve the noise reduction, for instance

[1] Maxime LEBRUN was head of the Snecma Acoustics Department at the time when this paper was starting to be written.

more substantial noise reduction under take-off conditions than on approach. It is worth noting that this stringency will be further reinforced, since ICAO adopted the new "Chapter 14", which will become mandatory for new design on the 31st of December 2017 and which will demand future aircraft to prove a 17 dB cumulative margin compared to Chapter 3 [6].

These global regulatory requirements are even strengthened by some local airport rules, such as noise exposure limits, noise charges, curfews, operating quotas, operational noise limits, restrictions on Chapter 3 aircraft, noise abatement procedures and preferential runways. In this regard, the famous "Quota Count" system enforced in London airports is one of the most stringent and surely the most critical for large airplanes, considering the importance of this international hub [7, 8]. In this system, aircraft are ranked in eight 3 EPNdB-span noise categories. For each category, the quota count doubles according to the following table. The critical point is that this classification is applicable irrespective of the aircraft take-off weight (TOW).

Cat. (dB)	<84	84 to 87	87 to 90	90 to 93	93 to 96	96 to 99	99 to 102	>102
Weight	0	0.25	0.5	1	2	4	8	16

Table 1 : Noise category according to the British "Quota Count" system

Aircraft are then sorted according to these categories, both at departure (averaged at sideline and cutback) and arrival (referring to the certified approach noise level). Since London airports have yearly revised operating quotas, airlines are strongly urged to use low-quota aircraft. This has led aircraft manufacturers to prioritize noise concerns in their design and the most significant example is the Airbus A380, whose design has achieved QC/0.5 at arrival and QC/2 at departure, whereas Boeing B747 achieves QC/2 and QC/4 under the same respective conditions. Since the operation of QC/4 and above airplanes is not allowed at nighttime, there is a strong incentive to use low QC aircraft when operating at all three of the London airports.

EU recommendations and technical agenda

Each of the aforementioned regulations triggered an ongoing effort by aircraft and engine manufacturers and by their associated research centers to define and follow a path toward more silent aircraft. This ambition was concretized by explicit targets set forth in 2001 (published in 2002) by the Advisory Council for Aeronautics Research in Europe (ACARE) [9] and regularly updated since then [10,11]. These targets were endorsed by the official European bodies and especially by the European Commission: its political demand to lower by half the noise stemming from civil aviation was finally given a more technical wording, i.e., to achieve between 2000 and 2020 a 10 dB reduction in the noise perceived by the community per plane and per operation (take-off and landing) (see figure 1).

This clear and widely shared expectation pushed the European Commission, as well as national agencies, to upgrade support for various technological research projects. In particular the European Commission fostered a great number of projects through its successive Framework Research Programs (FP) [12].

In fact, several Level 1 projects – so-called "technological bricks" – were granted to address various technological challenges related to aircraft noise reduction, for various specific devices or technologies, or to achieve a better understanding of their underlying physical mechanisms. For instance, projects such as TEENI [13], FLOCON [14], TIMPAN, LAGOON [15, 16] or COJEN [17] respectively addressed Turboshaft Engine Exhaust noise, Flow Control for Fan Broadband Noise, Landing Gear and High Lift Devices Airframe Noise or Jet noise. A good review of these projects and of the associated progress is provided by the X-Noise network [12]. For the sake of simplicity, these technological bricks are often split and referred to as NRT1 and NRT2 (first and second generation Noise Reduction Technologies respectively), according to whether they are able to reach TRL 6 before 2010 or between 2010 and 2020.

Moreover, these kinds of component-oriented projects are still supported and carried out but they have been superseded since 2001 by demonstration platforms and integrated programs aimed at synthesizing the advances made on individual components. Silencer was the first of these programs and was then followed by Openair [18] and CleanSky [19].

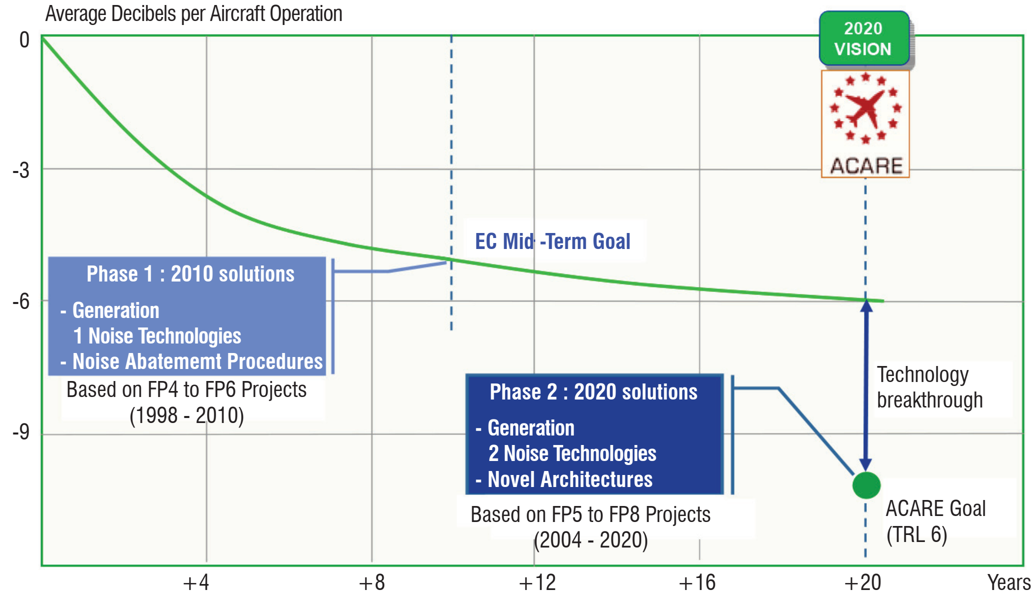

Figure 1 - Expected advances on noise reduction with NRT1 and NRT2, as well as the Noise Abatement Procedure [21]

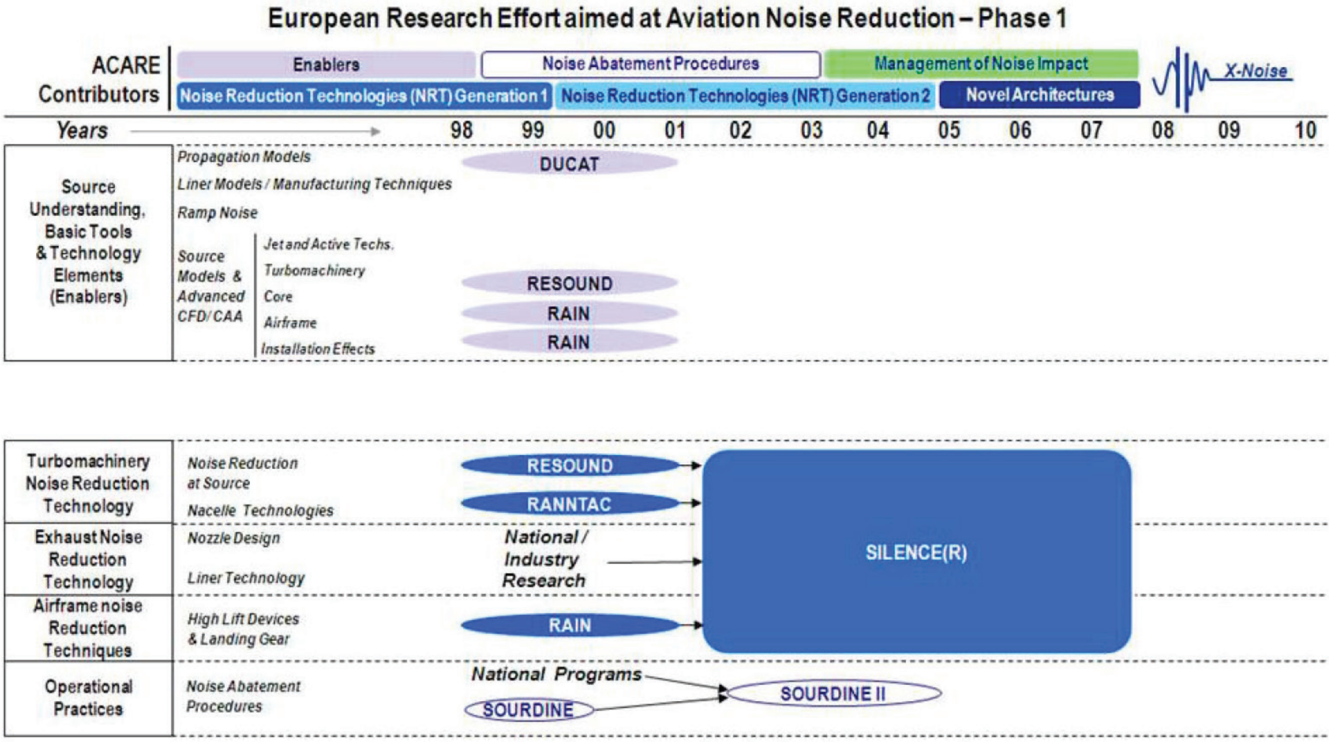

Figure 2 - European Research Effort aimed at Aviation Noise Reduction – Phase 1 [21]

