AIRCRAFT NOISE REDUCTION – PROGRESS AND PROSPECTS

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1 HISTORICAL PERSPECTIVE

The problem of noise from aircraft is over 40 years old, having emerged with the use of the jet engine in civil aviation. The early jet engines, and rapid expansion of civil aviation in the 1960's led to a rapid growth in complaints from communities in the vicinity of airports, and this in turn led to the imposition of aircraft noise regulation through the International Civil Aviation Organisation (ICAO). A new noise unit for characterising aircraft noise was derived – the Effective Perceived Noise Level (EPNL) – which took account of the human ear response to noise, the effects of annoying discrete tones, and the duration of an aircraft operation (take-off or landing). Three phases of regulation stringency based on the EPNL have been imposed since the 1970's, and as a result aircraft produced today are about 20dB quieter per operation than the early jet aircraft, see **Figure 1**. However, growth in civil aviation of around 5% per annum has led to a large growth in the worldwide aircraft fleet size, and an increase in the average size of aircraft.

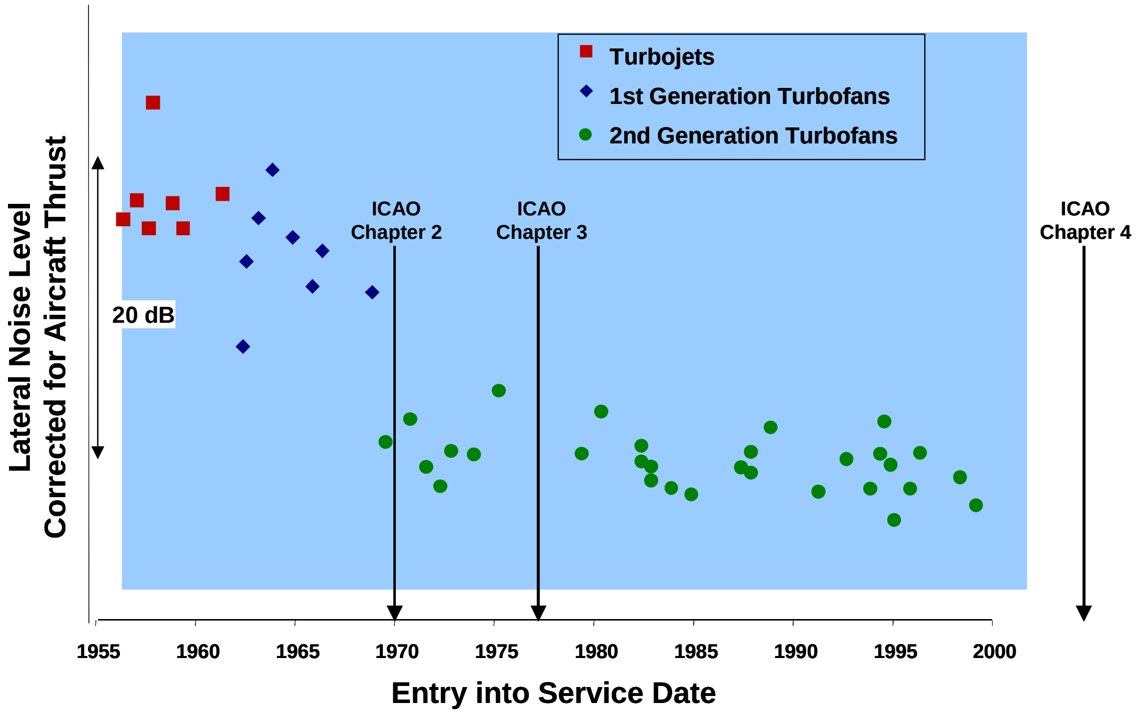


Figure 1: Historical Progress in Jet-Powered Aircraft Noise Reduction

Today, aircraft noise remains as emotive an issue as it ever has been. The recent UK Government White Paper on the Future of Air Transport[1] clearly recognises the environmental impact of aviation on the local communities near airports. The UK Government is to play a greater role in pushing for new solutions and stronger action by international bodies to address the environmental impact of aviation. This means increasing stringency of standards, withdrawing old aircraft and the use of economic instruments.

More recently, control of the noise within the aircraft cabin has also begun to receive more attention. The airframe manufacturers are marketing passenger comfort as a competitive discriminator, and there are new health and safety concerns for cabin crew, exposed to noise for very long durations.

2 THE NATURE OF THE PROBLEM

Reduction of aircraft noise is about optimisation of the whole vehicle, including the way it flies. Both the engine *and* airframe designs are important in determining the total aircraft noise (see **Figure 2**).

