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PREDICTING AND REDUCING AIRCRAFT NOISE

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Abstract

The aircraft noise problem is defined and the engine and airframe sources which contribute to it are described. The international framework for assessing and measuring aircraft noise is outlined, and the use of Effective Perceived Noise Level (EPNL) as a measure of aircraft noise is related to the engineering task of developing technologies to reduce noise. The considerable progress that has been made in reducing aircraft noise over the last four decades is reviewed and the targets which have been set in Europe for further noise reduction by 2020 are discussed. The state of the methods currently available for predicting the different elements of whole aircraft noise is presented and their effectiveness is reviewed in four specific areas; fan and turbine noise, jet noise, airframe noise and installation effects. Noise reduction technologies which have been developed or are currently being developed are also presented. More radical measures which may be needed to address the the problem in the longer term are also touched upon.

1. INTRODUCTION

Aircraft noise has long been a major concern to residents around airports. The strengthening of regulations on community noise near airports has ensured that the reduction of noise generated by aircraft at take-off and approach remains an essential consideration in the design of new commercial aircraft. In a broader context, the environmental impact of air transport as a whole poses a major threat to its continued expansion. The reduction of noise and emissions is now critical to the continued prosperity of the aerospace sector and an essential prerequisite for the successful development of new aircraft.

The environmental impact of aircraft noise is essentially a 'local problem'. It arises at takeoff and landing, affects populated areas close to airports but is not generally an issue at cruise, except in the case of supersonic transport over land which will not be touched upon here. Aircraft emissions on the other hand, particularly carbon emissions, pose a global problem, being related directly to fuel burn throughout the flight. These two major environmental issues, noise and emissions, are not however unrelated. It is usually possible to reduce noise

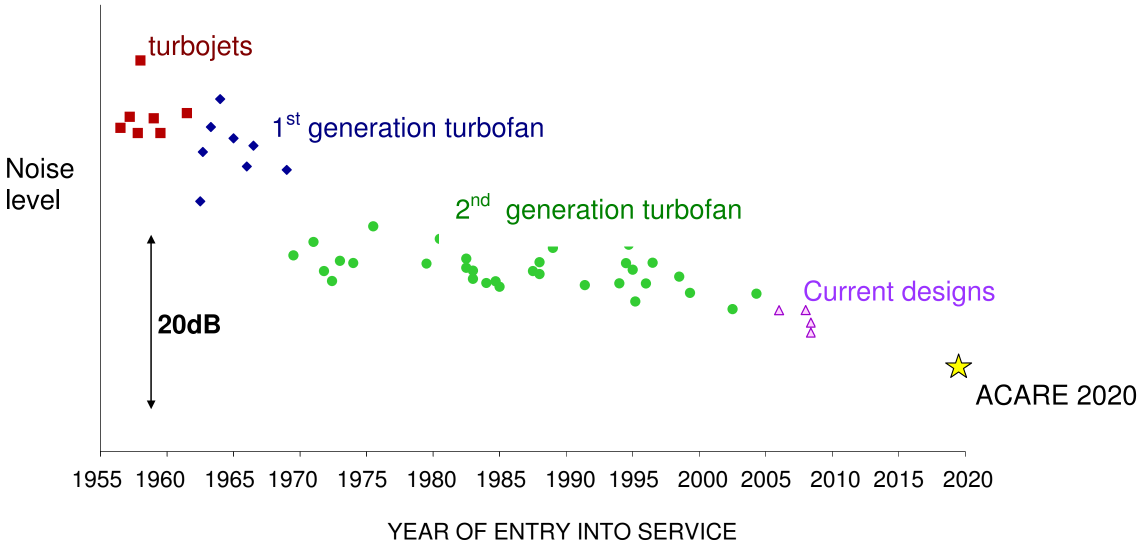


Figure 1. Progress in aircraft noise reduction.

at the expense of weight and/or aerodynamic drag, and hence fuel consumption. In the past, purely commercial arguments have mitigated against tradeoffs of this type except in exceptional circumstances. The argument against them now is more compelling, being based not only on operational cost, but on the associated environmental impact of increased fuel burn and carbon emissions. Noise benefits must now be secured without compromising fuel burn, and must indeed deal with new noise challenges such as contra-rotating fans and propellors, where these are able to deliver significant carbon benefits.

The scale of the challenge that is faced by the aviation industry is formidable. In the UK, air traffic has increased five-fold in 30 years. Half the population now flies at least once a year and freight passing through UK airports doubles every ten years. Such statistics will be eclipsed in the decades to come by the expansion of civil aviation within emerging giants such as India and China. It seems unlikely that curtailment of the demand for civil aviation will be acceptable to the global community as these new economies seek to enjoy the benefits of air travel which exist currently in the developed nations. These benefits are enormous. Aviation links communities, individuals and businesses and is a critical factor in the development of the global economy. If these benefits are to continue to be enjoyed in a sustainable environment, expansion in seat capacity and aircraft movements must be accompanied by a commensurate reduction in the environmental cost. If this is to be achieved, it will require innovative technology solutions for noise and emissions.

While the challenge is formidable, past performance tells us that the situation is not impossible. The modern commercial aircraft is 75% more fuel efficient per passenger kilometer than the first generation of jet aircraft. Noise reduction is no less spectacular. Figure 1, shows the record of the aviation industry in reducing the noise[2] of aircraft entering service since the widespread introduction of commercial jet aircraft in the 1960s. The record is remarkable. The

[2] we will define what we mean by this a little later

‘jumps’ which occur are due to distinct changes in engine design and bypass ratio, but there is also a steady improvement within each generation of engines which reflects incremental advances in other noise reduction technologies. This has steepened in the last decade as analysis techniques and prediction methods have improved. It is encouraging to note for example that the target set by the the Advisory Council for Aeronautics Research in Europe (ACARE)[3] for a 10dB reduction between 2000 and 2020 is being achieved on a ‘pro rata‘ basis in the first half of that period. The latter stages of the ACARE target will however be harder to achieve and may require more radical measures and acceptance by airlines and regulatory authorities of new operational procedures.

In this paper, research and development activities directed at predicting and reducing aircraft noise are reviewed. The problem of characterizing aircraft noise both for regulatory and engineering purposes is described in section 2. The complex balance between different engine and airframe sources as they contribute to whole aircraft noise is described in section 3. The current state of prediction methods and noise reduction technologies are outlined in sections 4, 5 and 6 for fan noise, jet noise, and airframe noise respectively. Installation effects and acoustic shielding are discussed in section 7. The importance of measurement and source location techniques is touched upon in section 8, and conclusions are drawn in section 9.

2. CHARACTERIZING AND REGULATING AIRCRAFT NOISE

Characterizing the the ‘noisiness’ of an aircraft for certification and regulatory purposes became necessary in the 1960s as the use of commercial jet aircraft became widespread and contributed to a growing noise nuisance near airports. In 1969 the US Federal Aviation Administration issued a noise certification regulation, Federal Air Regulation, part 36 [1] commonly known as FAR36. The International Civil Aviation Organisation (ICAO) subsequently issued an annex (Annex 16) [2] to the Convention on International Civil Aviation along similar lines. Annex 16 and FAR36 were essentially equivalent and remain so although both have been modified from time to time to make the requirements more stringent. ‘Chapter 4’, the latest modification to Annex 16 applies to aircraft certified after the beginning of 2006. Reference [3] gives further details on the history and substance of FAR36 and Annex16 and the relationship between them.

In FAR36 and Annex16, the metric used to measure public annoyance response to aircraft noise is the ‘Effective Perceived Noise Level’ (EPNL) measured in dB. This is determined by the frequency content, duration and tone content of the noise in addition to overall sound pressure level. The EPNL for an aircraft entering service is calculated from sound pressure recordings taken at three certification points. Two of these are at takeoff, one to one side of the flight path when the aircraft is climbing steeply at full power (the *sideline* or *lateral* condition) and the other below the flight path when the aircraft has cut back to (approximately) 80% of maximum power (the *cutback* condition). The third certification point is below the flight path as the aircraft comes in to land at a steady 3 degree glide angle (the *approach* condition). The location of the certification points is shown in figure 2. An EPNL figure is obtained at each point and rated against prescribed maximum values which vary with take-off weight and number of engines.

The regulatory situation has become more complex in recent years with the growth of lo-

[3] ACARE is a non-governmental, industry-led organization responsible in 2002 for defining a Strategic Research Agenda which informs research priorities within the aeronautics sector in Europe.

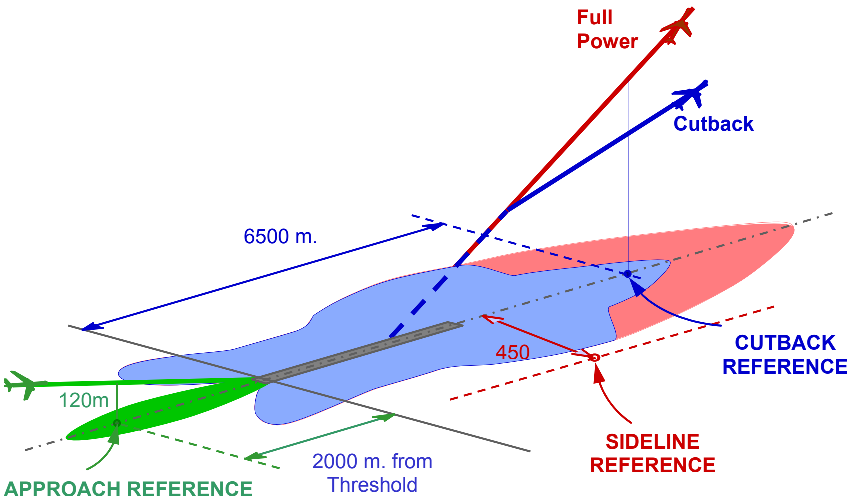


Figure 2. Noise certification points for ICAO Annex 16 and FAA FAR36.

cal airport regulations which are generally more restrictive than ICAO or FAR36 requirements. These often do not adjust for aircraft weight and apply equally to large and small aircraft. The Quota Count (QC) system developed by the UK government in 1995 to manage the noise generated by aircraft night movements at the three London Airports is perhaps the most influential of such local regulations in Europe. The impact of such requirements is illustrated in figure 3 which shows the status of Rolls-Royce powered aircraft at approach with regard to ICAO annex 16 and the Heathrow Quota Count (QC) bands. The latter regulate the number of aircraft movements which are permitted during the night curfew period (11.30pm to 6am) by means of a movements quota and a noise quota. An aircraft with a QC1 rating contributes 1 to the movements quota and 1 to the noise quota; an aircraft with a QC2 rating contributes 1 to the movements quota but 2 to the noise quota and so on. An important point to note here is that although the ICAO requirements increase with gross tonnage the QC limits do not. The commercial impact of such rules for aircraft and engine manufacturers is significant. While ICAO Annex 16 and FAR36 requirements remain the basic noise goal for engine and airframe manufacturers, achieving a satisfactory QC rating presents an additional challenge.

These certification and regulatory issues play an important role in engineering strategies to 'reduce' aircraft noise, since the success or failure of any proposed design from the point of view of noise, will be measured solely by the reduction in whole aircraft EPNL measured at the three certification points. It is not a straightforward exercise however to assess the impact of specific noise reduction measures on aircraft EPNL. Whole aircraft noise arises from a number of sources and these do not contribute equally (if at all) to EPNL at all certification points. For example, jet noise could be reduced by 10 dB at approach in a modern aircraft without having very much impact on the EPNL rating. However, if one could achieve a similar reduction at sideline or cutback this would represent a very significant improvement in EPNL. This aspect of noise characterization is examined more closely in the next section.