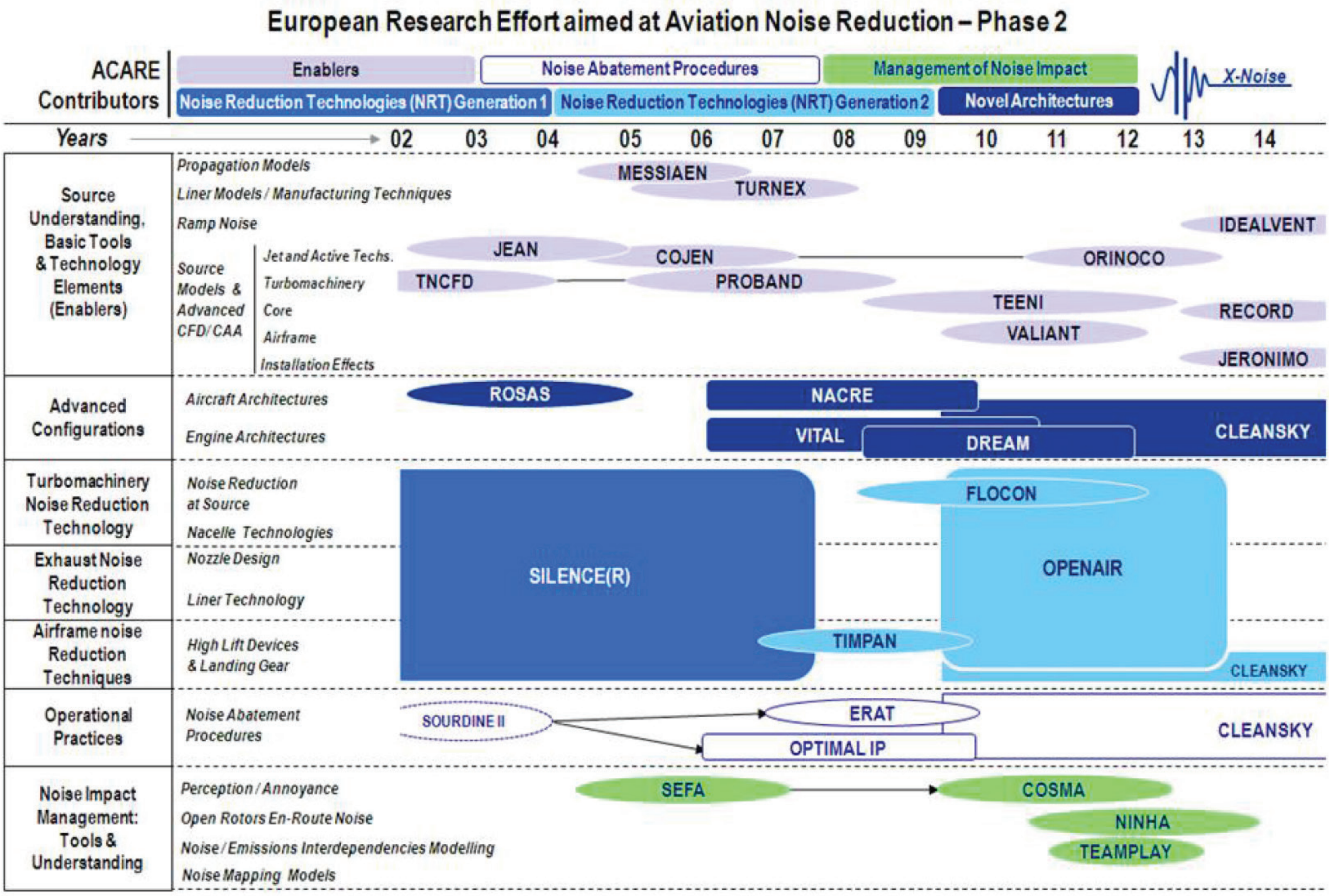

Figure 3 - European Research Effort aimed at Aviation Noise Reduction including Noise impact Management – Phase 2 [21]

A glimpse of such research programs at the European level is provided by the figures 2 and 3, which classify them by addressed technology streams and by year. The two most noteworthy differences between these two charts, which do not address the same time span, is the emergence of new categories dealing with "advanced configurations" on the one hand and "noise impact management" on the other hand. It clearly illustrates the extent to which the integration of various technologies into single platforms is an issue by itself and to what extent aircraft noise is now dealt with not only as a technological issue, but also as a perceptive one.

Beyond programmatic details, one can notice that both the 2020 ACARE horizon and the 2017 ICAO cut-off date more or less fit very concrete industrial milestones, at least in Europe: the development of the A350, a new long-range aircraft and of the A320 single aisle aircraft family with a New Engine Option (NEO), such as the CFMI LEAP1A. However, the entry into service of these two families of aircraft is foreseen between 2015 and 2016. Therefore, in the following parts of this article, we will often refer to this so-called "reference configuration" – to discriminate between NRT1, which will probably be embedded therein, and the most advanced NRT2 technologies that will not.

In this article, we will give a wide overview of NRT1 and NRT2 technologies, classified by components – such as nacelle, engine or airframe – as well as an assessment of their respective benefits. As an outcome, we will also recapitulate the overall gain stemming from all of these technologies – whether NRT1 or NRT2 – and from the associated Noise Abatement Procedures (NAP) compared to the Acare target. Finally, we will conclude by giving some trends about the current research aimed at providing more advanced technologies and solutions for low-noise architectures beyond 2020.

NRT1 and NRT2 technologies

It is well-known that most noise reduction achievements have been made so far by reducing the jet noise. In comparison to aircraft dating back to the 70s, current engines display a dramatically increased bypass ratio (BPR), up to 10-12. This means that most of the thrust is currently due to the moderately-compressed secondary flow. As a result, the jet noise, which fits a strong power law with the jet velocity $(\sim v_{thrust}^{8})$, has been dramatically reduced. Therefore, previously minor noise sources, such as the tonal and broadband components of fan noise, have become comparable to – and now may overtake – the residual jet noise even at take-off. More precisely, the larger the fan, the stronger this noise source, since it stems from various phenomena, all correlated to this fan size [20] :

- interactions of the rotor fan blade-tip with the turbulent boundary layer on the inlet-duct, (rotor boundary layer interaction noise) ;
- turbulent eddies convected in the rotor boundary layer with the rotor trailing edge (rotor self-noise) ;
- interactions between the rotor wake and the downstream outlet guide vanes (OGV interaction noise) ;
- Turbulent eddies convected in the vane boundary layer and the vane trailing edge (OGV self-noise).

On the other hand, during the landing phase, the engine regime decreases so that the airframe noise becomes comparable to – or sometimes dominates – the overall remaining engine noise. Among its various contributors, landing gear on the one hand and flaps and slats on the other hand are predominant (see figure 4).

Beyond those remarks on the relative weight of each contributor, it is commonly admitted that the process of correlative noise reduction with BPR increase will probably come to an end in the forthcoming years: the nacelles, so far considered as a major support of turbomachinery noise reduction through acoustic liners, would become so large and so heavy that they generate both a spurious drag and an unbearable additional weight, therefore annihilating the possible gains in both consumption and noise. Consequently, the nacelles of Ultra High Bypass Ratio (UHBR) engines are to be considerably reduced in length and volume, leading to a dramatic reduction of potential turbomachinery noise absorption by acoustic liners and making the noise produced by the fan system and the jet mixing much more sensitive to the flow around the aircraft (detrimental installation effects).