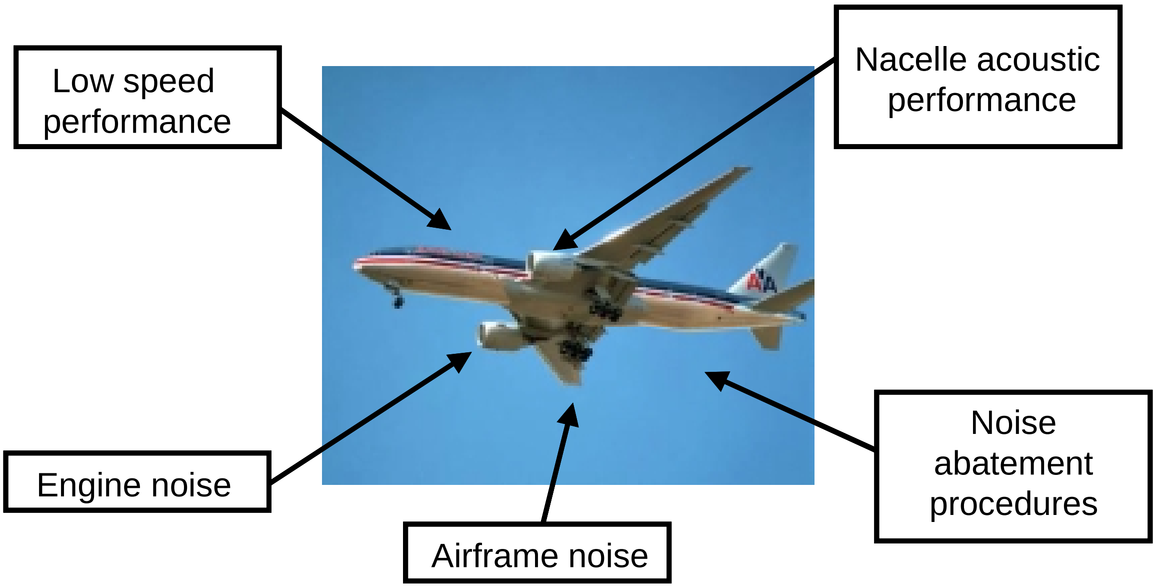


Figure 2: Aircraft Noise control

At take-off, the engine is the major source of noise and the performance of the acoustic treatment built into the engine nacelles is important in attenuating the noise sources associated with the rotating machinery. In addition, however, on modern aircraft the noise of the airframe moving through the sky is as important as the engine noise at the approach to landing condition. The aircraft low-speed performance has an important influence on take-off noise, since the thrust required, and altitude gained, greatly affect the noise heard on the ground. Finally, noise abatement procedures have been developed and are being implemented by local airports, to minimise the noise suffered by nearby communities.

Aero-engine design has undergone a revolution since the early jet age, to address both improvements in fuel efficiency and noise reduction (see **Figure 3**). The pure turbojets and early turbofans of the 1960's were dominated by high jet exhaust noise, a loud roar or rumble. In this figure, the size of a lobe indicates the magnitude of the noise source, and the direction of the lobe indicates where the sound level peaks. Jet exhaust noise was high because the early jet engines accelerated a small quantity of air to a very high jet velocity.

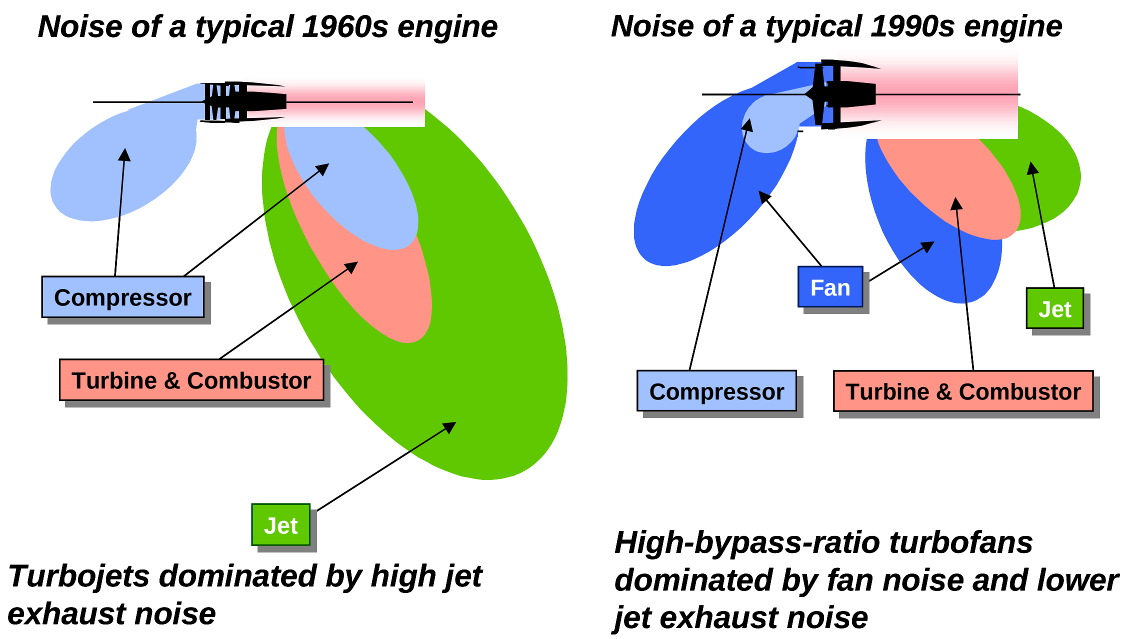


Figure 3: Sources of Aero-engine Noise

The high-bypass-ratio turbofans of the 1990's were designed to accelerate a larger quantity of air to a lower exhaust velocity. Therefore, they have significantly reduced jet velocities for the same thrust and consequently make much less jet noise. These engines are dominated by fan noise, a high-pitched whine or whistle, although jet noise is still a significant contributor at take-off conditions.