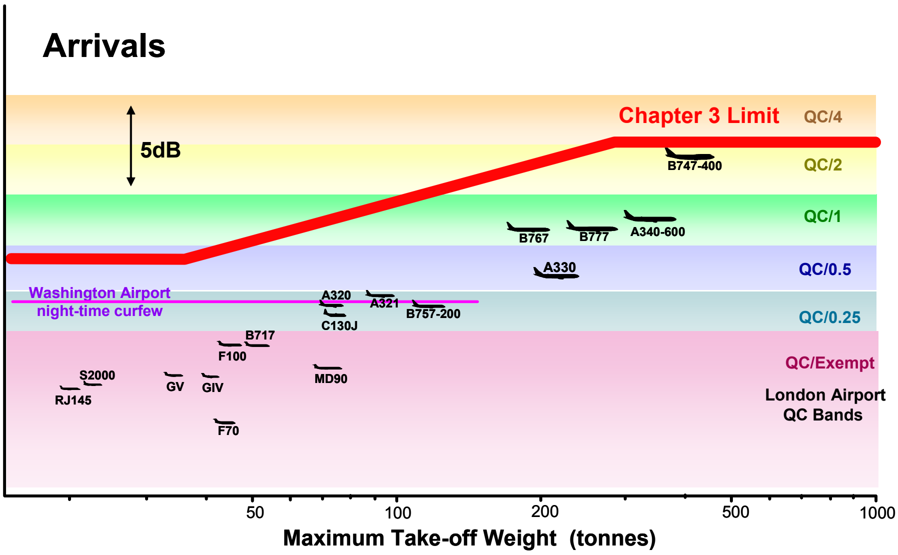


Figure 3. Noise levels for Rolls-Royce powered aircraft at approach.

3. SOURCES OF AIRCRAFT NOISE

The major sources of aircraft noise are illustrated in figure 4. The engine generates fan and compressor noise which radiate from the intake; fan, turbine and core noise which radiate from the bypass and exhaust ducts, and jet noise which is generated by turbulent mixing downstream of the exhaust nozzle. Noise is also generated by the airframe as a result of unsteady flow over the landing gear and high lift devices (flaps and slats) at landing and takeoff. All of these sources have their own strengths and directivities and combine to give the 'whole aircraft' noise signature for a given certification point.

The extent to which the balance between different engine sources has changed over the last forty years is indicated in figure 5. Here the directivity and magnitude of the sound power

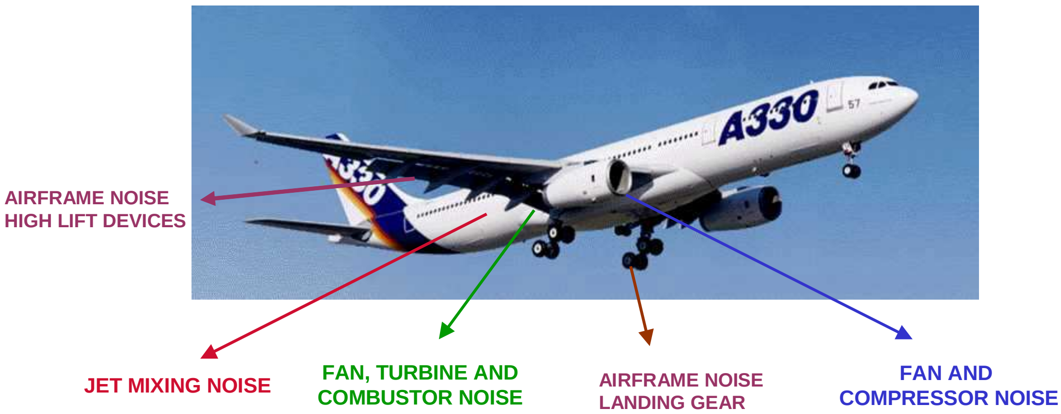


Figure 4. Aircraft noise sources.

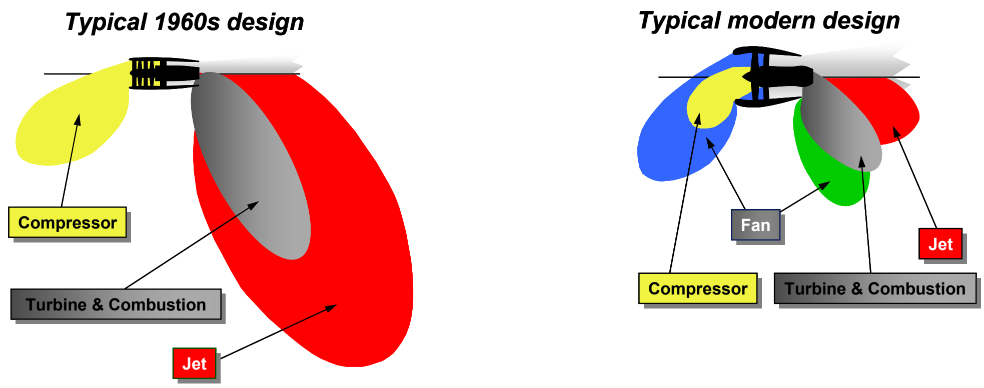


Figure 5. Engine noise sources: 1960s versus a modern design.

radiated by an early commercial turbojet is compared to that of a modern, high-bypass-ratio turbofan engine. The individual contributions from the various engine noise sources are indicated separately. The most conspicuous feature here, apart from an overall reduction in the total magnitude of the radiated sound power, which echoes the data in figure 1, is the huge reduction in jet noise. This results from the move to larger and larger coaxial streams which reduce exhaust noise by reducing the overall jet velocity. As a consequence, fan noise has equalled or replaced jet noise as the major engine contribution to whole aircraft noise. This is illustrated also in figure 6 in which the contributions of the various aircraft noise sources to the radiated acoustic power is shown at takeoff and approach. These data are typical of a modern wide bodied aircraft powered by a high-bypass ratio turbofan engine. The contributions to overall sound power level (PWL) are plotted for each major source (fan, compressor, combustor, turbine, jet and airframe). At approach, airframe and fan noise are dominant. At takeoff, the airframe contribution is small, while jet and fan noise dominate at broadly similar levels. Although not shown here, the forward and aft radiated components of fan noise are more or less evenly balanced, an important consideration when acoustic treatments are considered for the nacelle. To reduce EPNL at takeoff for example, fan noise and jet noise must be reduced, other sources being of lesser importance, especially when the logarithmic scale is taken into account. To reduce EPNL at approach however, fan noise and airframe noise must be reduced, while jet mixing makes almost no contribution in a dB sense. In the remainder of this article each of these major sources will be reviewed in more detail and the state of current prediction and noise reduction technologies in each area will be discussed.

4. PREDICTING AND REDUCING FAN NOISE

4.1. Noise generation by fans

The starting point for any discussion of fan, compressor or turbine noise is the notion of a rotating pressure field and its associated tones in a stationary frame of reference. These are ‘locked’ to the shaft rotational speed, Ω. In turbomachinery applications such *‘rotor-locked’* tones generated for example by an N bladed rotor, are periodic in the azimuthal direction with a period equal to the angular blade spacing $2\pi/N$. The associated pressure field $p(\theta_f, r)$, where θ_f is an angle in the rotating frame, can be written as a complex fourier series in θ_f on the

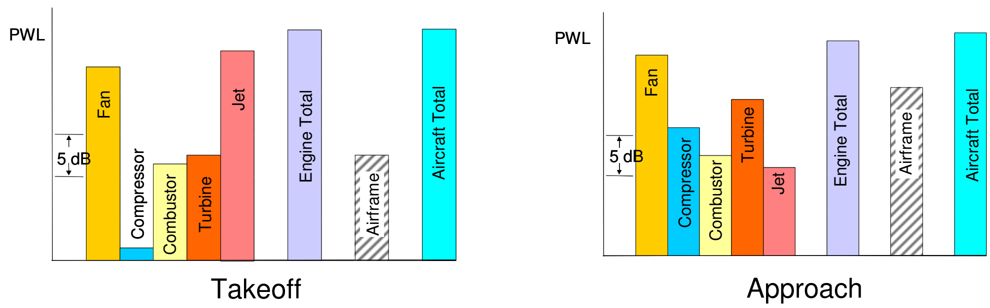


Figure 6. Relative power levels of aircraft noise sources at takeoff and approach.

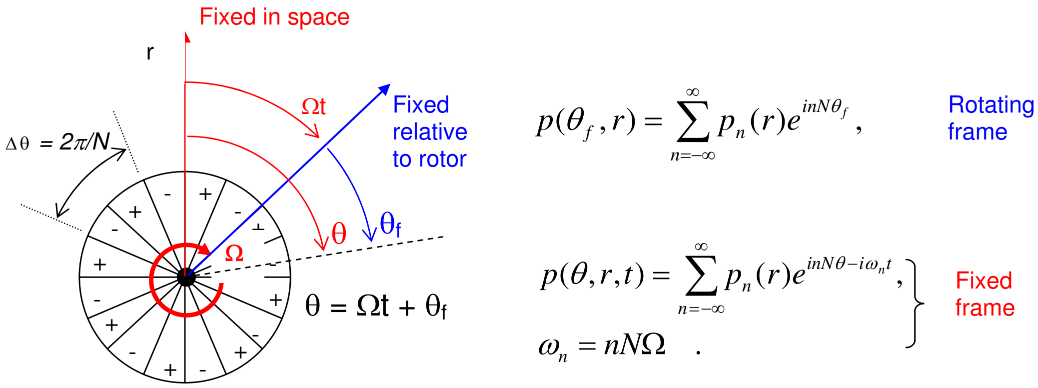


Figure 7. A rotating pressure field in fixed and rotating frames of reference.

interval $2\pi/N$, as indicated in figure 7. This transforms to an unsteady pressure field $p(\theta, r, t)$ in a frame fixed in space, where θ is given by $\theta = \theta_f + \Omega t$. The resulting pressure field has a discrete spectrum with components only at frequencies $\omega_n = nN\Omega$, integer multiples of the number of blades times the shaft rotational speed. The first of these ($\omega_1 = 1 \times N\Omega$) is termed the Blade Passing Frequency (BPF). Tones are therefore generated by this mechanism at discrete harmonics of the blade passing frequency, i.e BPF, 2BPF, 3BPF etc.

Rotor locked tones are also generated by a different mechanism at *subharmonics* of the blade passing frequency. These result from imperfect periodicity in the rotating pressure field. Termed ‘multiple pure tones’ or ‘buzz saw’ tones, they occur when the rotor tip speed is supersonic in which case shocks form upstream of the blades, as indicated in figure 8. Small angular variations in stagger angle of the individual blades are then strongly amplified by non-linear propagation close to the fan. This produces significant components in the rotating pressure field which are no longer periodic of period $2\pi/N$, and generates rotor-locked ‘Engine Order’ (EO) azimuthal subharmonics which correspond to simple multiples of the shaft rotation frequency (EO1=Ω, EO2=2Ω etc). Since the fan tip speed is supersonic in the ‘sideline’ and ‘cutback’ conditions, buzz saw tones can be significant at these certification points. They are particularly

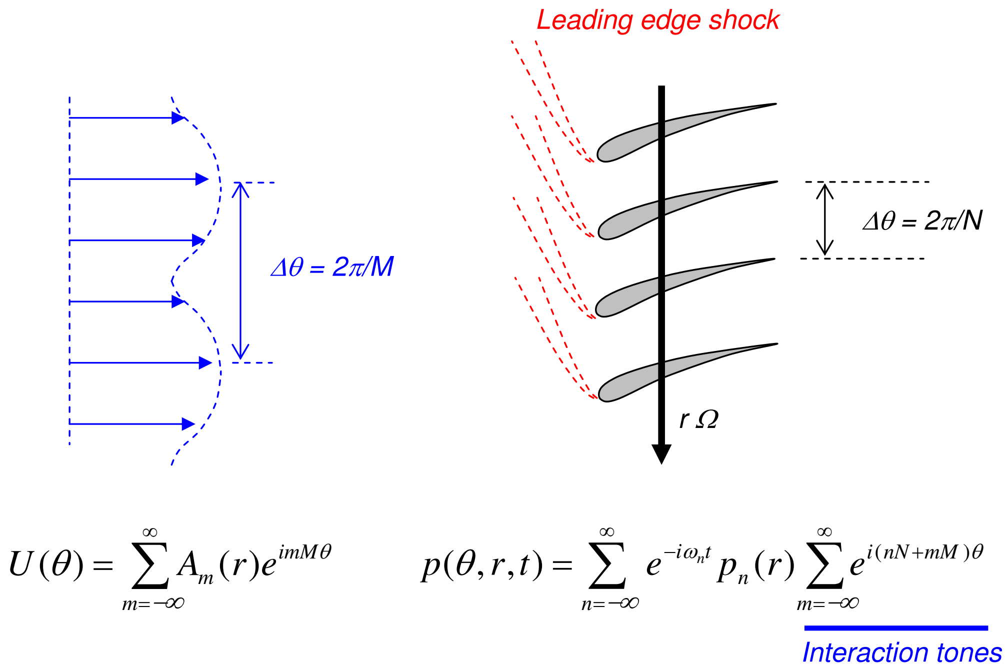


Figure 8. Interaction tones.

difficult to predict with precision since they depend upon random misalignments of the blades.