In between, as shown by figure 5, present turbofans, future Ultra High Bypass Ratio (UHBR) and Open Rotors (OR) [23].

Nacelles

In order to lighten the nacelle, aerospace industries are currently trying to shorten it both upstream and downstream. Therefore the fan noise and other internal noises are less absorbed by shortened nacelle ducts and various technologies are considered to limit this drawback.

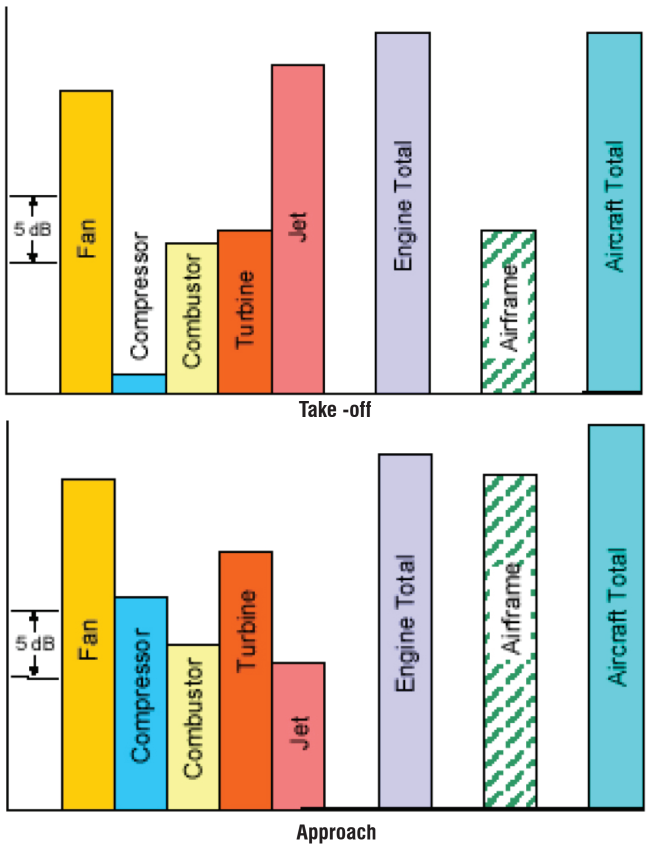

Figure 4 - Relative weights of noise sources at take-of and landing according to [22]

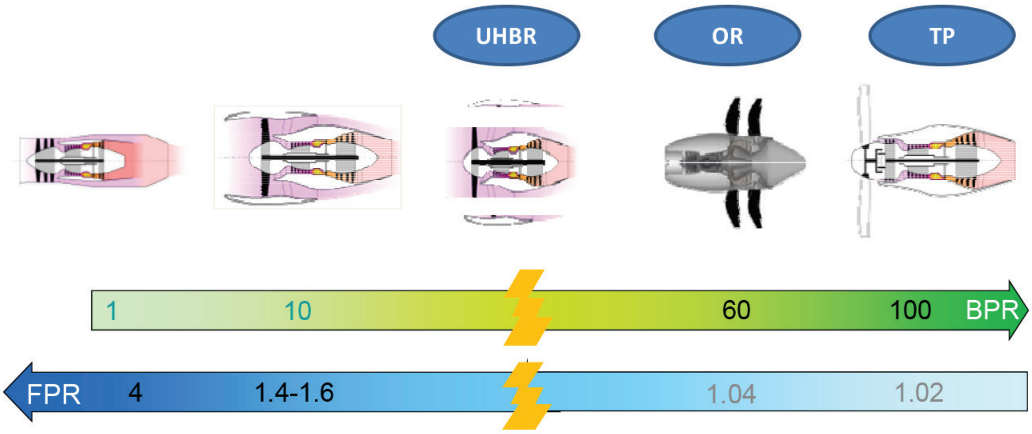

Figure 5 - BPR and FPR (Fan Pressure ratio) from simple flux turbojets to turboprops (TP)

As a first trend, further optimization of noise absorbers – the so-called "liners" – is considered. Currently, those materials consist of classical honeycombs, where the outer plate is porous or perforated as illustrated by figure 6. Basically, these liners behave like Helmholtz resonators, i.e., they allow noise to be reduced within an optimized frequency range. Therefore, they are well suited to fan noise, which is basically a tonal noise. Quite often, superimposed layers or such liners – called "2 degrees of freedom" (2DOF) or even "3 degrees of freedom" (3DOF) – are used in order to broaden the absorption frequency range.

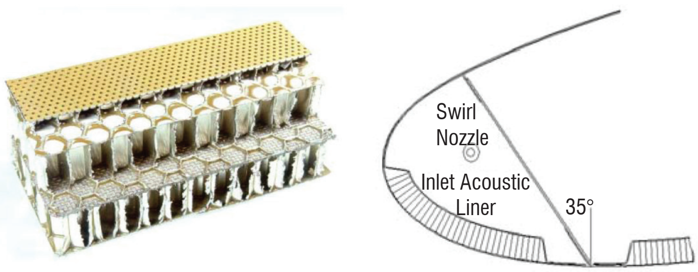

Figure 6 - A 3 DOF Honeycomb liner sample (left) and a sketch of extended lip treatment (right)

Lip treatments

Optimization could mean an extension of the surfaces treated with such absorbers. More precisely, computations and experiments have proven that treating up to the inlet lip is quite efficient. However, this ambition challenges the current concept of the nacelle, since this zone is used for de-icing and since de-icing techniques and noise techniques are not necessarily compatible [24]. Currently, there are two kinds of de-icing techniques, which can be either pneumatic (hot air blowing pipes) or thermoelectric. However, intake liners are often made of glass-fiber composites, i.e., insulating materials. Two kinds of technologies are currently under study to overcome this compatibility issue, pneumatic (hot air blowing pipes are the conventional technology on most of current aircraft) or thermoelectric. An acoustically treated lip technology integrating a pneumatic anti-ice system has been developed and its efficiency has been shown at full scale by in-flight experiments on an A380. A lip acoustic lining technology compatible with thermoelectric anti-ice systems is still a very low TRL.

Smart liner distribution

Beyond the lip treatment, much expectation also arises from smarter liners or smarter liner distribution. For instance, current air intake treatments are usually split by longitudinal splices bordering separate treated parts. This technological limitation entailed sharp azimuthal variations within the acoustical impedance of the intake and thus limited acoustical performance, especially when facing shock waves generated by the fan tip leading edge at transonic speed. Some "zero-splice" liners [28] (figure 7) have been developed and used for the first time on the Airbus A380 and they are being used on the new A350 XWB, on the SSJ100 and will be available on the new Silvercrest engine. The challenges lie in the very accurate design and production processes required just in front of the fan, in order to keep the 0-splice benefit available.

Figure 7 - True zero-spliced liners as tested (left) and mounted on the A380 (right) from [28] ; reprinted by permission of the American Intitute of Aeronautics and Astronautics Inc.

To move forward, it is now envisaged to use more finely-tuned liners in order to optimize the absorption process [24] (figure 8). More precisely, some work is currently being carried out to modulate the liner inner thickness along the intake. This modulation must be computed to optimize the impedance matching, as long as the acoustic wave gets out of the intake. This concept borders another one that considers sophisticated impedance distributions. Ideally, such smart distributions would favor acoustic modes with an upward directivity, in order to spare the community. This concept is aimed at achieving the same goal as the so-called negatively-scarfed air intake, i.e., orienting outgoing waves toward the sky. Though quite old, these ideas remain up to now at TRL6 in the case of the first one and at lower TRL for the other and have not led yet to an industrial design.

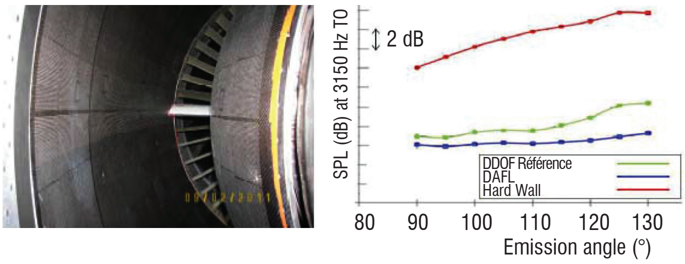

Figure 8 - Distributed Aft Fan Liners and their dramatic effects on noise reduction as tested in [24]; reprinted by permission of Snecma.