As a result, engine noise sources are now more evenly balanced, and indeed, at approach conditions, where the engines are at low power, noise from the engines and the airframe itself are roughly equal. This means that further reductions must rely on addressing noise from many individual engine and airframe sources. **Figure 4** illustrates that reductions in jet exhaust, fan and airframe noise are required equally to make a significant impact on total aircraft noise.

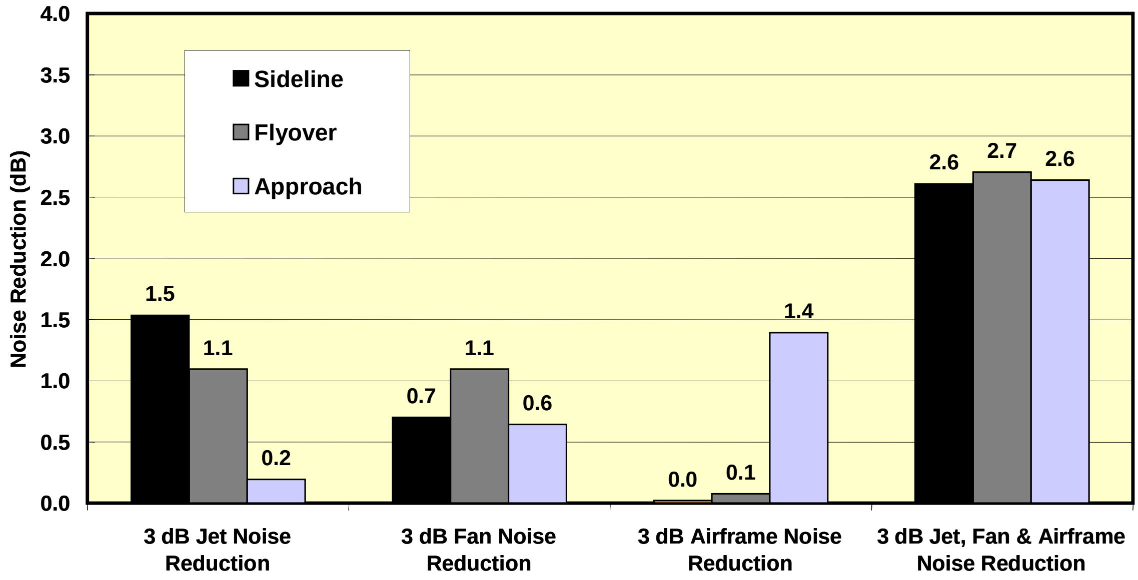


Figure 4: Typical Relationship Between Component and Overall Aircraft Noise Reductions

3 FUTURE AIRCRAFT NOISE TARGETS

In 2000 the European Union Commissioner, Philippe Busquin asked a distinguished group of representatives from the European Aviation industries, to set out their vision for the future of aviation in the medium and long term. Their report[2] "European Aeronautics – a vision for 2020" was published in 2001. The Advisory Council for Aeronautics Research in Europe (ACARE) was set up with the objective of realising this goal. In 2002 the Strategic Research Agenda was published which set out a challenging and holistic programme which included a noise goal aimed at meeting the environmental challenge for 2020 - to reduce perceived external noise by 50 percent, or 10dB (see **Figure 5).**