BPF harmonics and buzz saw tones are not however the only tones which are generated in the fan stage. The presence of stators or guide vanes upstream or downstream of a rotor or fan leads to *'interaction tones'*. These are *not* locked to the shaft rotational speed but are generated at the same frequencies as the BPF harmonics. They arise through the interaction of the rotating pressure field with azimuthal variations in the mean flow onto the rotor and through interactions of the rotor wakes with the outlet guide vanes. If the variations in the mean flow profile are periodic with an angular spacing $2\pi/M$ as indicated in figure 8, or if the stator has M guide vanes, the rotating pressure field in the stationary frame, from figure 7, behaves as though it was modulated by a factor of periodicity $2\pi/M$. The resulting unsteady pressure field shown in figure 8 is a summation of modes of azimuthal mode order $nN + mM$, where n and m are integers. These 'Tyler and Sofrin' modes [4] can radiate strongly even when the rotor tip speed is subsonic in which case the rotor-locked tones radiate weakly.

The general character of the fan noise spectrum generated by a modern turbofan aero-engine is illustrated in figure 9. Here typical spectra are shown for the Sound Pressure Level (SPL) measured in the forward arc during a static engine test. The frequency is normalized with respect to blade passing frequency and spectra are shown for the *approach* and *sideline* conditions. At *approach*, the first three BPF harmonics protrude from the spectrum by 20dB or more. At *sideline* they are also present but are lost within a forest of buzz saw tones. Also noticeable in both spectra is a non-tonal broadband (BB) component. Broadband fan noise is generated by random unsteady turbulent flow which occurs within the fan-stator stage. It will be discussed in greater detail a little later in this article.

Mitigation of fan noise can be achieved either by reducing the noise at source - through low noise design of the fan and stator - or by attenuating the sound by acoustic treatment in the intake and bypass ducts before it reaches the observer. These two aspects of the problem will be discussed separately, as will tone and broadband sources.

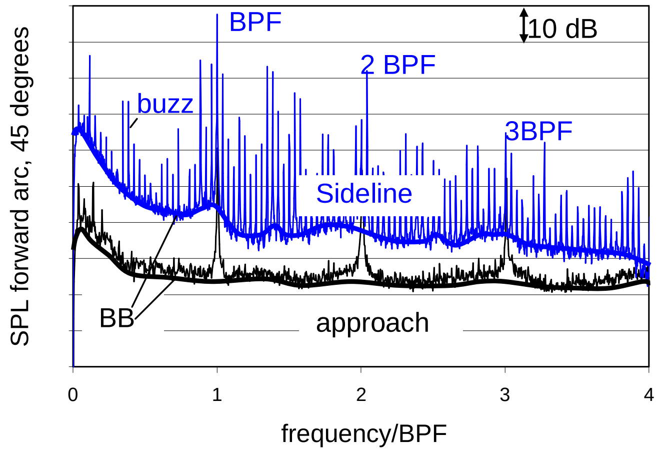
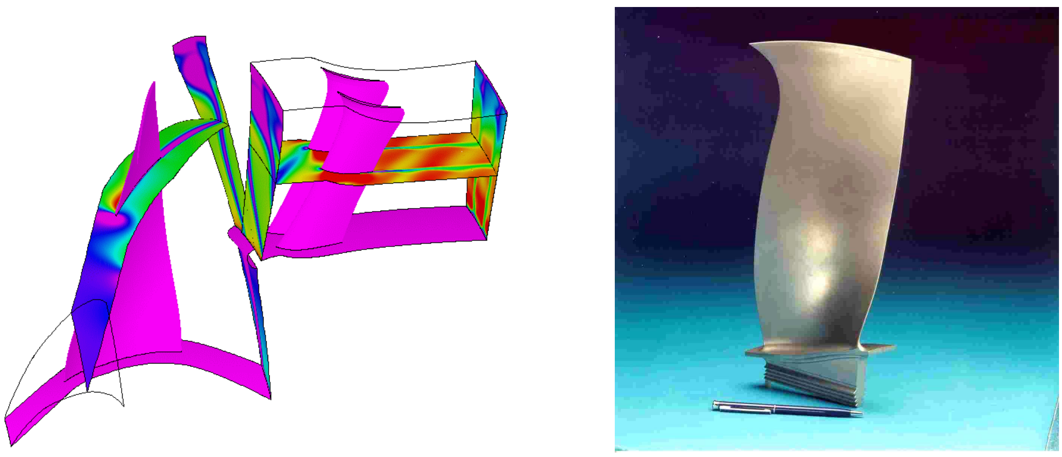


Figure 9. Forward arc engine noise spectra at *approach* and *sideline* from a static engine test.



(a) (b)

Figure 10. (a) CFD calculation of Fan / Outlet Guide Vane Interaction Tones using the Rolls-Royce HYDRA code. In this example the blade/vane ratio has been altered to 1:2 to reduce the size of the model. Alternative linear calculations require only a single passage to be modelled. (b) Example of research fan blade designed for low tone noise using CFD methods (Cambridge University and Rolls-Royce).

4.2. Predicting and controlling fan noise at source - tones

Over the last 50 years the most significant trend in engine noise has been the reduction due to increasing bypass ratio. Accelerating a larger amount of air to a lower velocity has a major effect on jet noise, but can also reduce fan noise - particularly if more time can be spent with the fan running subsonically, when the fundamental tones are naturally attenuated in the intake duct before they can be radiated to the farfield. More recently, the introduction of more highly three-dimensional designs of rotor and stator vane has given the opportunity to optimise the geometry for reduced fan tone levels. In previous years this was driven by experiment, backed

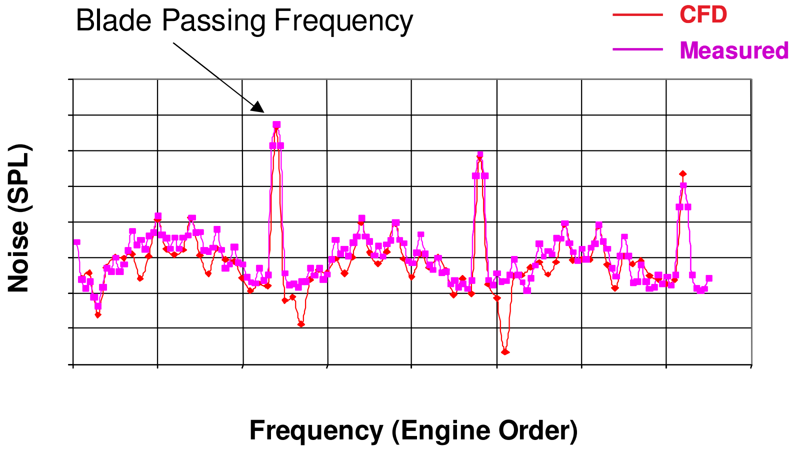


Figure 11. Measured buzz-saw tone source levels close to a fan (hardwall duct) compared with CFD predictions using the Imperial College AU3D code.

up with approximate analytic techniques. In more recent times the increase in available computing power has seen much greater use of Computational Fluid Dynamics (CFD) calculations to predict all types of fan tones. Figure 10(a) for example shows a CFD calculation of Fan / Outlet Guide Vane (OGV) interaction tones emanating from a swept OGV. The whole process, from the generation of the wake behind the rotor through the generation of sound waves on the OGV is modelled in a single high-fidelity calculation. Figure 10(b) shows a low noise research fan blade, designed using CFD methodology. Modern calculations of transonic rotor tones for blades such as this include not only the "ideal" situation with perfectly uniform blades, but also the effects of very small blade-to-blade differences. If these differences are properly accounted for it is possible to predict the source level for these "buzz-saw" tones to within a few decibels (figure 11).

It is important to note that calculation has not yet replaced the need for experiment. In terms of OGV lean and sweep, for example, calculations have in general predicted large noise reductions (up to 10dB). Experimental results have tended to be more modest. Tsuchiya et al [5], for instance, measured up to 3dB reduction in acoustic power, compared to a prediction of between two and three times that amount. The measured reductions are still very significant, however, and swept and leant vanes (as well as fan blades) have been introduced into service in many aeroengines. The future holds ever more complex three-dimensional blade geometries. It may also hold new complex flow control devices aimed specifically at reducing noise. A number of such devices have been proposed. One promising example for the longer term is "wake filling". Air is ejected at the rotor trailing edge to reduce the velocity deficit in the rotor wake, and hence reduce the noise generated when the wake hits the downstream vanes. Sutliff et al [8, 9] recorded a reduction of between 5 and 12dB in farfield tone power levels and a reduction in unsteady pressure disturbances on the downstream vanes consistent with a reduction of around 2.5dB in broadband noise.

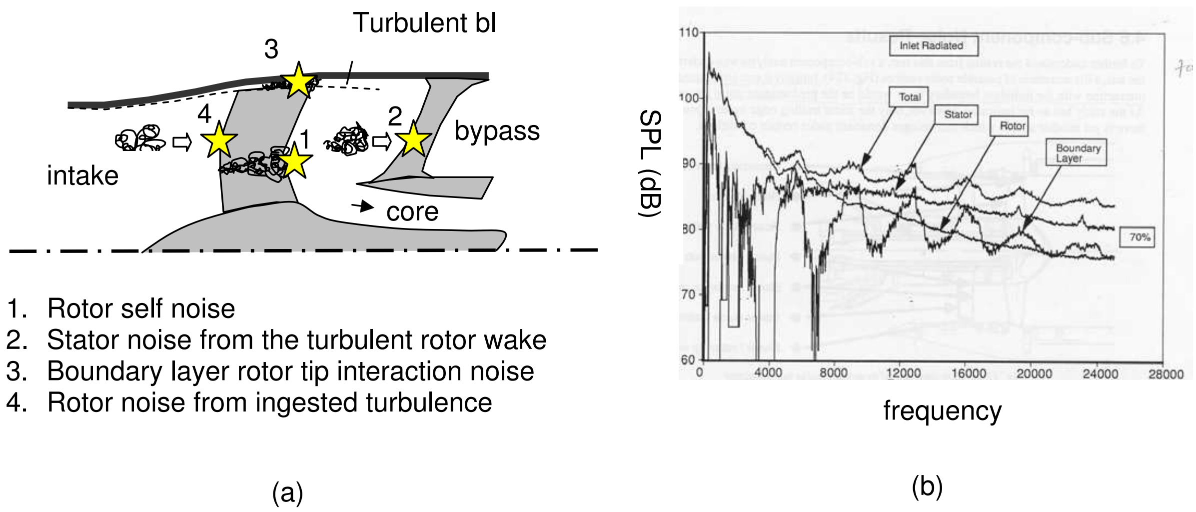


Figure 12. (a) Source mechanisms for fan broadband noise. (b) A breakdown of measured total fan broadband noise showing contributions from rotor self-noise, rotor-stator interaction noise, and rotor-boundary layer interaction noise (Reproduced with permission from Ganz et al [11]).