Fan noise

Although nacelle technologies may be seen as external devices to treat the fan noise (and the core noise too), some technologies are also being developed for the fan components themselves. However, these parts are directly involved in the thermodynamic processes ruling the efficiency and the consumption of the engine. Therefore, any optimization of the fan components will be will first and foremost assessed in this last regard. Moreover, little information is publicly disclosed by engine manufacturers on the implementation of these inner technologies, since they directly challenge their competitiveness.

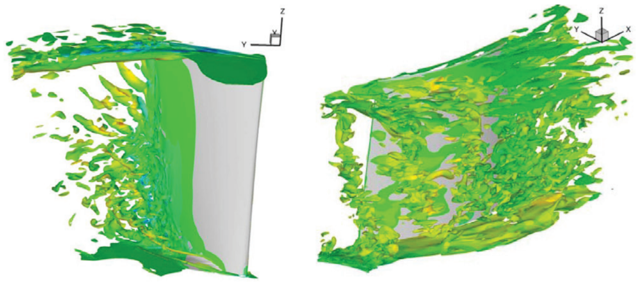

Figure 9 - LES-computed isosurfaces of the axial component of vorticity on rotor (left) and stator (right) blades [20]

Shape optimization and other passive technologies

As previously mentioned, rotating parts generate two kinds of noise, i.e., self-noises and interaction noises, both of which are enhanced when the rotation speed increases: fan broadband noise is proportional to $u_{tip}^{5/2}$ [20]. Basically, two general strategies are being experimented with to reduce fan noise : attempting to optimize the blades, or to directly act on the air flow. Generally, the first technological route does not use liners or absorbing materials because their implementation on 3D rotating parts is quite delicate and challenges their structural properties.

Thus, the actual challenge is rather to optimize the 3D blade shape. Through this route, engine efficiency is expected to be optimized over a wide range of regimes. Geometries stemming from this kind of trade-off provide good results at cruise and take-off conditions, when aero performance is crucial, but they suffer some drawbacks on approach, hence affecting the noise performance under this latter condition. Several works are still under investigation to address this issue, but most of them remain confidential since any step forward in this technical domain could provide decisive advantages to manufacturers in the commercial competition.

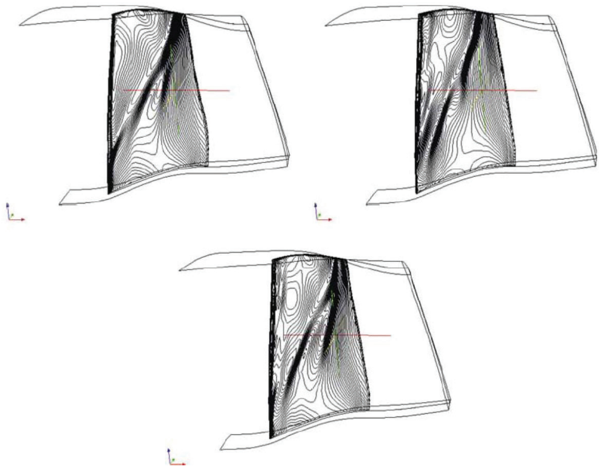

Figure 10 - Suction side density contours of variously-optimized blades: initial geometry (left), aerodynamic optimization (center), and aeromechanical optimization [25]

Another well-explored way to reduce the fan noise is to regularize the air flow and to reduce its velocity. This is especially important for large fans, since the blade tip velocity could become transonic. To reduce this speed, fans can be de-coupled from the primary shaft with the help of gearboxes. This solution has, for instance, been used on the Pratt & Withney PW1100G, whereas it has not been implemented on the CFM LEAP-1A, though both were designed for single aisle midrange aircraft such as the Airbus A320. The choice is strategic and has led to different optimized solutions where weight, temperature and low pressure turbine performance are key parameters. Finally, there are different sizes of engines: the PW1100G measures 2.057 m, whereas the Leap-1A measures only 1.981m. The blade tip speeds are respectively 60m/s using the gearbox and 75m/s in direct drive. One can thus say that one company chose to push conventional technologies up to their limits, whereas the other preferred to integrate a new optimized component. The trade-off between the two solutions may be carefully assessed, since the additional gearbox also induces and increased weight. This remark applies to any additional technology. For instance, for the same sake of optimizing the air flow through optimal pressure conditions, Pratt & Withney tested Variable Area Fan Nozzle (VAFN), i.e., sliding flaps that focus on pressure discharge, versus the regime downstream of the fan. Although the manufacturer claims some genuine performance gain, it avoided implementing this technology on the PW1100G family, probably because of the increased weight and complexity that it would have induced [26].

Beside this effort, some attempts have also been made to reduce the fan noise downstream, through liners. Past endeavors to implement porous materials on OGV did not show any evidence of actual benefit. However, recent experimental tests made with carefully-computed Distributed Aft Fan Liners (DAFL) in the secondary duct of a full scale demonstrator achieved very significant noise reduction [24]. According to the data presented, the aft fan broadband noise reduction was of up to 5 dB and important blade passing frequency tonal noise almost completely disappeared. It is still unclear whether this performance stems from standard absorption processes, or from more subtle modal redistribution mechanisms.

Active stators

A longstanding effort has also been conducted to reduce the fan noise - both forward and rearward - through active devices. The idea is basically the same as that in any feedback loop, i.e., measuring the residual signal and acting in order to nullify the latter. Thus, the technology requires measurement microphones, or sensors, and speakers, or actuators. Efforts regarding these technologies were made within national and European programs. Low TRL advances achieved, for instance, in EU-funded programs such as RANTAC or RESOUND, led to integrations attempts in SILENCER and OPENAIR [27].

Two competing technologies tested in SILENCER used inlet wall-mounted and OGV-integrated actuators respectively. It is worth noting that SILENCER tests were performed on a large-scale mockup at the RACE and ANECOM anechoic fan noise facilities. In addition to this program, it appears that active stator technology with OGV-integrated actuators is better suited, both because their presence does not affect the passive liners that can be implemented additionally and because their intrinsic efficiency is higher since they are closer to the noise source.

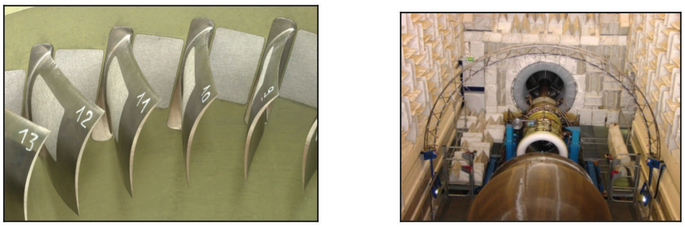

Figure 11 - Active fan stator and 3D measurement fitted with Piezo Actuator System on and between blades at the RACE Anechoic Facility [21]

These preliminary integration works have been extensively continued in OPENAIR with a special focus on the most significant fan contribution, i.e., its rearward noise (whereas SILENCER focused on the forward noise). At the beginning of OPENAIR, the project was aimed at reaching TRL 5 for this technology. Currently, it reaches only TRL 4 because of both severe integration issues and limited achievements in related control and signal processing. Moreover, some related issues arise, such as the energy supply for these devices and trade-off considerations for balancing rearward and forward noise reduction. However, the proven benefits of these active stator technologies are significant enough to pursue the effort in forthcoming research programs [21].

New engine architectures

Beyond these local improvements, some attempts have been made to experiment far more dramatic modifications of the engine architectures. Preliminary studies to probe various technologies have already been conducted, or are being conducted, both for Ultra High Bypass Ratio engines and for Open Rotors. These two technological tracks are both presumed to lower fuel consumption and to reduce noise emission (at least jet noise, since tonal noise may dramatically increase for Open Rotors).

For instance, from 2008 to 2011, within the DREAM project (EC 7th framework program), preliminary campaigns were led to compare noise measurements and numerical simulations on some Open Rotor configurations. Computational Fluid Dynamic (CFD) and Computational AeroAcoustics (CAA) made by Onera (France) appeared to be in good agreement with the measurements performed by Tsagi (Russia) [29, 30].