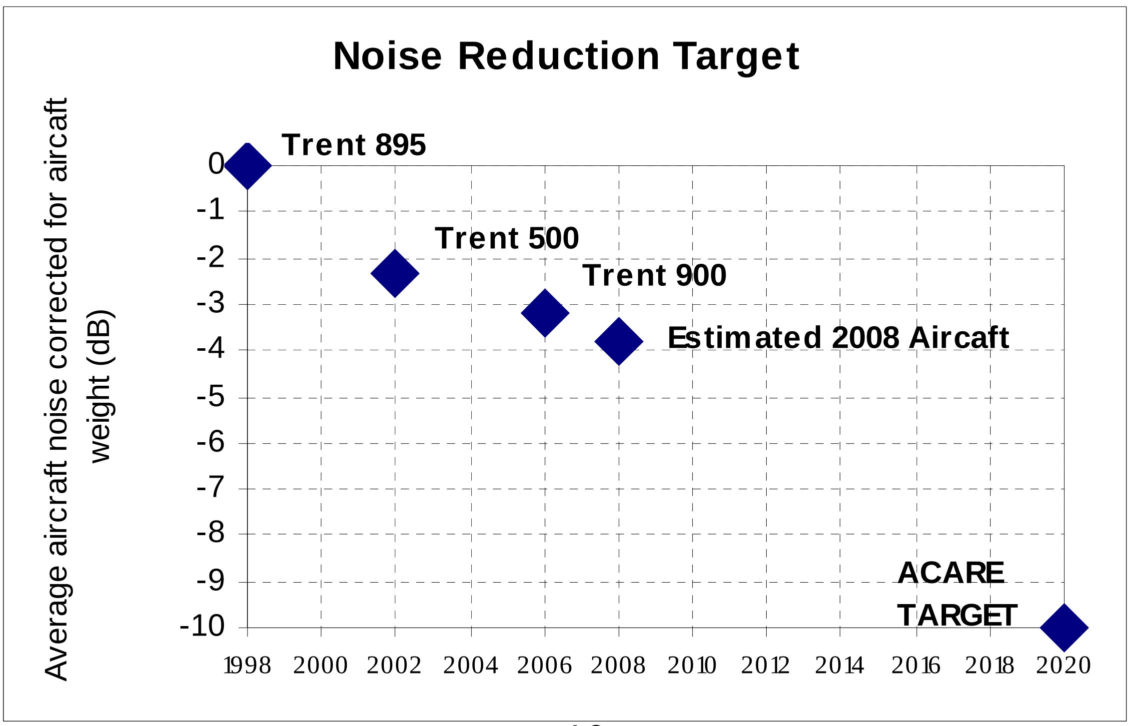


Figure 5: Aircraft Noise Reduction Research Targets

The European (and US) aircraft noise research programmes are aimed at meeting this ambitious goal, and success is dependent on sustained funding. Also, there are several conflicting requirements in designing an aero-engine and noise solutions must be compatible with other requirements, namely emissions and fuel burn, the aircraft performance, the aircraft operating costs and the business needs of the manufacturer and operator.

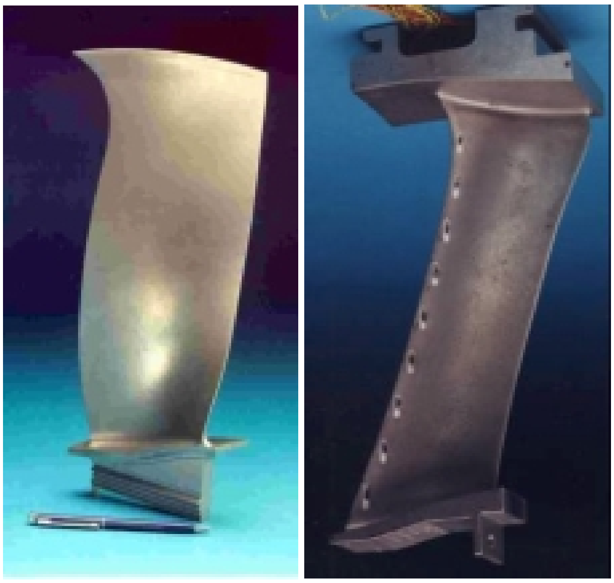
Associated with the implementation of any new low-noise technology, there is inevitably a benefit gap (a reduction in the noise benefit achieved in the final product compared with early expectations) and a product transition time (a delay between technology being available 'on-the-shelf' and its general appearance in the world aircraft fleet)

4 ENGINE NOISE TECHNOLOGY

4.1 Fan Noise Reduction

Design features of the fan system for minimum noise have included optimizing blade/vane numbers and axial gaps, sweeping the rotors to minimize shocks, and sweeping stators to minimize fan rotor-stator interaction tones. Key issues are the fan aerodynamic and mechanical performance, stability and stall margin, and the manufacturing complexity and cost.

Just as swept propellers developed for regional aircraft have reduced noise, sweeping fan rotor blades (**Figure 6**) also reduces noise and is particularly effective when the fan blades operate at supersonic speeds. Sweep can reduce the shocks ahead of the fan rotor and benefits of the order of 2 to 4 decibels are seen for fan tone noise radiating from the intake at high power. Great care must be taken in ensuring good design and off-design fan aerodynamic performance and stall margin, as well as adequate mechanical stability margin.



Swept Fan Rotor **Swept Fan Stator**

Approach:
- **Minimise aerodynamic shocks ahead of fan rotor blades**
- **Reduce unsteady loading on stators**
- **Reduce efficiency of radiation of stator noise**

Key Issues:
- **Fan aerodynamic and mechanical performance, stability and stall margin**
- **Manufacturing complexity & cost**

Figure 6: Fan System technology

Advanced stationary guide vanes behind the fan blades, with reduced response to the fan wakes, have been designed and tested. 3 to 5 decibel reductions in fan interaction tone noise have been demonstrated in rig tests for certain geometries using the concept of sweeping and leaning the vanes to avoid simultaneous wake "slap" all along the length of the vanes. This concept holds promise for both nearer term and longer-term engine designs. Risks include adverse aerodynamic performance, manufacturing cost and complexity, and mechanical integrity.