4.3. Predicting and controlling fan noise at source - broadband

Fan broadband noise is generated as turbulence ingested into the engine interacts with the fan and as turbulence generated in the boundary layers of the fan and intake interacts with the fan itself and with the outlet guide vanes (stator). The importance of broadband noise to perceived annoyance of overall aircraft noise was highlighted in a study into turbomachinery noise by Gliebe [10] who noted that even if one could *completely* eliminate all fan tones, total system noise (EPNL) would be reduced only by between 0.5 to 1.5 dB, depending on the operating conditions. This highlights the importance of broadband fan noise as a target in aircraft noise reduction. The dominant broadband 'sources' in the forward and rear arcs are listed below.

1. Turbulence generated in the blade boundary layer and scattered from the trailing edge ('rotor self noise').
2. Turbulent rotor wakes impinging onto the stator ('rotor-stator interaction noise').
3. Blade tip interaction with the turbulent boundary layer at the casing wall.
4. Ingested turbulent flow interacting with the rotor.

These four mechanisms are illustrated in figure 12(a). Ganz et al. [11] have performed measurements on a low-speed fan rig in an attempt to decompose the total radiated broadband noise power into its constituent sources. A typical 'source' decomposition (with tones removed) is reproduced in Figure 12(b). It shows noise from three of the above sources present at broadly comparable levels. They must therefore be reduced simultaneously to achieve a significant noise benefit. For this reason alone, fan broadband noise is exceptionally difficult to reduce at source. The following approaches show some promise however in this very difficult area. All have in common the general notion of flow control to reduce noise at source.

- Modifying the flow to reduce turbulence levels or to delay transition to turbulence. Examples of this control strategy include blowing or sucking the air close to the rotor trailing edge and bleeding off the turbulence boundary layer at the casing wall.

- Modifying the rotor or stator aerofoil geometry and separation to reduce the intensity of the wake turbulence or the unsteady aerodynamic response. Examples of this strategy include introducing serrations to the rotor trailing edge and stator leading edge and by the use of porous trailing edge extensions.
- Vibration of the stators to reduce the unsteady aerodynamic response to impinging turbulence.

None of the above strategies has yet demonstrated that it can deliver significant noise reductions in an industrial environment. However, predicting broadband noise and simulating such mechanisms by using computational tools is fundamentally more difficult than for tone noise. It has proved impossible to model the details of broadband noise generation using unsteady Reynolds-averaged CFD methods alone [6]. Large Eddy Simulation (LES), on the other hand, is showing considerable promise. At the same time detailed measurements are being made (for instance those in the PROBAND [7] European research programme) to validate the numerical methods. In time this will lead to highly optimised blade geometries for broadband as well as tone noise, but at the moment LES is still too expensive computationally to apply in the quantity required for true optimisation.

4.4. Reducing fan noise by acoustic treatment

Improved acoustic treatment within intake, bypass and core ducts has been one of the most successful and durable strategies for reducing fan noise. Fan noise generated by the Fan-OGV stage propagates through the intake and bypass ducts as illustrated in figure 13 before radiating to the far field. The walls of these ducts are generally treated with single or double cavity liners with porous facing sheets. The design of the liners themselves, the selection of target impedances and the placement of lined segments within the duct can be used to scatter and attenuate the modes present at the fan in such a way that the far field sound pressure level is greatly reduced. In a modern $3/4$ cowl nacelle, reductions in radiated acoustic power of the order of 10-20 dB can be achieved for multimode broadband sources and much larger values are in theory (and occasionally in practice) achievable for specific tones. The prediction of attenuation in such ducts including the effects of liners and mean flow has advanced in recent years and this has led to considerable improvements in the performance of intake and bypass liners in new aircraft.

4.4.1. Prediction methods

Computational and analytic techniques for predicting propagation and absorption in engine nacelles and radiation to the far field, are a relatively mature technology within well defined limits of validity. Analytic methods continue to play a large role in the practical design of duct liners. These are generally based on mode theory for uniform circular (intake) or annular (bypass) ducts. The modes present are calculated for uniform mean flow and matched with or without mode scattering at liner discontinuities. A review of such methods is to be found in reference [12]. Recent examples of their application to the optimization of axially segmented intake liners are given in references [13] and [14]. Analytic mode methods of this type are restricted to circular or annular ducts with axisymmetric liners. However, an equivalent numerical procedure has recently been demonstrated for more general duct cross-sections and for peripherally varying

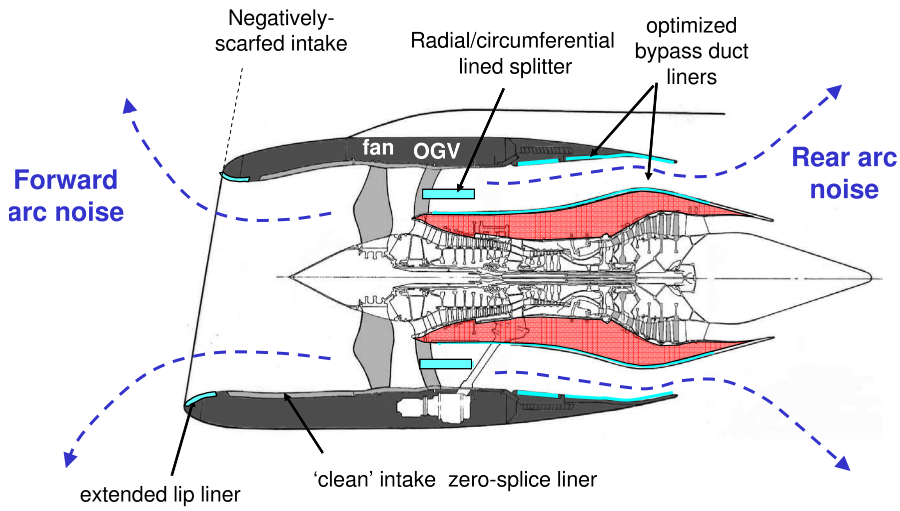


Figure 13. Fan noise propagation and advanced acoustic treatment in a turbofan nacelle.

liners [15].

Analytic methods can provide only an approximate solution however for the axially non-uniform geometry of real intake and bypass ducts. Numerical methods must then be used. Boundary Element methods have been applied to such problems, but are restricted to the case of zero or uniform mean flow [16], and treatment of boundary impedances is problematic. For more general non-uniform flow fields, the propagation problem is most satisfactorily treated as a numerical solution of the Linearised Euler Equations (LEE). Several approaches are commonly used.

- *Finite element methods for the convected wave equation*. When the mean flow is irrotational, the problem can be formulated in terms of a convected wave equation in the acoustic velocity potential, and solved numerically in the frequency domain. High order Finite and Infinite Elements [17, 18] are commonly used. This type of formulation is implemented in a number of commercial codes such as ACTRAN/TM, and LMS Virtual Lab acoustics. The use of infinite elements has the advantage that far field directivity is computed as part of the near field solution.
- *Time domain LEE, finite difference and DGM*. When the mean flow is rotational, the full LEE equations must be solved. This is done most effectively in the time domain by using high order Dispersion Relation Preserving [DRP] finite difference stencils [19], high order finite difference compact schemes [20, 21], or high order discontinuous Galerkin Finite Element Schemes [22]. Standard second order industry CFD codes are also quite commonly used but require much finer meshes than the high order schemes above. In all of these methods, the computational domain is terminated with an absorbing or non-reflecting boundary, and a secondary integral over a Kirchhoff or Ffowcs Williams-Hawkings surface is necessary to evaluate the far field directivity.
- *Frequency domain schemes for the full LEE*. These have recently been proposed to circumvent stability problems associated with time domain LEE solutions [23, 24]. Direct solvers must however be used and the solution of large frequency domain problems by di-

rect methods poses a major challenge for efficient parallel implementation, more so than the equivalent time domain schemes.

The methods described in the first of the above categories, are the most mature from the point of view of industrial take-up. They have been used quite extensively over the last decade, particularly in Europe, to evaluate new intake and bypass duct liner concepts, and have made a significant contribution to EC framework 5 and 6 programmes such as SILENCE(R)[4] and TURNEX [5]. The methods in the second category - time domain LEE - are more powerful but stability issues remain with regard to propagation through shear layers and the correct implementation of time-domain impedance boundary conditions. This has meant that their application to industrial problems is still at a preliminary stage and no commercial codes are currently available with the necessary features. Methods in the third category show promise but are very much at the research stage and not yet at a point where they can be used with confidence for industrial computations.

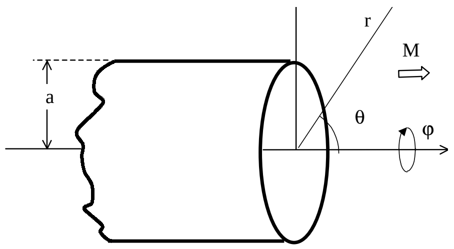
The practical difficulty which is encountered when any of the methods listed above is applied to a real turbofan duct, particularly in three dimensions, is simply one of problem size. With the exception of more speculative recent techniques which use plane wave bases [25], all of the above methods rely upon implicit or explicit polynomial approximation within elements or between grid points. Even when high order methods are used, controlling dispersion and dissipation in wavelike solutions requires a reasonably large numbers of grid points per wavelength in each coordinate direction, typically 7 or more. At BPF, the non-dimensional wavenumber kD - where D is the outer diameter of the fan - for a modern turbofan engine can exceed 60 at cutback or sideline, and is proportionally larger for higher BPF harmonics. The characteristic wavelength of the acoustic disturbance is then of the order of one tenth of the fan diameter requiring a mesh with perhaps 100 nodes or grid points across the intake duct. For an axisymmetric model this gives a discrete problem with tens or hundreds of thousands of nodes. This is quite manageable in terms of computational effort and can be solved for a single frequency in minutes rather than hours on a single processor. For three-dimensional models however, the discrete model has millions or tens of millions grid points, and this poses a much greater challenge. Days rather than hours of compute time are required for a single frequency calculation and efficient parallelization of the code is essential. While the application of CAA propagation models to axisymmetric intake and bypass duct is therefore well advanced [18, 26, 27], their application to fully 3D models is at a much earlier earlier stage of development and validation [28, 29].

The effectiveness of an axisymmetric CAA model in resolving high order spinning modes in an intake is illustrated in figure 14. This shows an ACTRAN finite and infinite element solution for modes radiating from a uniform, thin-walled cylindrical duct in the presence of flow. The reduced wave number kR and Mach number M in this case are typical of the sideline condition. This is a benchmark problem for which an exact solution is available [30] and it can be seen that the predicted and exact far field radiation patterns are in very close agreement. Further discussion of these results is to be found in [**?**].

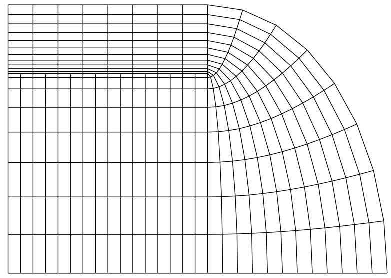
The effectiveness of similar models for lined configurations is indicated by a comparison of predicted and measured data for rig tests of idealized bypass duct configurations conducted at the ISVR in an anechoic environment as part of the EC SILENCE(R) project. These are shown

[4]EC Framework 5, GROWTH project,'Significantly Lower Community Exposure to Aircraft Noise'

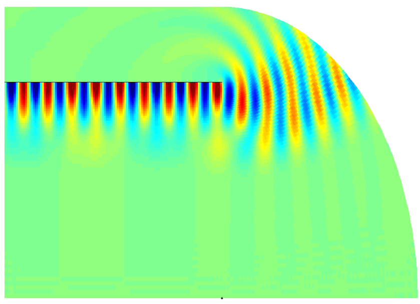
[5]EC Framework 6 STREP, 'TUrbomachinery Noise radiation through the Engine EXhaust'



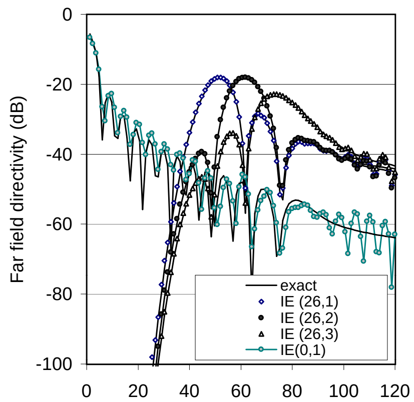
(a) Problem geometry.