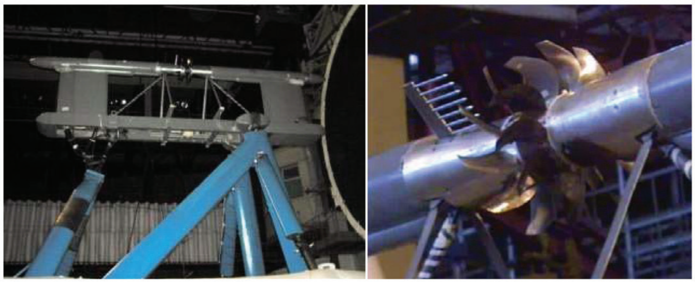

Figure 12 - VP107 test vehicles in TsAGI T104 low speed wind tunnel. The mock-up is a 0.6373 m diameter propeller at model scale with 12 blades on the front propeller and 10 on the rear one [29]

Extensions of these works are now conducted within the CleanSky Framework: In France for instance, Snecma's Hera test vehicle underwent preliminary testing in Onera's S1 wind tunnel in July 2013. Full-scale propeller tests are expected in 2015.

Figure 13 - Snecma's Hera test vehicle mounted in Onera's S1 wind tunnel facility

Further new technological research programs have already been launched. Especially, it is worth mentioning COBRA, a new EU-Russia cooperation program that started in October 2013 and that is considered as the continuation of VITAL and DREAM. Actually, COBRA is dedicated to the consolidation of Ultra High Bypass Ration (UHBR) ContraRotating TurboFan (CRTF) that was once explored by Kuznetsov – one of the Russian partners – in the early 90s and further explored within VITAL. CRTFs associate two contrarotating fans in a nacelle and thus appear as a kind of hybrid between turbofans and Open Rotors.

CRTFs envisaged by COBRA strongly differ from those experimented with within the VITAL program and by the Russian engine manufacturer. Kuznetsov's NK-93 (BPR ~ 16.5) depicted in the picture above highlight the good behavior in term of performance of this concept, but the design was made over more than 20 years ago without the current computational tools and free from present environmental constraints. At the time being indeed, first NK-93 full scale tests showed that noise performances of such UHBR CRTFs were not so bad and that the combustion chamber has been up to now one of the most efficient among the Russian ones. Compared to VITAL, COBRA plans to explore a higher bypass ratio (BPR ~ 11 within VITAL) with the obligation to use a gear box in order to reduce the fan speed. This reduction will directly impact the tip velocity and thus will allow the fan noise to be reduced. Within the COBRA project, the BPR investigated is from 15 up to 25, according to the detailed specifications proposed by the partners in charge of this activity (Snecma and Kuznetsov). A specific conception/optimization will be proposed by European research centers (Onera and DLR) and by Russian partners (CIAM, Kuznetsov, AEROSILA and MIPT). Both designs will be manufactured by COMOTI and tested at CIAM's C3-A test rig facility.

Jet noise and nozzle exhaust technologies

Though jet noise has been significantly reduced within double flux engines, it remains an important source of noise, especially at take-off. Towards the end of the 20th century, new momentum was given to research aimed at its reduction, especially through US programs. Phases 1 (2000-2005) and 2 (2005-2010) of the Quiet Technology Demonstrator Program gave evidence that the so-called chevrons lead to some jet noise reduction [32].

Chevrons

Chevrons are geometrical corrugations of the cylindrical exhaust of either the primary jet (core chevrons) or the secondary one (fan chevrons). The detailed mechanisms through which chevrons act are still under investigation. Actually, there is evidence that several mechanisms may contribute to the efficiency of this kind of device and that these mechanisms are strongly affected by the chevron geometry. For instance, core chevrons are directed inward with respect to the jet and are known to lower mainly the take-off noise. On the other hand, fan chevrons are generally parallel to the engine axis and reduce shock-cell noise, so they are rather efficient during cruising, when this phenomenon appears [33].

Currently, several computations and experimental works are being carried out to improve the understanding of the impact of chevrons on noise and especially to quantify this impact. However, while current numerical simulations - mostly based on Computational Fluid Dynamic and Acoustic Analogy – can provide qualitative ranking of various geometries, or can lead to a good noise reduction impact, they have not been able to provide reliable absolute noise levels in some cases. This is especially true when considering installation effects, which are now the big challenge for chevron computations. In addition, these effects will become more significant as engine BPR increases and as engines get closer to the wing. Complex effects such as the loss of jet axisymmetry, jet instability and appearance of new noise sources due to jet interaction with the wing or the pylon are then to be taken into consideration.

However, despite their efficiency or the challenges that they entail and though they have actually reached TRL 8-9, chevrons are not always considered as mandatory from the standpoint of end-users and thus they have not been generalized on all engines and all aircraft. Some regulation issues may indeed interfere with the trade-off: Since the chevron can be considered as an optional kit, it can help to achieve few decibels in order to be compliant with the most stringent regulations; for instance, chevrons lead to a 2 EPNdB additional cumulative margin necessary for the A321 to be compliant with Chapter 4. As far as the A320NEO is concerned, the jet noise is sufficiently reduced for chevrons to not achieve a sufficiently large enough global aircraft noise reduction compared with the aero performance penalty that they generate when cruising.

Virtual chevrons

The true reason behind this reluctance to systematically add chevrons is that they are suspected to increase the aircraft overall weight and, above all, they lead to additional drag, which downplay their interest with regard to fuel consumption. Therefore, current research is being conducted to develop what is known as "virtual chevrons", i.e., microjet devices that would blow pressurized air into the main jet and that are supposed to act as physical geometrical chevrons. Most advanced works are now dealing with continuous jets, which are easier to implement, whereas low TRL works are carried out on pulsed jets. In France, these works have been performed through various programs, such as OSCAR, ORINOCO or REBECCA, in connection with European collaborations such as OPENAIR or even with international cooperations with JAXA. However, few results have been published [34, 35].

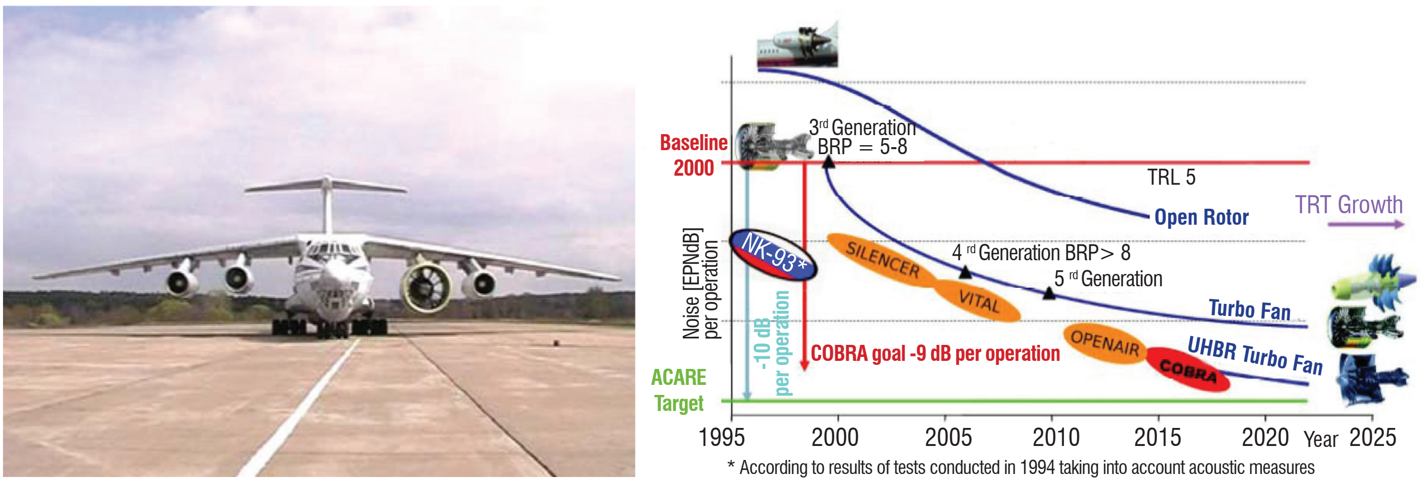

Figure 14 - The 1980 s Kuznetsov NK-93 on a flight test bed (left) and expected position of COBRA's deliveries on a noise roadmap (right)