4.2 Nacelle design to attenuate turbo-machinery noise

Enhanced attenuation of turbo-machinery noise within the nacelle can be achieved both by optimizing acoustic lining design and technology and by optimizing the nacelle aerodynamic design for noise.

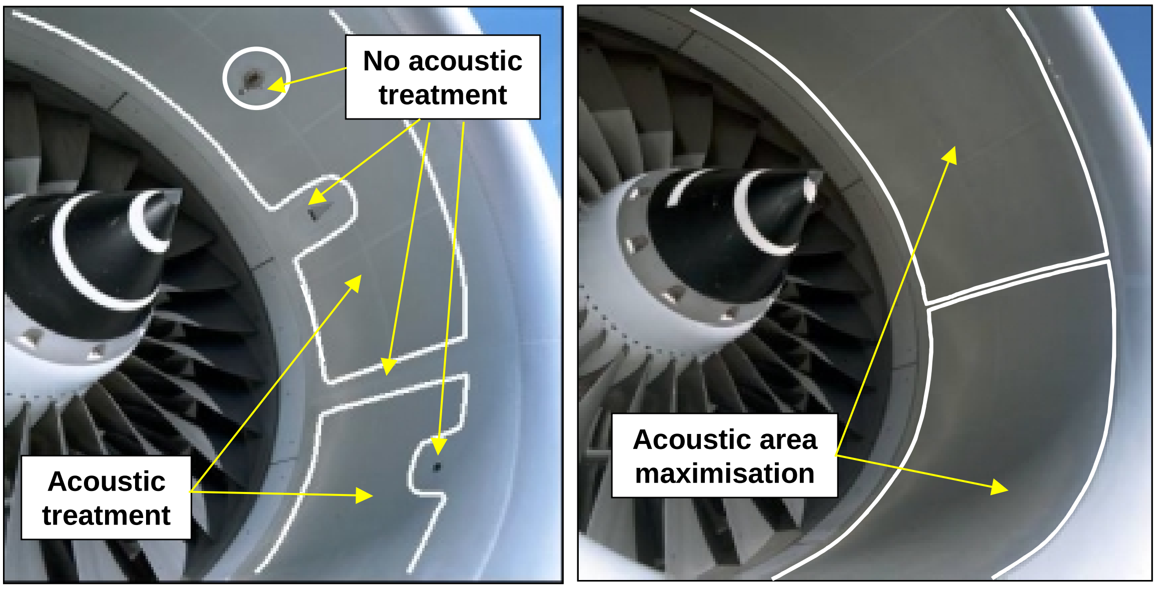


Figure 7: Inlet Acoustic Liner

Acoustic liner area maximization and continuity are key manufacturing and design technology trends being developed to increase effective acoustic liner areas in the inlet, fan case, and bypass ducts. The technology includes extending the inlet liner to the lip highlight and minimizing acoustic liner splices, gaps, and patches (see **Figure 7**). This has not only led to substantial noise reductions for communities near the flight path, but also within the aircraft cabin.

Significantly increased in-duct sound absorption can be achieved not only by extending effective treated areas but also by better matching the liner specification to the acoustic wave pattern. Advanced anti-icing systems are required for liner area maximization to the lip highlight. Other key implementation issues include structural integrity, weight, and maintenance in terms of replacement or repair of damaged panels.

The concept of a negative-scarf inlet with a lower lip extending forward of the upper lip has the potential to reduce forward fan noise by up to 3 decibels by redirecting the forward fan noise pattern away from the ground. The major challenges for the negative-scarf inlet are aerodynamic performance and operability, weight penalty, potential cabin noise increase due to higher buzz-saw noise, and difficulty in retrofitting to existing aircraft.

4.3 Jet Exhaust Mixing Noise Reduction

The advent of the high-bypass-ratio aircraft engine has provided a substantial, revolutionary reduction in engine noise. In recent years, technology advancements have allowed even higher bypass ratios to be considered- from today's bypass ratio of around 5:1, to bypass ratios of 8:1 to 10:1 and beyond. These very-high-bypass-ratio engines provide a noise advantage, because the engines can run at lower speeds and expel exhaust gases at slower velocity for the same thrust, thus reducing the generated noise. They also provide reduced specific fuel consumption (fuel flow rate per pound of thrust produced). The price to pay for very-high-bypass-ratio engines is increased size, weight, and drag, which can result in more mission fuel burn. These costs must be weighed against the noise benefits. Higher bypass ratio engines require much higher pressure-ratio and temperature gas generator cores, which may have a negative effect on emissions, especially NOx. Nevertheless, substantial exhaust noise benefit has been demonstrated for aero-engines with very high bypass ratios, the B777 powered by the GE90 and the A340 powered by the Trent 500 being examples.