(b) FE Mesh.



(c) Computed near field acoustic pressure; mode $(26,1)$, $ka = 35, M = -0.5$.



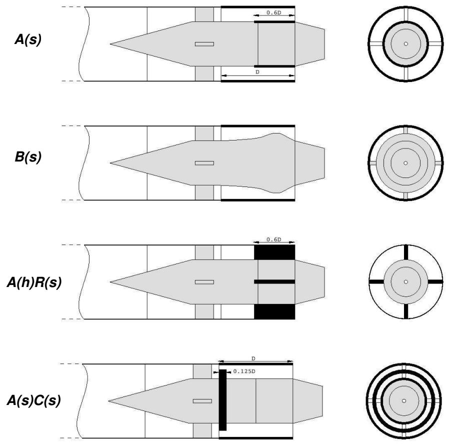
(d) Exact and computed far field directivities. $M = 0.5, ka = 35$. Modes $(26,1), (26,2), (26,3)$ and $(0,1)$ incident.

Figure 14. Radiation from an unflanged duct with flow [30]. A benchmark problem for intake propagation.

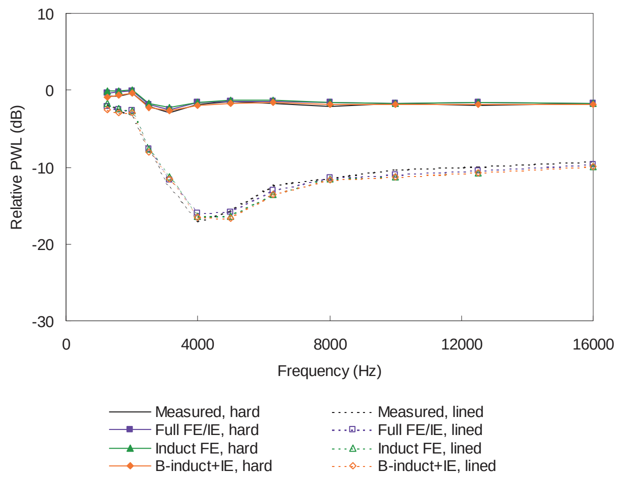
in figure 15. The location of the lined elements in the bypass duct for which results are shown is shown in figure(a) as configuration ‘B(s)’ . Predicted and measured acoustic power loss are shown in figure (b). A multimode source is used in which all propagating modes are present with equal acoustic power. Measured impedances were used and the correspondence between measured and predicted acoustic power is seen to be excellent. A more detailed discussion of these comparisons is to be found in [27].

4.4.2. Liner design and optimization, new developments.

Acoustic treatment in the intake and bypass ducts of aero-engines has proved an effective means of reducing fan noise. The liners themselves are manufactured in segments and installed with ‘hard’ axial and circumferential splices between panels. Traditionally these splices have been several centimeters in width. The liners themselves are generally designed to be most effective for frequencies in the range 1-2BPF at cutback and sideline and this leads naturally to cell depths of the order of an inch or two. The design of liners for most of the last thirty years has been based on the notion of a uniform axisymmetric ducts and a continuous uniform liner. Scattering at axial and circumferential liner discontinuities was often ignored. The computational methods



(a) Duct configurations, lined areas.



(b) Measured and predicted radiated sound power for duct configuration B(s) of figure (a).

Figure 15. No-flow ISVR bypass duct tests.

described in the preceding subsection have made such predictions more accurate and comprehensive over the last decade. They confirmed that large acoustic penalties can be associated with liner discontinuities, particularly liner splices. This is illustrated in figure 16. Two intakes with and without significant splices and patches are shown as subfigures (a) and (b). The first was typical of production intakes. The second is an experimental ‘clean’ intake with minimal splices and hard patches. Both were tested in flight in 2001. The clean intake gave a significant noise dividend, particularly for tones. The mechanism here is that of mode scattering by the splice and to a lesser extent by the patches. A BPF tone for an N-bladed fan, for example, is scattered by M splices into spinning modes of azimuthal order $N \pm M, N \pm 2M, N \pm 3M etc$ according to the Tyler and Sofrin law of figure 8. Many of the scattered modes are then further from ‘cut-off’ than the original BPF tone and are attenuated less effectively by the liner. Overall attenuation in the duct can be dramatically reduced by this mechanism, particularly in instances where the original tone is heavily absorbed. This is demonstrated in figure 16(c) which shows the axial attenuation of an $N = 24$ mode incident in a duct with six splices ($M = 6$). The acoustic power of the individual scattered tones (in this case $24 \pm 6, 24 \pm 12, 24 \pm 18 etc$) and of the sum of all scattered tones is plotted against axial distance along an intake duct. The ‘spliced’ and ‘zero-splice’ values of attenuation at the end of the liner differ by 30 dB. These results were obtained by using an asymptotic method but can also be obtained from a finite element numerical code [31] and by using a Boundary Element approach [32]. The practical solution is to eliminate splices or patches wherever possible or to reduce them to a minimum. This philosophy has been implemented in recent intake designs. This is one of several novel liner concepts to have been validated in recent years by improved prediction methods. Some others are noted on figure 13, and many tested at rig or engine scale in the EC SILENCE(R) project. They include;

- *Extended intake lip liners*. Here the issue of whether an acoustical benefit exists in extending the barrel liner to the highlight of the intake was investigated using Finite and Infinite elements [18]. These studies confirmed that the acoustic benefit was greater than

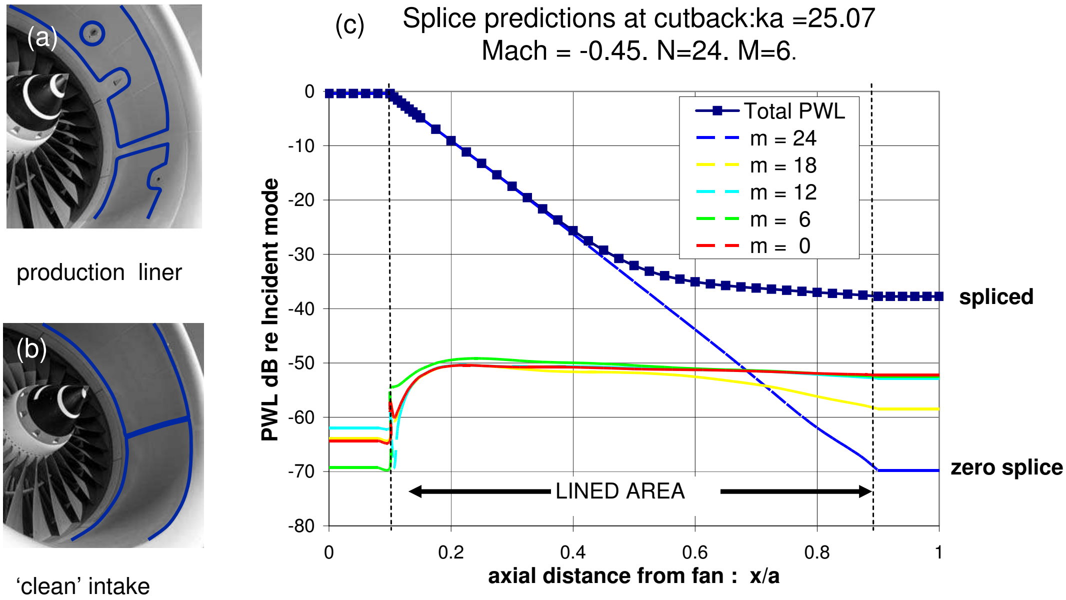


Figure 16. The acoustic effect of hard splices in an intake liner

(a) (b)

Figure 17. The Negatively Scarfed Intake (NSI). (a) Basic concept. (b) NSI flight test (SILENCE(R)).

would be expected purely from an increase in liner area.

- *Negatively scarfed intake*. The Negatively Scarfed Intake (NSI) is based on the simple notion illustrated in figure 17 (a), that an intake with an extended lower lip will reflect noise upwards away from an observer on the ground. This concept was tested within the SILENCE(R) project (figure 17 (b)). Appraisal of data from aircraft and rig tests and from numerical simulation, has indicated that significant benefits - in excess of 1.0 EPNL dB at take-off and approach - can be achieved [16]. Whether an NSI can be accommodated without negative impact on aircraft performance is yet to be determined.
- *Lined radial or circumferential splitters in the bypass duct*. Rear arc fan noise has become particularly important as bypass ratios have increased and the propagation path through the bypass has become larger and more direct. There is strong evidence from predictions

and rig tests that liners placed on radial or circumferential splitters in the bypass duct can significantly reduce tones and broadband noise radiated through the exhaust [26]. Tests of such devices have been delayed by the practical issues of actually installing them in current engines.

- *Fully optimized liners*. CAA prediction methods for intake and bypass ducts have reached a stage where they can be embedded within general optimization programmes. Optimization studies which use integrated CAA and optimization tools are currently being implemented and are likely to play an increasing role in the acoustic design of engine ducts in the future[14].

5. PREDICTING AND REDUCING JET NOISE

To the non-specialist, the term "Jet Noise" means the total noise emanating from a jet engine. In the context of the current article it is used in a far more restrictive sense to describe only those sources of noise which are associated with the mixing process of the engine exhaust and the atmosphere, and the noise associated with the shock structure within an imperfectly expanded jet. These sources are somewhat different from those described in section 4 in that although they are generated by the engine and treated as an engine noise source, they are not located in the engine itself but in free space *downstream* of the exhaust nozzle(s). They are therefore not susceptible to mitigation with acoustic liners within the engine ducts, as in the case of fan noise, but must be controlled at source. In terms of environmental impact, jet mixing noise remains a major component at takeoff and the subject of intense investigation over the last four decades.

5.1. Prediction methods for jet Noise

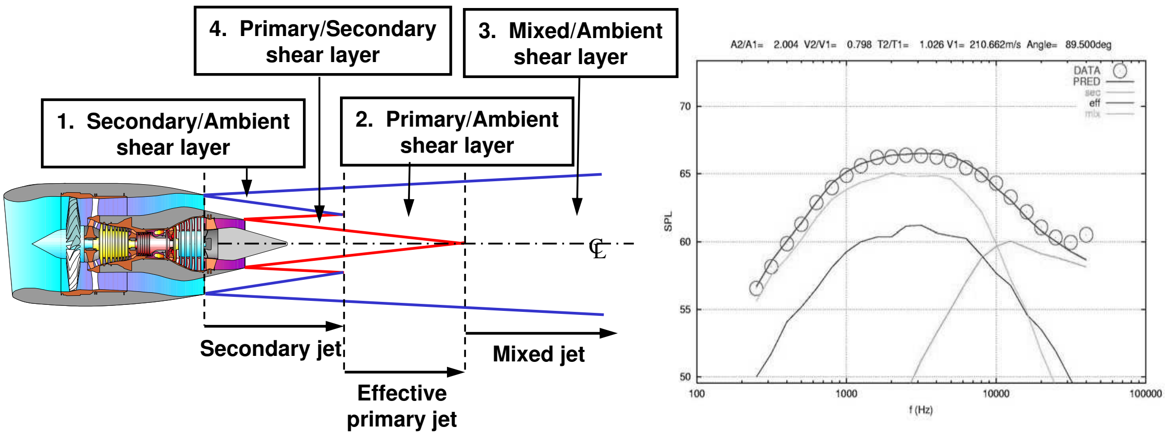
There is a long history associated with the prediction of jet noise. Indeed, it was chosen by Lighthill as a first application of his Acoustic Analogy [33]. Lighthill showed that mixing noise from a free jet scaled as the eighth power of the jet velocity, a result that, subject to some qualifications, has been demonstrated over the years to be substantially correct.