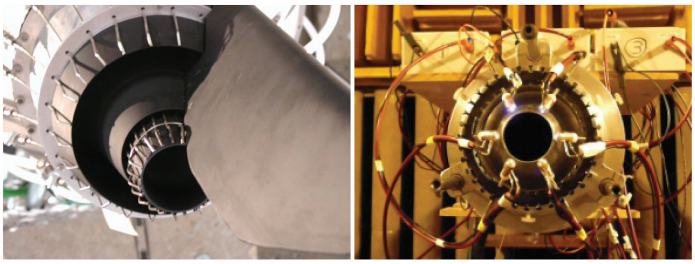

Figure 15 - Double-stream nozzle with continuous microjets at the Martel facility (Poitiers) within the framework of a French-Japanese cooperation (left. A plasma-based pulsed microjet developed at Onera and tested at the Ecole Centrale de Lyon (right)

For continuous microjets, several experiments have been made by various teams, testing rings of several microjets (typically between 10 and 40) obtained with flaps and hatches scooping the main jet. These tests have helped to explore various parametric configurations, varying the number of microjets, the microjet nozzle shape and orientation, the jet mass flow, or its pressure gradient. In particular, a large-scale cooperation between France and Japan within this framework is worth mentioning [36]. This cooperation, involving JAXA and IHI in Japan, and Snecma and Onera in France features a large facility providing experimental simulation of microjets, the STA-R (Système de Technologie Active Réduit). Measurement campaigns performed under various conditions in the Onera's anechoic wind tunnel CEPRA 19 have shown that continuous microjets could lead to nearly 1 EPNdB reduction, even under take-off conditions at Mach 0.3. This reduction effect is measurable from 90 degrees (lateral side of the exhaust nozzle) to 150 degree (i.e., downstream of the jet).

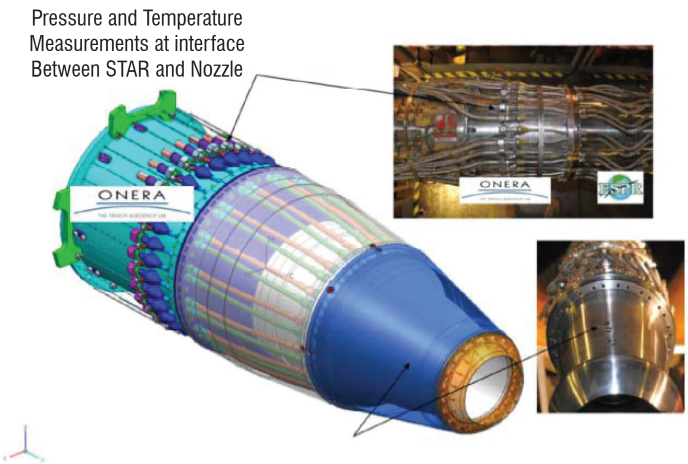

Figure 16 - sketch of the Japanese test rig mounted on the STA-R as described in [36]; reprinted by permission of Nozomi Tanaka.

Additionally, several other integration technologies have been carried out within the Level 2 EU-funded program OpenAir. As for the STA-R, these tests basically showed that the order of magnitude of the overall gain achievable from continuous virtual chevrons is roughly 1 dB, i.e., similar to physical chevrons.

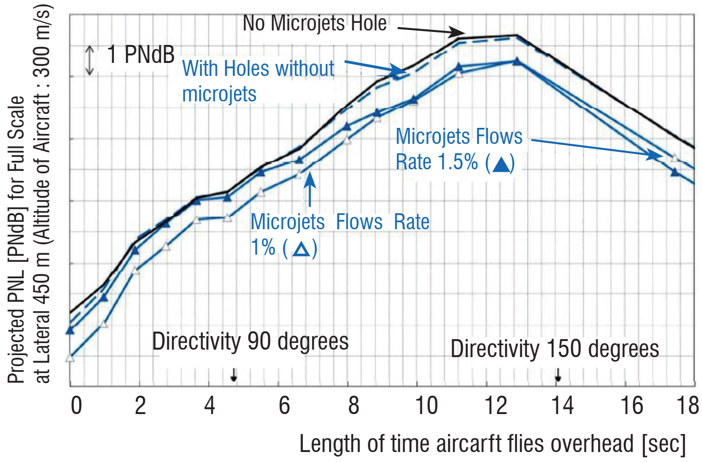

Figure 17 - overall noise reduction with additional microjet flows. According to [36],roughly 1 EPNdB is achievable .

Some complementary work is also being carried out, mainly by research centers, on pulsed jets. This work tends to prove a potential increase of efficiency compared to continuous microjets, though the physical mechanisms are still unclear. What is clear however, is that this expected increased efficiency requires a fine control of the microjet relative phases and frequencies, otherwise spurious additional noises nullify the expected benefit. It is also worth mentioning that both the continuous and the pulsed microjets act on the broadband jet noise and not on its possible tonal components, such as the screech noise. When using pulsed jets, the broadband noise reduction is achieved at the expense of the appearance of a tonal noise. The frequency of this tonal noise is the frequency of the pulsed jets – usually some kilohertz – and care must be taken to ensure that its magnitude does not balance the gain stemming from the broadband noise reduction at a lower frequency.

Airframe

The airframe is the other major source of noise. As for the engine noise, this category may be divided into several subcategories, among which the two main contributors are the landing gear and high-lift devices (HLD) [37]. As could be expected, the larger the plane, the more significant the effect of the landing gear is compared to that of the HLD. For instance, the HLD noise is dominant in regard to airframe noise for an Airbus A320, whereas the landing gear noise is more important for an A380. Therefore, this latter source of noise has been extensively studied and reduced on recent large carriers, especially with regard to the critical Quota Count policy enforced in London. One can even say that, in this regard, the A380 has specifically been designed to comply with this local regulation.

Nowadays, the physical mechanisms leading to landing gear noise are well understood, but remain quite hard to simulate or to lead to reliable quantitative estimations. These noises are due to complex phenomena of boundary layer separation, laminar-to-turbulent boundary layer transition, shear layer transition, laminar separation bubble and associated dynamic effects. Generally speaking, these sources account for some broadband noise, but are usually less noisy than high intensity tonal noise due to resonating cavities and holes. Though easy to describe with academic geometries, these phenomena could lead to odd behaviors when complex shapes are involved and even more so in the case of interacting bodies. Predicting the overall airframe noise stemming from such geometries usually requires both deep physical analysis and massive computation facilities. A good example of such academic studies addressing both HLD and landing noises is provided by the program VALIANT [38]. However, in parallel with these scientific developments or even in their absence, some technical recipes may be applied to limit the sources of this noise.

Figure 18 - Flow computation in and around a wing-flap gap (left) and a two-strut landing gear (right) as performed in [38]. The computation on the left is a so-called DES computation, whereas the one on the right is a LES computation.

Landing gear

For instance, minimizing landing gear noise often requires the landing gear geometry to be simplified, in order to avoid spurious noise sources or interactions. Many experimental attempts have been performed in this regard, within programs such as RAIN, SILENCER and TIMPAN [39] or LAGOON [15, 16]. The preliminary work achieved in RAIN was conducted on a non-operable mockup that featured complete fairings. Though unrealistic from an industrial point of view, the concept proved to potentially lead to a more than 10 dB reduction over a wide span of frequencies. Work has thus been pursued within SILENCER, with both a nose landing gear (NLG) and a main landing gear (MLG). Tests were performed on A340 1/10 scaled mockups in the German DNW LLF facility and some actual flight tests were also performed at Tarbes (France).

These flight tests just featured "simple" bogie fairings, which allowed a significant overall reduction of 2.0 EPNdB for the landing gear noise and of 0.4 EPNdB for the aircraft as a whole. The tests done in the DNW-LLF facility were performed on more advanced (but non-operational) configurations, both for the NLG and the MLG. These innovations proved to account for a 4.1 EPNdB noise reduction in the LG noise itself and 1.6 EPNdB for the whole aircraft.