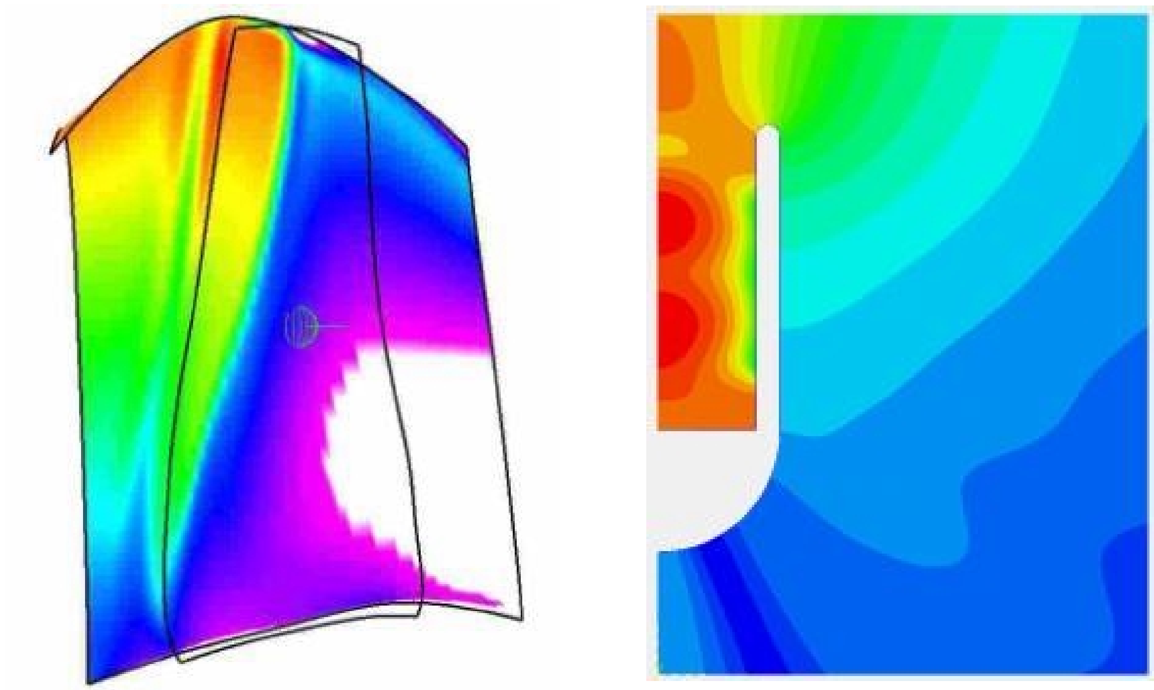
The efficiency of exhaust nozzle "lip treatment", in the form of serrations or "chevrons" at the edge of the nozzle has been verified on engine tests statically and in flight (see **Figure 8**).

Figure 8: Exhaust nozzle "serrations" or "chevrons"

This concept provides 2 to 4 decibels reduction in jet exhaust mixing noise with minimal effects on fuel burn. It works best at the lower (3 to 6) bypass ratios, where the expelled exhaust gases are at higher velocity. The nozzle lip treatments promote rapid mixing of the expelled exhaust gases with the outside atmosphere, but without the generation of high turbulence that past mixing devices have created. However, some challenging issues still need resolution, for example, how better to design these treatments in the vicinity of the engine support pylon, how to improve structural design to minimize chevron vibration and fatigue, and how to preserve nozzle flow performance at off-design and cruise conditions. Nevertheless, the concept has been shown to be effective with the suitable airframe and engine configurations and has been incorporated on some jet aircraft including the newest regional jets.

4.4 Advanced Computational and Measurement Techniques

The design of low-noise components are benefiting significantly both from advanced computational techniques (such as Computational Fluid Dynamics and Computational Aero Acoustics applied to airframe, nacelle and aero-engine noise problems) and from advanced measurement techniques (such as noise source identification and localization techniques applied on rigs and to aircraft and engines). Computational Fluid Dynamics and Computational Aero Acoustics contribute to improved understanding of the noise generation and propagation, and hence to the optimization of component designs (see **Figure 9**). Noise source location techniques contribute to improved understanding of the dominant noise sources and hence to the definition, evaluation and refinement of solutions to reduce noise.