Lighthill's U^8 theory does not however predict directly the constant of proportionality and hence is unable to give absolute levels of jet noise in terms of the jet parameters. This was first made practical by the work of Lush [34] who showed that the third octave spectra of single stream jets collapse onto a single curve when written in terms of the correct non-dimensional parameters. In this way careful measurement on one jet allows the prediction of the spectrum of another. The veracity of Lush's work is demonstrated by the fact that remarkably good predictions for full size jet nozzles can be made on the basis of measurements taken on much smaller model scale jets. After more than fifty years of aeroacoustic research, the basis of industrial jet noise prediction remains empirical, based on measured data.

The introduction of dual stream engines in the 1960s and the further development of engines with significant bypass streams in the 1970s and 1980s, brought additional complexity to the problem of jet noise prediction. A new prediction scheme was introduced by Fisher et.al. [35, 36] in the 1990s to predict noise from coaxial jets of this type. Known as the 'four source model', it forms the basis for many industry predictions of jet noise. The four source model was based on the observation by Ko and Kwan [37] that different parts of the flow in a coaxial jet scale in the same way as "equivalent" single stream jet flows. In this way single stream jet noise databases can be adapted to yield coaxial jet noise predictions. The nature of this approach, whereby separate noise predictions are made for the various mixing layers in the coaxial jet, is illustrated in figure 18(a). The superposition of the resulting source spectra for a modern jet is shown in figure 18(b).

Empirical models such as the four source model although effective in predicting gross noise levels for conventional configurations, cannot resolve or discriminate between more subtle changes to the nozzle geometry or to the turbulent structure in the jet. These have become important as complex nozzles are considered in an attempt to reduce jet noise. While empirical methods of prediction have therefore served the industry well for four decades, they are no longer an adequate tool with which to develop the next generation of active and passive flow control devices which are perceived to be the most effective way to further reduce jet noise. The idea of such devices is to modify the turbulent structure within the jet and thereby reduce the mixing noise or move it to frequencies where it has less impact. A more detailed analysis of unsteady turbulent flow within the jet is needed for such studies and the development of computational techniques to predict the noise generated by such flows motivates much current research on jet noise.

Methods based on 'Reynolds Averaged Navier Stokes' (RANS) CFD modeling of the jet have been quite successful. In such approaches, a steady RANS calculation for the jet is performed. Turbulent mixing is modelled by using a turbulence closure model such as the $k - \epsilon$ model or similar. Some information about the turbulent unsteady motion in the jet mixing region can be obtained from the computed turbulent parameters in the flow (the turbulent kinetic energy k and dissipation ϵ in the case of the $k - \epsilon$ turbulence model). This data can be used to construct equivalent noise sources in the jet [38, 39] and these are propagated to the far field by using Lighthill's acoustic analogy or by an analytic or numerical propagation model. The difficulty in this approach lies in extracting enough data from the RANS calculation to reconstruct the sources. However, when used with care the method can predict quite well the noise generated by single and coaxial jets. A RANS solution for a coaxial jet and the associated noise spectrum



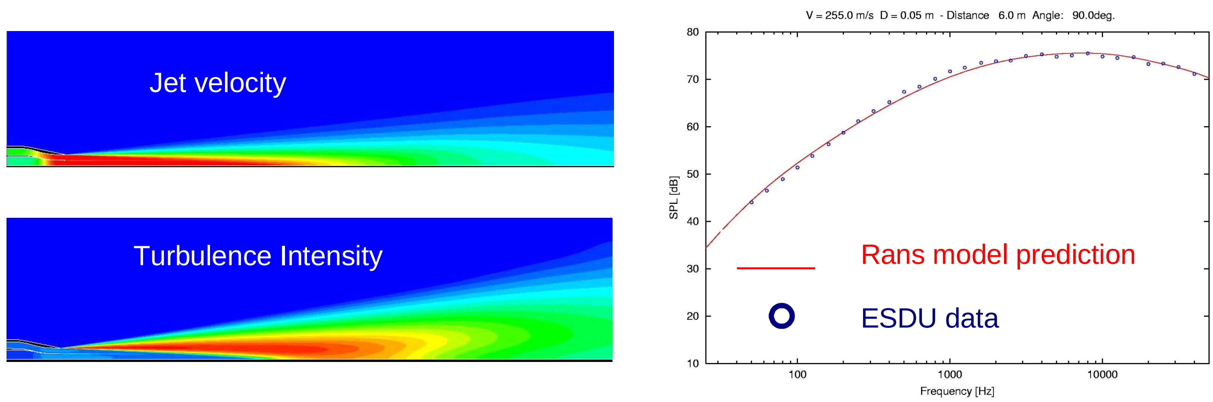
(a) (b)

Figure 18. (a) The four source model for a coaxial jet. (b) Superposition of the source spectra.

at 90° are shown in figure 19.

Large Eddy Simulation offers a more direct approach to jet noise prediction. LES computation can be used to resolve the near field of the jet including unsteady turbulent eddies down to a prescribed grid scale. The transfer of energy to and from a 'subgrid' scale is also modelled. Care must be taken to impose accurate non-reflecting or absorbing conditions at the outer boundary of the computational domain. When this is done, the far field sound pressure can be obtained by integrating the computed solution over an embedded surface within the flow. While LES is capable of generating a much more detailed description of unsteady phenomena within the jet and of resolving the larger turbulent scales, the nature of the acoustic solution has been found to be dependent on the subgridscale model which is used. Such computations are also limited in practical application by the prodigious quantities of computer resource which they require [40].

At present, empirical methods and RANS calculations are able to predicting jet noise for conventional nozzle geometries. Predicting directivity as well as overall sound power still presents a major challenge. Whether or not more advanced computational methods such as LES will deliver reliable solutions for heated coaxial jets within industrial timescales is still an open question. Current research effort in Europe on jet noise is however high. Two major research programmes have been funded by the EC in frameworks 5 and 6, with the specific objectives of improving jet noise modelling and investigating novel noise reduction technologies. JEAN (Jet Exhaust Aerodynamics and Noise, 2000-2004) concentrated on amassing a large database of aerodynamic and acoustic measurements of single stream jets [41, 42]. CoJEN (Coxial Jet Exhaust and Noise, 2004-2007) extended the database to dual stream flows and supported the development and validation of RANS and LES models. A complete PIV survey of several coaxial jet flows has also been taken within CoJEN. Both projects leave a wealth of data that will be valuable in future years.



(a) (b)

Figure 19. A RANS model for jet noise. (a) Computed contours of jet velocity and turbulent intensity for a coaxial jet. (b) Predicted and measured noise spectrum at 90 degrees to the axis (provided by R H Self and M Azerpeyvand).

5.2. Reducing jet noise

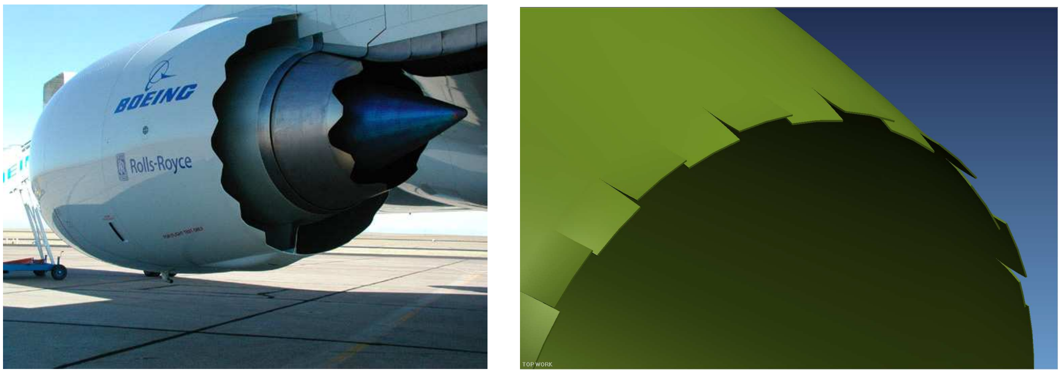
Aircraft noise generated by the jet exhaust has decreased dramatically since the 1950s. Much of this reduction can be attributed to the introduction of coaxial jets and the increasing size of the bypass steam. In simple terms, the larger nozzles of modern aero-engines mean that the same thrust can be achieved with lower exit velocities. Because of Lighthill's U^8 law, this implies significantly reduced jet mixing noise. Much of the reduction in aircraft noise evident between 1960 and 1980 (see figure 1) can be attributed to this effect. There are however limits to this process. Larger bypass ratios and engine diameters may reduce the noise, but they also increases the weight and drag. Ultimately a point is reached where there is no net benefit. With bypass ratios close to or in excess of 10.0, this point is approaching for current aircraft configurations.

While jet noise has reduced steadily over the last forty years this has not removed it from consideration as an important noise problem. It has ceased to be the *dominant* source of engine noise at *all* engine conditions but remains a major contributor to whole aircraft EPNL at sideline and cutback. Paradoxically however, as other noise sources are reduced, particularly fan noise through improved fan design and liner technology, these reductions can only be converted into effective decreases in EPNL by continuing to reduce jet noise. The need to find further ways to reduce jet noise is as pressing now as it was forty years ago.

Current attempts to reduce jet noise centre on the notion of flow control; reducing noise indirectly by modifying the turbulent structure in the jet. Forced or lobed mixers have operated on this basis for many years, modifying turbulent mixing in exhausts with buried core nozzles. They are based on the effective elimination of the high-speed core flow by mixing upstream of the final nozzle. However there can be an associated penalty in the form of the generation high frequency 'excess' noise, which exceeds the noise that would be produced by the ideal fully mixed jet. To achieve net noise benefits in such cases a careful balance must be struck between eliminating the high speed core flow and generating significant turbulence level increases in the initial portion of the outer jet shear layer. Recently RANS models have been used to understand this behaviour but these may not be able to provide sufficiently accurate estimates of the noise parameters through the turbulent kinetic energy alone, in which case more refined CFD models will be required which take account of the effect of temperature through the dipole jet noise source.

A more recent proposal for flow control of jet noise is the use of tabs or chevrons on the exhaust nozzle(s). These are illustrated in figure 20 where they are shown on the core and bypass nozzles of a modified Rolls-Royce Trent engine which was flown on the 'Quiet Technology Demonstrator' by Rolls-Royce and Boeing in 2001. Chevrons protrude into the flow and introduce streamwise vorticity that enhances the mixing process close to the nozzle. The net result is an increase in high frequency noise close to the nozzle and a decrease in the lower frequencies further downstream. Since high frequencies suffer more atmospheric attenuation this gives an effective reduction of EPNL measured in the far field. However, as with most things to do with jet noise there is no such thing as a free lunch. Chevrons must intrude into the flow if they are to work, but this increases the blockage and reduces thrust. Thus a quieter engine is bought at the expense of an increase in fuel burn. Current research seeks to mitigate this effect and to give a noise benefit without a significant economic penalty. Methods currently under investigation include:

- Deployable chevrons or tabs using shape memory alloys which would operate only at



(a) (b)

Figure 20. (a) Chevrons on a Rolls-Royce/Boeing ‘Quiet Technology Demonstrator’ aircraft (2001). (b) Simulated shape memory alloy tabs.

takeoff and landing and retract at cruise.

- Flow modification by offset, scarfed and non-circular nozzles geometries.
- Microjets within the exhaust nozzle to modify turbulent mixing in the jet.
- Plasma actuators mounted in the jet nozzle.

Of these, the deployable tabs or chevrons are at the highest state of technology readiness and closest to being implementated on real aircraft.