Efforts on the landing gear noise have been pursued in TIMPAN and OPENAIR. Since this latter program has not ended yet, a summary of the progress made is not available yet. However, these new programs addressed the possible benefit of splitters between the bogie fairing and the strut. It is expected that such fairing could attenuate

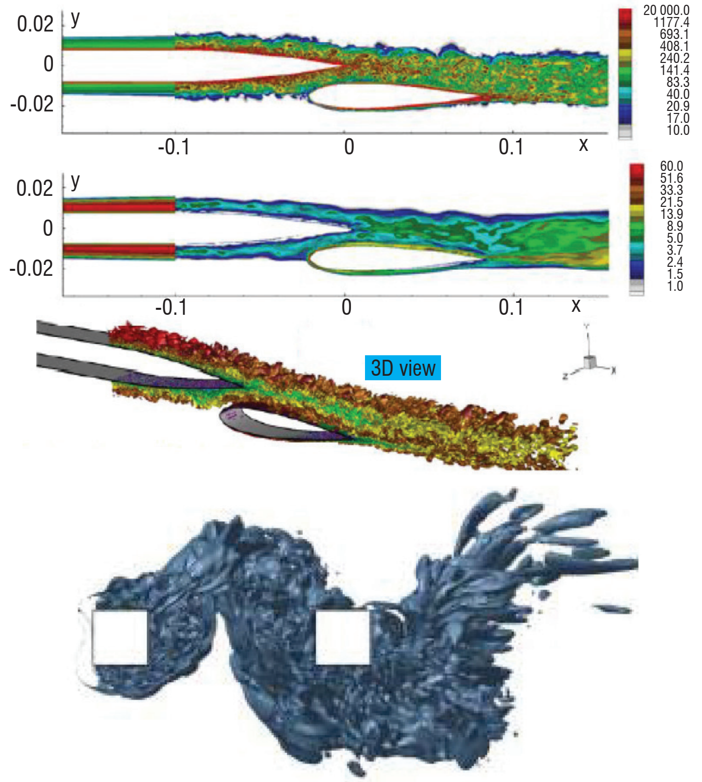

Figure 18 - Flow computation in and around a wing-flap gap (left) and a two-strut landing gear (right) as performed in [38]. The computation on the left is a so-called DES computation, whereas the one on the right is a LES computation.

communication between shear layers, thereby preventing the formation of large scale and noisy vortices. It is even expected to explore such splitters without fairings, the latter being quite unpopular among manufacturers, since they increase the LG weight.

In addition to this research, some technologies have been applied to the most recent aircraft, such as the Airbus A380 or A350: as previously mentioned, caps are used on cavities, for instance on inner and outer hubs, and rims are applied on wheels. Moreover, some smart dressing techniques are used in order to avoid putting cables, wires and accessories in the wake of high flows. It has been shown that this so-called "slow down flow" concept – i.e., putting bodies either in front of the main strut, where flow velocity goes to zero, or behind it in

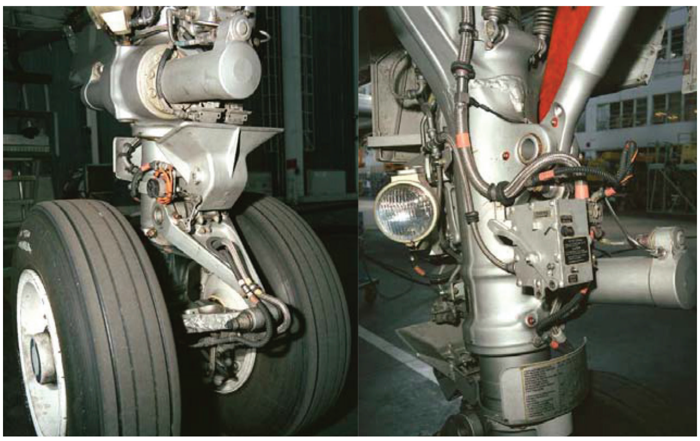

Figure 19 a - An actual landing gear with all its associated devices and commands

Figure 19 b - NLG and MLG fairings tested in SILENCER the quiet zone – significantly reduce the downstream turbulence and noise. Optimizing this masking technique however requires advanced capacities in simulation, in order to predict, or at least to assess, the interaction between the involved parts and the bluff body and great efforts are currently being made in this regard within OPENAIR. However, caps, rims and the "slow down flow" concept, still enforced today on some modern aircraft, allow the global aircraft noise to be reduced at landing from 1 to 2 EPNdB. Moreover, it is expected that some 0.5 dB more can be gained from specific acoustic techniques, such as plain perforated or even porous fairings, which are now at TRL 5. More probably however, these techniques will be deployed only when absolutely required as, for instance in 2018-2019 for the forthcoming A350-1000, which is aimed at reaching the London QC/0.5 category with the help of such fairings.

High Lift Devices

Compared to landing gear, the progress made on flaps and slats noise reduction appears to be quite less mature. This is mainly due to the fact that known technologies to reduce this noise strongly reduce the lift performance. Currently, at landing, this degradation is so critical that it often forces the aircraft speed to increase, and therefore the regime, so that the expected gain is nullified. In addition to this technical limitation, HLD noise is quite complex to describe and to compute: it involves challenging mechanisms of unsteady vortex recirculation, free shear layer vortex flow reattachment, or edge scattering tone noise. The overall result is a broadband noise with some tonal components, the whole and especially the latter becoming more intense when the angle of attack increases. Overall, the slat component generally dominates in that of the flap and fits a strong power law with the aircraft velocity (v9/2). This slat component is rather rearward and accounts for the tones. On the contrary, flap noise is purely broadband but the flaps also account for strong spurious interactions: For instance, even though little is known about outboard spoiler deflection, these are known to modify the wing circulation and therefore the slat noise. In the same vein, flaps may interact with the wake of the main landing gear to produce a strong low frequency interaction noise [31].

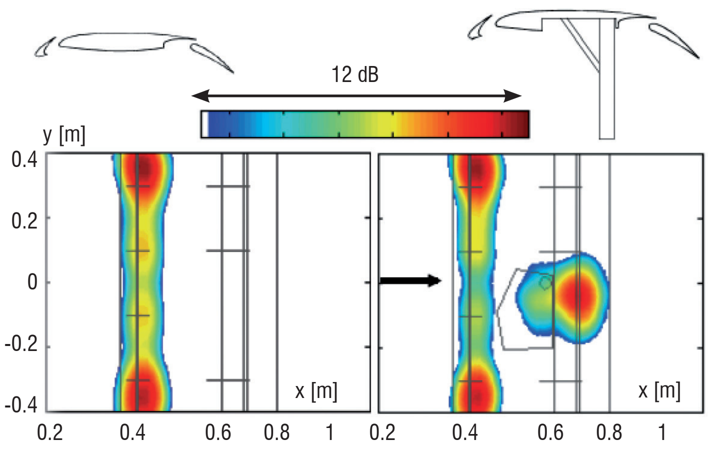

Figure 20 - Gear wake / flap interaction according to [31].

Currently, few technologies are used to limit HLD noise. On the recent A380 and A350, slats are tilted to avoid any gap between them and the wings, so that the flow cannot pass in between. It is quite effective, both from the acoustic and performance standpoints, even though this solution can be applied only on limited parts of the wing. However, some more advanced solutions are envisaged, among which slat gap optimization or suppression (for instance with inflatable cuffs), HLD edges made of porous materials, slat chevrons or even fractal spoilers are included. All of these solutions have been studied within TIMPAN and are still under investigation within OPENAIR. For instance, slat gap optimization has proven to be neutral from the aerodynamic point of view, but beneficial for acoustics: 2D simulation made in TIMPAN showed that slat noise may be reduced up to 2 EPNdB with this technology. However, the TRL for this technology is currently only 3 and is expected to reach 4 or 5 by the end of OPENAIR.

As for porous materials or fractal edges, or brushed edges, the idea behind these concepts is always the same, i.e., to avoid sudden flow discontinuities. Up to now, however, porous materials have been too brittle to comply with the requested thinness of slat trailing edges and solutions based on grids or metallic meshes are suspected to generate additional tonal noise. Investigations with a Kevlar cloth cover are being continued in OPENAIR, but airworthiness considerations may still hinder this kind of technology in the future. Slat chevrons, i.e., corrugations on their trailing edges, will be experimented with also in OPENAIR, in order to suppress coherent vortex structures in the gap, as well as fractal spoilers to limit or suppress the noise presumably originating from both the spoiler side-edges and the interaction of the turbulent spoiler wake with the downstream flap.

Some much more advanced ideas have been suggested, such as adaptive leading edges (for instance with shape memory alloys or more probably through actuators) that would suppress slat gaps. However, safety concerns, which require traditional slats (in case of rear wind for example) have prevented advanced investigations of the concept up to now.