Fan Blade Computational Fluid Mechanics (CFD) Assessment

Inlet Computational Aero-Acoustics (CAA) Assessment

Figure 9: Computational Methods applied to Aero-engine noise

5 FUTURE CHALLENGES

In the future, technology will continue to play a significant role in reducing the noise around airports. Significant progress has already been made in reducing aircraft noise over the past 40 years, and aircraft, engine, and nacelle manufacturers are investing in extensive research programs targeted at delivering additional technologically feasible and economically reasonable improvements. Further significant noise reductions, however, will depend on substantial progress in reducing the many different complex noise sources that contribute to the aircraft noise signature, and will therefore necessitate sustained investment. Comprehensive international noise research programs have been launched, involving industry, research establishments and universities; many promising and exciting concepts for reducing noise are being evaluated and developed, but substantial efforts will be required to prove and implement these ideas for product aircraft application. In parallel with the development of such technologies to reduce noise, it is crucial that technology is not considered in isolation, but in the broader context of the balanced approach to reducing the noise around airports; all possible cost-effective means to improve the noise situation must be explored, including noise abatement procedures that can themselves benefit from technology advances. Finally, the noise benefits achieved must be protected through proper land-use management around airports.

Some active aircraft noise research areas for the future are outlined below.

5.1 Active Noise and Flow Control, and Adaptive Systems

Active control techniques for reducing noise have been considered for some time. Various approaches have been adopted, all essentially generating anti-noise with opposite phase, controlled in real time. Active noise control has been developed and demonstrated for relatively simple sources of sound, for example quieting of air-conditioning duct noise and automotive engine exhaust noise. For aircraft engines, however, the noise sources are an order-of-magnitude more complex, and of significantly higher intensity, making the application of Active Noise Control much more difficult. The technology has been developed for reducing aircraft cabin noise but it still needs considerable development before it is ready for application in commercial aircraft to reduce the community noise around airports. Concepts being developed involve actively canceling the sound generated by the fan, either by introducing fan intake and exhaust duct “anti-sound”, or by actuators that are mounted on the stator vanes to cancel out the sound generated by the interaction of fan rotor wakes with the vanes (see **Figure 10**).

Approach:
Generate anti-noise with opposite phase, controlled in real time to achieve optimum reduction of fan noise at source at all conditions

Key issues:
- **Design, manufacturing & integration complexity**
- **Affordable micro-controllers**
- **Potential weight penalty**
- **In service reliability & maintenance**

Figure 10: Active control of Aero-engine Noise

This is a longer-term high-risk research concept, involving complicated actuators, sensors and control system. Some of the issues associated with active noise control of fan noise are controllability, weight, manufacturing and integration complexity, performance impact, and in-service reliability and maintainability. It is yet to be demonstrated that active noise control methods can compete with simpler passive methods.

Active Flow Control to reduce noise at source can be applied to fans, jets and airframes. Suction or blowing can be used to modify the flow characteristics of wakes, flow separations and shear-layer development, in order to reduce noise.

In engine and nacelle ducts the character of turbo-machinery noise depends on the aircraft and engine operating conditions, so that significantly improved noise attenuation could be achieved by replacing or complementing passive liners by systems capable of adapting their acoustic properties to match the in-duct sound field. Solutions under investigation include mechanical adaptive liners, the geometry of which can vary according to sound field, and acoustic adaptive liner, where the acoustic pressure in the liner is actively controlled. Like active control systems, these technologies are long-term high-risk concepts, which will be very complex to integrate and require further demonstration.

5.2 Aero-acoustic Broadband Noise

As the bypass ratio of aircraft engines is increased, jet exhaust noise is reduced and fan noise becomes a more significant component of aircraft noise at both landing and take-off conditions. Fan noise is composed of tone and broadband noise. For many years, great efforts have been made to study, predict and reduce the tone noise component. As a result, periodic deterministic mechanisms such as Fan/OGV interactions, shocks at the Fan leading edge, inflow distortion interacting with the Fan and others can be currently predicted by using CFD codes, and controlled through design changes.

With the introduction of aero-engines with wide-chord rotor blades and large fan diameter, the fan broadband noise has shifted to lower frequencies and has increased in relative importance. As a consequence, renewed interest and concern in the broadband noise component have arisen.

Tone noise is generated by deterministic periodic flow fluctuations. Conversely, broadband noise is generated by stochastic wall pressure fluctuations induced on both the fan blades and the stator vanes by the turbulent part of the flow (inflow perturbations, inlet-duct turbulent boundary layer, wake behind the fan rotor blades, tip-clearance vortical flow, trailing edge fluctuations, etc.). Since the source mechanisms involved in broadband noise generation are complex and scarcely separable from each other, the aero-acoustic research must be extended beyond the level available today for tone noise predictions.

Broadband noise prediction techniques currently used by aero-engine manufacturers are substantially semi-analytical approaches developed in the past for simplified geometries, e.g. isolated semi-infinite flat plates. An important progress at this primary stage should consist in taking into account some turbo-machinery features in order to develop improved theoretical models. This is particularly the case of the following source mechanisms.

- Fan/OGV interaction. The noise is predicted using semi-analytical techniques based on approximated expressions of the blade/vane acoustic response to impinging turbulent disturbances, modelled as gusts. The turbulence characteristics can be estimated by using conventional CFD calculations.

- Trailing-edge noise, also referred to as self-noise. This is a quite complex problem that has been firstly investigated by using analytical approaches based on spectral flow quantities and simplified blade geometries. The spectral flow characteristics are scarcely determinable by means of conventional CFD techniques.