6. PREDICTING AND REDUCING AIRFRAME NOISE

6.1. Sources of airframe noise

During landing approach, when engines are operating at low thrust, the noise of the airframe contributes strongly to the overall noise signature of modern aircraft (see figure 6). As noted in section 3, reducing airframe noise is a critical component in any reduction of EPNL at approach. Airframe noise is generated by the airflow over the surfaces of the aircraft. Flow over smooth surfaces does not however cause significant noise radiation. The main sources of airframe noise are therefore the high drag elements such as landing gears and also the high lift devices on the wings. Within these broad categories however there are contributions from many individual sources; in the case of the landing gears this includes the wheels, struts, hub cavities, brakes, hydraulic fittings, door fairings, etc.; for the high lift slats and flaps the noise is generated particularly by flow over trailing edges (2-D sources), but also by 3-D features such as fixing brackets and side edges [43, 44, 45].

6.2. predicting airframe noise

Prediction methods for airframe noise can be divided into numerical Computational Aeroacoustics models (CAA) and semi-empirical models. The former typically consist of RANS or LES computations of the flow in the vicinity of the source followed by a Ffowcs Williams- Hawkings solution for the acoustics using an on-body or off-body data surface. For high lift devices,

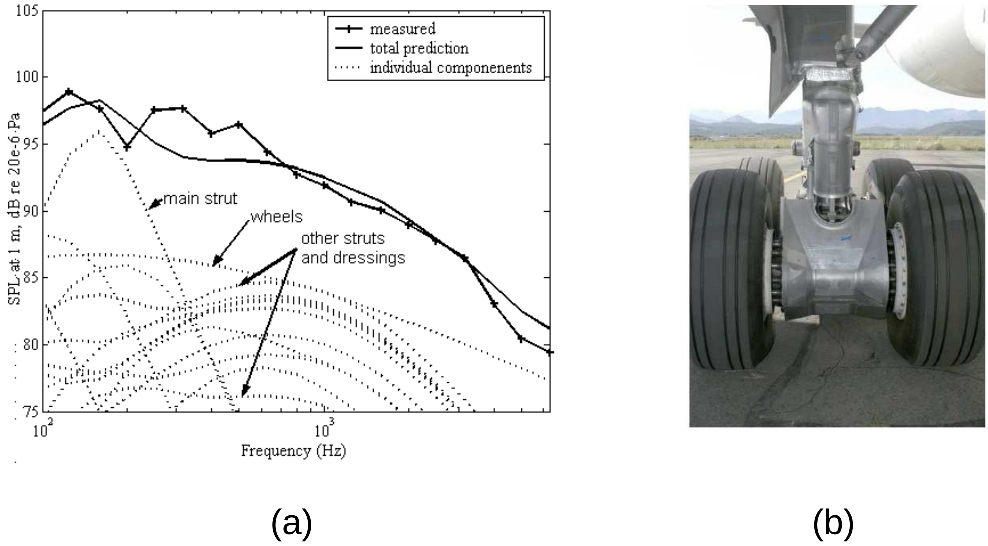


Figure 21. (a) Noise source breakdown for a typical landing gear. (b) Fairings flight tested on an A340 aircraft.

where the geometry is relatively simple, CAA is now capable of predicting many features of the main 2-D and 3-D sources and so is being used as a useful tool in establishing the physics of the noise source mechanisms [46, 47, 48].

The full geometric detail of complete landing gears is generally too complex for CAA. For this reason practical prediction models for landing gear have a strong empirical bias [49, 50]. A typical result from a semi-empirical prediction model is shown in figure 21 [50]. The model provides an estimated far-field noise spectrum for each of the major components of the gear, and this may be used to guide general engineering design and the priorities for remedial treatment. Such models are, however, limited by their inability to predict the effect of detailed design changes, and so new ways of incorporating data from CFD flow calculations (which are less demanding than CAA calculations) are being sought [51].

6.3. Reducing airframe noise

The control of airframe noise both from landing gears and high lift devices, is constrained by factors unrelated to noise. In the case of the high lift devices the priority is lift, and the ideal noise reduction solution would be a method for increasing the lift coefficient of the wing, since this would permit lower landing speeds, which would in turn be beneficial in reducing *all* sources of airframe noise. Failing that, 'add-on' noise control treatment, such as brushes and porous side edges [43, 44], must not reduce the lift coefficient since this would be counterproductive for both noise and the overall operational performance of the aircraft. This constraint has limited progress in reducing high lift device noise to date.

In the case of landing gears, the over-riding requirements are safety (including access for pre-flight pilot inspections) and weight. Thus while landing gear fairings (see figure 21(b)) [43] have been shown to provide useful noise reductions, they have not yet been implemented on production aircraft for these reasons. The most productive option in the near future for reducing noise from landing gears lies in low noise design of new aircraft [51] whereby the gears can be re-configured so that noisy components are placed in the wake of clean aerodynamically shaped

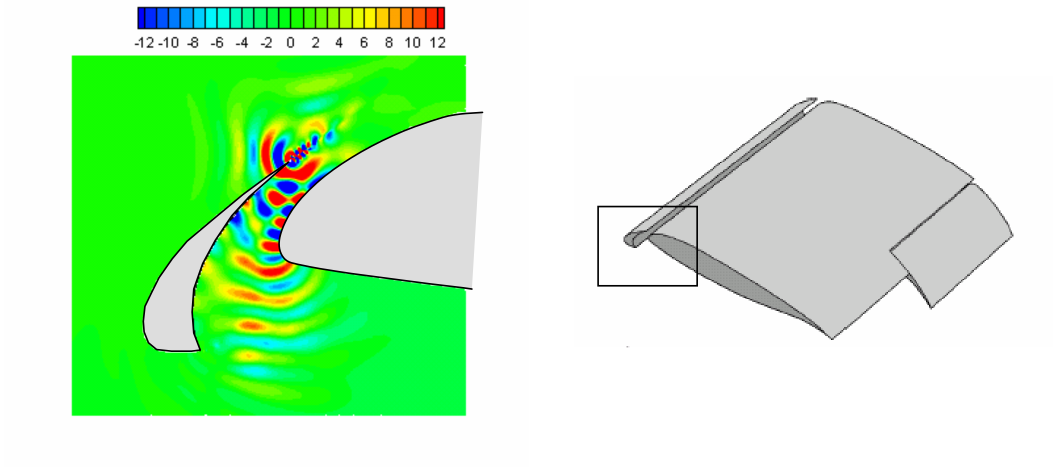


Figure 22. CAA model for slat noise. Noise generated at the trailing edge of the slat is ducted through the slot between the slat and the leading edge of the wing [48].

upstream components. In the longer term, noise from landing gears, and indeed the whole issue of airframe noise, will become part of a wider consideration of entirely new airframe and engine configurations.

7. INSTALLATION EFFECTS AND ACOUSTIC SHIELDING

7.1. The acoustics of installed engines

The noise radiated by an installed engine differs from that measured or predicted for an isolated engine due to various flow and acoustic interactions with the fuselage, with the other engines and with the wing and tailplane. The closer these elements are to the source the more significant the effect. They are particularly significant for obvious reasons in the case of jet exhaust noise radiated from under-wing mounted engines as illustrated in figure 23. Three important mechanisms can be identified. These are;

- Reflections and scattering from the wing and fuselage.
- Shielding by the airframe.
- Jet wing aerodynamic interaction.
- Jet-flap aerodynamic interaction.

The first two are the most obvious; reflection and scattering of the radiated noise by the wing itself, downward towards the observer in the case of under-wing mounted engines, and upwards to give shielding in the case of over-wing mounted engines. The third arises because the wing itself is in the near field of the jet and hence acts to modify the noise sources. The fourth is in reality an additional source rather than an installation effect *per se* since flaps protruding into the jet and act as new noise sources. Measured data from installed engines suggest that the last two mechanisms are significant at lower frequencies while the first is important at higher frequencies (see figure 23).

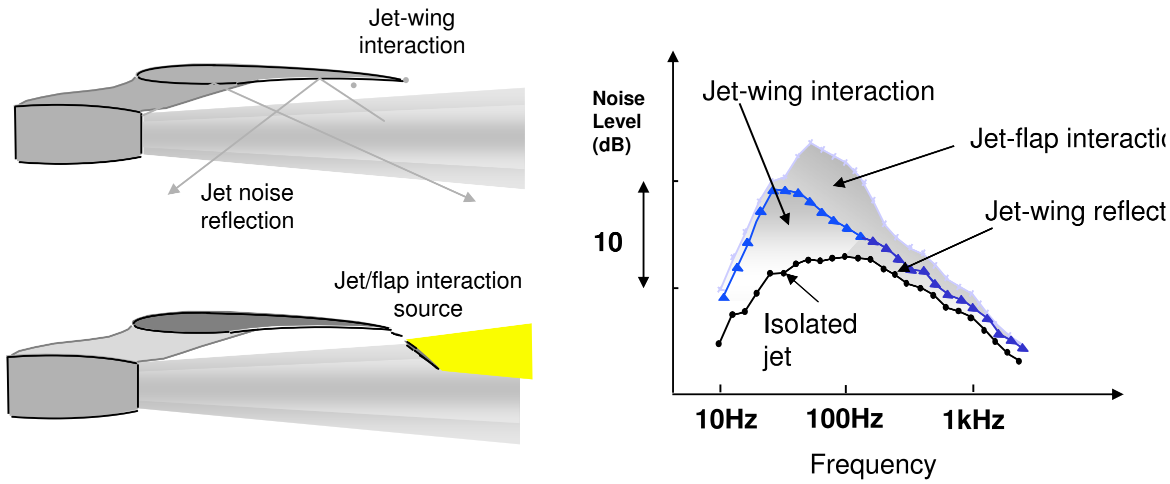


Figure 23. Installation noise effects. Mechanisms and spectra.

7.2. Prediction methods

The most common approach for predicting such effects is to supplement measured data with simple high frequency ray calculations. Only recently have diffraction effects needed to be included in such calculations and these have only been applied to some rather specific geometries [52].

In theory, domain based CAA propagation methods, based on LEE (see section 4.4) could also be applied to such problems. The practical difficulties are however formidable. The 'nodes per wavelength' considerations which are restrictive for nacelle acoustics are much more so for whole aircraft studies. The few computations that have been presented using such methods, such as those of Stanescu, for example, which use a high order spectral, discontinuous Galerkin scheme [53], have been restricted to small portions of the airframe, and to low frequencies. The 'Fast Scattering Code' developed at NASA Langley which is based on an equivalent source method has also been applied to whole aircraft problems at low frequencies though with no indication that it captures flow effects correctly. Traditional boundary element methods have also been applied to such problems [55], but are again limited to zero or uniform flows and only applicable in practice at low frequencies.

7.3. Acoustic shielding

An 'installation effect' which has the potential to actually *reduce* aircraft noise is the notion of acoustic shielding, that is to say, the design of airframes specifically to shield the ground observer from noise sources on the aircraft. Present day commercial aircraft do not exploit acoustic shielding, except in the case of fuselage mounted engines where shielding by the fuselage can be significant. For a conventional tube-and-wing aircraft, one way to shield the forward-propagating engine noise is to mount the engines above the wing. Ricouard et al. [59] have recently studied the shielding of fan noise by the main wing of a scaled model tube-and-wing aircraft similar to that illustrated in figure 24(a). In their experiments, the engine was mounted over the tail wing and in this situation shielding was effective in certain directions underneath the wing, mostly where there is no direct line of sight (shadow region) between the engine-intake and observers on the ground. In the case of engines which are mounted conventionally underneath the wing, some shielding of the forward-propagating noise can effectively be achieved by negatively scarfing the engine intake as noted in section 4.4. The shielding of jet exhaust noise is much more challenging since the sources extend many jet diameters downstream of the engine nozzle. Concepts for jet noise shielding were studied in the 1980s by Wong et al. [61] by mounting finite-length shields of various shapes underneath the jet. Reductions in the Overall Sound Pressure Level (OASPL) of up to 4 dB were measured. The weight and drag penalties of such devices are likely to rule them out of current consideration however.