Globally speaking however, HLD noise reduction technologies are quite recent and substantial progress may be expected even though basic understanding is sometimes still lacking and though noise reduction may conflict with other requirements, such as performance or airworthiness. The table hereafter summarizes expectations in 2007 about these technologies. Though new official assessment is not available, these figures can reasonably be expected to remain true.
Airframe noise component Achievable with previous technologies Overall gain including TIMPAN concepts.

Airframe noise component	Achievable with previous technologies	Overall gain including TIMPAN concepts
Landing gear	4.0 dB	6.0 dB
High Lift devices	0.2 dB	4.0 dB
Overall airframe noise	1.7 dB	5.0 dB
Overall aircraft noise	N/A	2.5 to 3 dB

Table 2 - expected gains for various devices before and after TIMPAN

Cavity noise

In addition to Landing gear and HLDs, cavities are also a matter of concern for noise. Actually, numerous devices are embedded in the surfaces of aircraft, which have surface irregularities (hatches, hooks, slits, holes) globally termed as "cavities". These cavities usually trigger detachments of the turbulent boundary layer, which act in turn as a noise source.

As for HLD and landing gear, the theoretical way to avoid this spurious noise source is well-known (i.e., basically filling the cavities!) though this harms their operational purpose. Therefore, recipes leading to the reduction of this noise source usually stem from compromises between the operational optimization and noise issues.

Future noise reduction technologies

What will the challenges beyond 2020 be? Previous sections presented different technologies applied, or to be applied, to still conventional engine architectures, i.e., so-called “tube and wings” equipped with turbofans. However, the challenge for reducing fuel consumption is so great that new architectures are requested. As previously mentioned, Ultra High ByPass Ratio engines (UHBR) are being studied, but with very hard integration issues, since the fan diameter is even greater than that presently used. With this option, noise reduction would basically entail pushing the same technologies further than those presented above.

However, it must be kept in mind that new noise sources could emerge from these more “open” engines, especially if traditional ones, such as fan and jet, are lowered. In this case, core machinery noise, such as compressor noise, turbine noise or even combustion noise would need to be considered. Currently, few things are known about these sources, but some preliminary work suggests that they could be more complex than expected. For instance, combustion noise is known to be divided into “direct noise” – i.e., sound directly stemming from the combustion process in the chamber – and “indirect noise”, due to the conversion of vortices into sound waves through the turbine stages. “Direct noise” was thought to be more important than “indirect noise”, however, a recent study tends to prove the contrary. Investigation work is still underway.

In addition to UHBR, another strategy could also be to continue increasing BPR using the Open Rotor architecture (OR). Noise is then the most critical issue, along with safety: Whereas single propellers radiate mostly tonal noise in the propeller plane, two counter-rotating rotors without nacelle radiate many tones over a wide frequency-range due to complex and intense noise interference mechanisms. Actually, the radiated frequencies combine all of the possible linear combinations between the two blade passing frequencies and this spectrum is propagated in all directions. Ongoing research activities are facing this drawback and several tricks are being investigated to lower this excessive noise: Tuning parameters, such as blades shape, blade length (especially differentiating the length between the first propeller and the second) and the gap between the two propellers, or even their respective rotating speeds or clocking, are among the various methods being experimented with [40]. Currently, there is reasonable confidence that Open Rotors will be able to meet the strictest regulation of Chapter 14 in a few years. From a programmatic standpoint, the main framework for such integrated research is the CleanSky research program, which will allow the engine manufacturer Snecma to produce a demonstrator by the end of the decade. Through this platform, new noise technologies, such as 3D-optimized blade design and pylon blowing in order to strongly reduce the interaction of the pylon wake with the blades, will be demonstrated. Current liner-based technologies will probably be used less, since they are both inefficient and impossible to insert into open architectures.

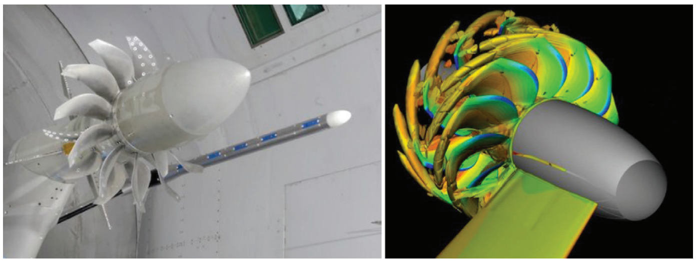

Figure 21 - Open Rotor mounted on Hera vehicle (Snecma) and under test at the S1 Onera wind tunnel and the simulation of interactions between the two propellers (Onera)

It is also worth mentioning that the most recent trends tend to locate these forthcoming Open Rotors rearward, near the empennage, between two vertical stabilizers, both to gain from the masking effect for community and to increase comfort and safety for passengers. Currently, aircraft manufacturers have not yet chosen between the two competitive technologies of UHBR and Open Rotors, but this critical choice is considered as imminent and is likely to arise before 2015.
Neither the first nor the second technological route will be sufficient to meet the stringent new objectives defined by ACARE for 2050 [21]. It is generally assumed that though 2020 objectives will be reached through enforcing new Noise Abatement Procedures (NAP) in addition to NRTs, 2050 objectives will require a breakthrough in aircraft architectures.

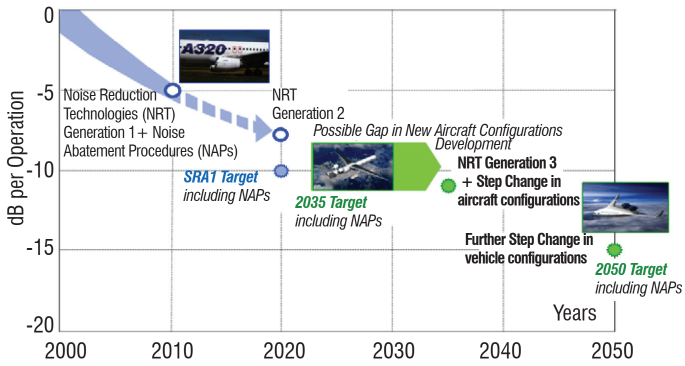

Figure 22 - Further ACARE objectives for 2050 [21]

Clearly, these most silent configurations would then involve integrating engines into the aircraft fuselage, or architectures where the engines would be completely shielded. Once again, these future configurations would strongly reduce both fuel consumption – through a dramatic reduction of the drag – and noise, with masking effects. Succeeding to build up such a configuration is a huge challenge, since it would involve fully reinventing the entire aircraft with unexplored aerodynamic effects and brand new propulsion systems. In particular, these engines would ingest air flows with intense distortion of the boundary layer, an unfamiliar configuration that remains to be addressed by research. However, the greatest challenge is probably not technical but commercial and psychological. Before engaging in such developments, manufacturers need to convince airliners of the expected benefits and the latter need to accustom their customers to the idea of embarking on such new aircraft. These are challenges that go far beyond technical issues ■

Figure 23 - Airbus views on a futuristic design for 2030 : rearward engines with or without Open Rotors (left) and embedded engines (right).

Figure 24 - The previous configurations could be ultimately superseded by flying wings in case of acceptance by the market

Acronyms

ACARE (Advisory Council For Aeronautics Research in Europe)
BPR (ByPass Ratio)
CAA (Computational Aeroacoustics)
CFD (Computational Fluid Dynamic)
CROR (CountraRotating Open Rotor)
CRTF (CountraRotating TurboFan)
DAFL (Distributed Aft Fan Liners)
DOF (Degree of Freedom)
EC (European Commission)
EPNdB (Effectively-Perceived Noise Decibels)
FP (European Framework Programs)
HLD (High-Lift Device)
ICAO (International Civil Aviation Organisation)
IGV (Inlet Guided Vane)
LG (Landing Gear)
NAP (Noise Abatment Procedure)
NEO (New Engine Option)
NRT (Noise Reduction Technology)
OGV (Outlet Guided Vane)
OR (Open Rotor)
QC (Quota Count)
STAR-R (Système de Technologie Active Réduit)
TOW (Take-off Weight)
TRL (Technological Readiness Level)
UHBR (Ultra-High Bypass Ratio)
VAFL (Variable Area Fan Nozzle)

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