- Rotor blade interaction with the turbulent boundary-layer in the tip-clearance region. A simplified theoretical model exists, but its exploitation in a turbo-machinery context is questionable. Advanced CFD/CAA techniques are probably the only way to feature this important source of broadband noise.

The use of direct numerical simulation of turbulent flows, now possible due to the seemingly endless improvements in computing performance, offers a additional means of addressing this complex problem. These numerical techniques, coupled with some detailed experiments, provide some hope that new engine component designs will eventually be capable of reducing broadband noise levels.

6 NOVEL AIRFRAME AND ENGINE ARCHITECTURES

Airframe and propulsion system design processes are becoming more and more closely integrated, and new aircraft concepts and architectures that minimize aircraft noise are expected to emerge. Engine noise shielding by the airframe can be achieved by installing propulsion systems either over the wing or at an upper position at the rear of the fuselage with the tail-plane providing some rearward masking. Beyond the optimization needed to obtain a substantial reduction of the noise perceived from the ground, considerable effort and innovation will be necessary to achieve propulsion system structural and aerodynamic integration that ensure aircraft safety and efficiency. Some novel airframe designs (see **Figure 11**) offer the potential for reducing noise, not just by reducing airframe noise or by shielding engine noise, but also by reducing the thrust required.

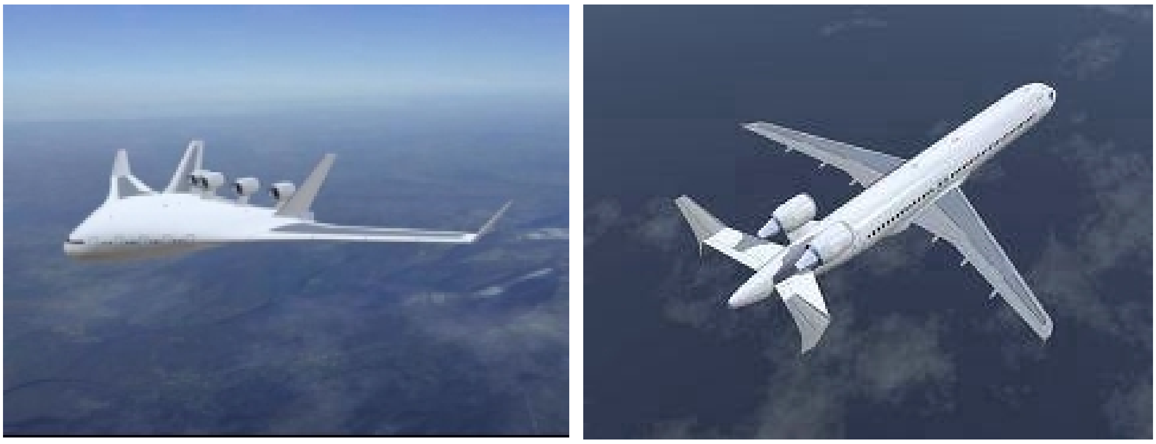


Figure 11: Novel low-noise Airframe & Engine installations

Increasing still further the engine's bypass-ratio and the fan diameter can reduce jet noise. However such ultra-high-bypass-ratio engines can result in excessive powerplant weight and drag. Research is therefore needed to develop lightweight fan systems and both lightweight and low-drag nacelles.

Decreasing its rotational speed can reduce noise from the fan. If the fan can be made to run at less than sonic tip speeds at important community noise conditions while still maintaining airflow and thrust, then a substantial noise reduction, of the order of 2 to 4 decibels on fan tones, can be achieved. Such a fan is probably best suited to ultra-high-bypass-ratio engines, where only modest fan pressure ratios are required. Key issues for this concept include maintaining good off-design performance and stall margin with re-design of the entire engine to drive a low-speed fan, either by a greater number of lower-speed turbine stages or through use of a gearbox. This brings the added uncertainty of gearbox horsepower limitations, maintenance and reliability. The noise benefits are substantial, but the concept is considered high risk, and therefore much development time and resources will be required to bring the concept to product fruition.

7 CONCLUSION

This paper has reviewed the progress that has been made in aircraft noise reduction since the early days of the jet age. Society still regards aircraft noise as a major environmental issue, and the aerospace industry has set itself very ambitious targets to address these concerns. Further aircraft noise reduction is more difficult now, as the noise sources are more evenly balanced between the engine and airframe. Effort therefore has to be targeted at all the major noise sources – engine/airframe, rotating machinery/exhaust jet, tones/broadband. However, as a research area, aircraft noise continues to thrive and many new ideas and techniques are being developed. These together have the potential to reach the ambitious targets that have been set.

8 REFERENCES

1. 'The Future of Air Transport', UK Department for Transport White Paper, December 2003.

2. 'European Aeronautics: A Vision for 2020', Advisory Council for Aeronautics Research in Europe, January 2001