Unconventional designs, such as flying-wing or ‘delta’ wing configurations with engines mounted above the wing, offer much greater potential for noise shielding but also a drastic change in all other aspects of aircraft design. Some 40 years ago Jeffery and Holbeche [58] studied the acoustic shielding from a full scale Hadley-Page 115 delta-winged aircraft in flight by centrally mounting a powerful acoustic whistle above the wing. They observed significant amount of shielding in the shadow region. In a much more recent study, Clark and Gerhold [56] experimentally investigated the noise shielding by a 3-engine Blended-Wing-Body (BWB) model of a type similar to that illustrated in figure 24(b) . A high-frequency broadband point source was placed in the nacelles of the engines. They observed shielding in excess of 20 dB for the OASPL in the forward sector of the shadow region. Numerical estimates for acoustic

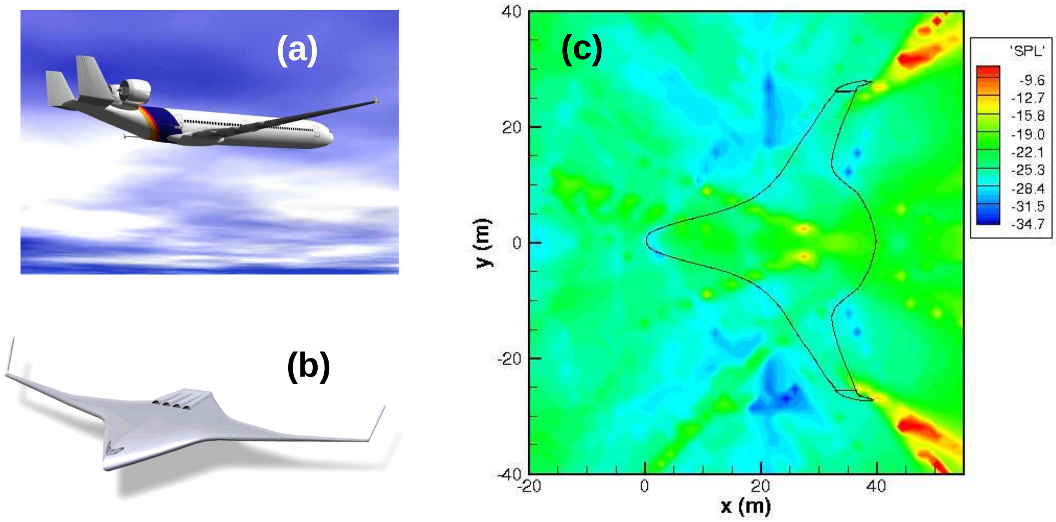


Figure 24. Airframe noise shielding concepts. (a) Wing and canard shielding for tail mounted engines. (b) Blended wing airframe with embedded engines. (c) Shielding contours on the ground for a blended wing design [52]

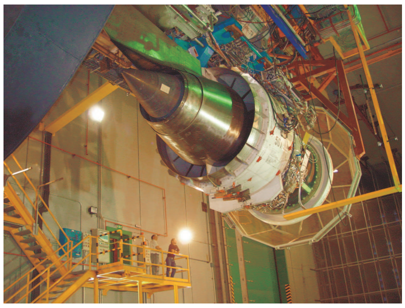
shielding have also been obtained. Jeffery and Holbeche [58] developed a simple model based on diffraction from a sharp-edged semi-infinite plate to predict the noise underneath their delta-winged planform. Wong et al. [61] used a similar procedure to estimate jet-noise shielding. Gerhold et al. [57] used a boundary element method to perform low-frequency calculations for a point source mounted above simple wedge-shaped wing with a triangular planform. Most recently Agarwal and Dowling [55] used a boundary element method to obtain the shielding estimates from the geometry of the “Silent Aircraft” (a flying wing design) airframe similar to that shown in figure 24. Because the engines are embedded in the airframe and hence are close to the upper surface of the wing, the shadow region is very large underneath the wing. This makes acoustic shielding more effective than for podded engines mounted above the wing. In the context of the shielding problem, boundary element methods have two drawbacks: they are restricted to low frequencies, and it is very difficult to account for the directivity pattern of the source in the shielding calculations. Agarwal et al. [52] show that these problems can be overcome by using ray theory. The dominant frequencies in the (forward-propagating) noise spectrum of the engines are sufficiently high that ray theory yields accurate results. Also, classic ray tracing techniques are applicable to moving body problems, provided the flow past the body has a low Mach number and is potential, in which case rays to particular observers can be tracked graphically. Ray tracing also indicates where the sound comes from, providing valuable physical insight. Such models must include diffracted rays (sharp-edged diffracted and creeping rays) to explain and quantify shielding effects in the shadow region. However, the acoustic field in the shadow region decays rapidly with increasing frequency which means that shielding is more effective for higher frequency sources, such as fan noise, compared to jet noise. It is worth observing that blended wing designs such as the silent aircraft have other noise advantages. When the engines are embedded in the fuselage, as indicated in figure 24(b), this permits a long exhaust duct which can be lined to reduce exhaust noise, forward arc fan noise being almost totally mitigated by acoustic shielding. Such designs are clearly a huge step change from existing aircraft configurations but have the potential to resolve simultaneously a number of noise problems. The issue of whether or not they satisfy necessary commercial, environmental, technical and safety criteria for a future passenger aircraft lies beyond the scope of the present discussion.

8. MEASUREMENT TECHNIQUES

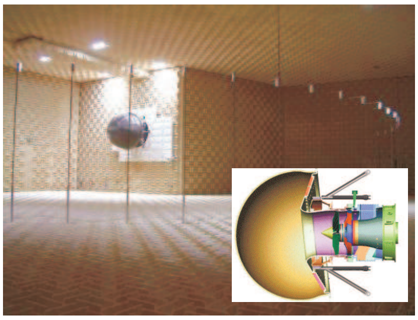
Historically, measured data have been central to noise prediction in new aircraft. The complexity of the source and propagation mechanisms has meant that theoretical and computational predictions often serve to down-select potential noise reduction strategies, rather than providing reliable predictions of absolute noise levels. While prediction methods in general and those based on CAA in particular have improved greatly over the last decade, airframe and engine manufacturers still call upon databases of historic data for noise predictions of new configurations, augmenting these where required with new test data, analysis and computation in order to estimate the effect of incremental changes. Noise data are collected in a variety of test situations. These include;

- *Noise measurements taken at full scale during outdoor engine tests or aircraft flyover*. Preparation for a SILENCE(R) outdoor static engine test at the Rolls-Royce test bed at Hucknall is shown in figure 25(a). Here a polar array of 125 microphones is being laid out for engine source location at variable spacing on an arc centred on the test stand. This is dominated by a turbulence control screen to reduce noise generated by ingested turbulence due to ground proximity and the absence of a forward flight stream.
- *Indoor test bed measurements*. Near field measurements of noise from full scale engines can be taken in the highly reverberant environment of an indoor test bed. A Rolls-Royce test engine mounted in such a bed - at INTA in Spain - is shown in figure 25(b).
- *In-duct and far field measurements in indoor fan rigs*. Here scale models of the fan-OGV

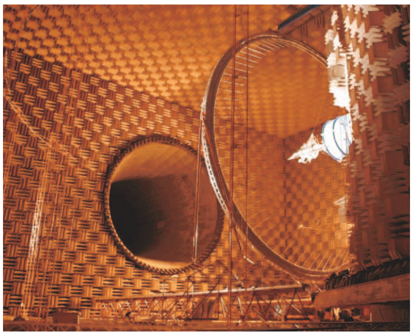
(a) Rolls-Royce outdoor test bed (Hucknall)



(b) ANTLE engine at INTA



(c) Fan Rig AneCom



(d) NTF jet test facility (Qinetiq)

Figure 25. Aero-engine test facilities.

stage are tested in isolation in an anechoic environment. The most advanced rig of this type in Europe, at the AneCom test facility in Germany, is shown in figure 25(c)

- *Noise measurements in jet test facilities*. Noise testing in the QinetiQ Noise Jet Test Facility (NTF) at Pystock, are shown in figure 25(d). Here a 1/10 scale coaxial jet vents into a large anechoic chamber, within which noise measurements are taken using various arrays of microphones.

Technology advances over the last decade have had a profound effect on measurement techniques which can be used in the facilities described above. In particular, advances in computer technology have made possible the use of large microphone arrays for assessing the in-duct and radiated sound fields. The use of large microphone arrays is, in itself, not new but the resources to process the acquired data have, in the past, been limited. Research in recent years has focussed on ways in which these data may be processed to yield more information about the radiated noise than has previously been available. As a general rule, the frequency range over which a particular array is useful depends upon the number of microphones in the array. The high frequency limit is set by the spacing between the microphones and the low frequency limit by the extent of the array. However, within these constraints, the position of the microphones relative to the noise sources of interest is also very important. This relates to the 'conditioning' of the inverse problem. The correct choice of microphone positions can significantly improve the reliability of the output from an array, and it is now possible through computer simulations to optimise the microphone positions for a given source geometry. Established array techniques, such as the 'delay and sum' or 'steered' beamformer can be used to establish the position of major noise sources, but can only yield accurate quantitative data in the presence of a single source. Recently, research into more advanced array processing techniques, such as the ‘inverse method’, has shown that a single microphone array can be used to determine the strength of multiple sources of arbitrary mutual coherence [63] albeit after a relatively large amount of data processing compared to the beamformer. Specific areas in which array techniques are being exploited routinely for aircraft noise measurement and prediction include;

- In-duct array measurements in fan rigs to infer modal breakdown and/or radiated sound fields.
- The use of large arrays to perform source breakdown for outdoor static engine tests.
- The use of arrays in jet test facilities to infer jet source distributions.
- The use of arrays as acoustic telescopes to identify acoustic sources on aircraft in flight an on aircraft components tested in wind tunnels.

A common theme here is the use of noise measurements, and arrays in particular, to determine the strength and location of individual noise sources. This is an important requirement given the importance from an EPNL perspective (see comments in section 3) of reducing not just overall noise, but noise contributions from specific sources at particular engine conditions.

All of the test situations shown in figure 25 are extremely expensive, and noise tests are therefore ‘piggybacked’ on other performance tests for this reason. Static engine outdoor tests which are the most definitive from a noise point of view are the most expensive and infrequent of the various engine test procedures. Since engines are routinely installed in indoor test beds for performance trials, however, it would be valuable to be able to take useful noise measurements on such occasions. Unfortunately, the acoustic conditions within an indoor test bed are quite different from those encountered in outdoor sites, so it is difficult to compare indoor noise measurements with those taken outside. One method that has been used to overcome his difficulty, is to exploit, where possible, any acoustic absorption on the walls of the test bed. In the special case where test beds have acoustic absorption on one wall *and* the ceiling, microphones placed along the junction between the untreated wall and the floor will receive a similar sound field to microphones in similar positions outdoors [64]. Most test beds do not have acoustically treated walls however. An alternative approach recently explored at the ISVR in collaboration with Rolls-Royce has concentrated on the application of more advanced microphone array techniques with a view to extrapolating the indoor measured data in a highly reverberant environment to predict the noise that would be measured under outdoor conditions. This is done by using the output from an array of microphones in the test bed to estimate the strengths of a number of elemental noise sources which represent the engine, and by using these to estimate the outdoor sound pressures. Various methods for doing this are being investigated. These include the use of measured, reverberant, Green functions in the beamforming and inverse methods which can be used in place of the usual geometry-derived free-space ones. For example, microphones attached to a board blocking the inlet of a jet engine have been used to measure the Green functions from each of the microphones to each microphone location in a test bed array using reciprocity. This in effect ‘de-reverberates’ the test enclosure and makes it possible to deduce from these data the far field sound radiation in an anechoic environment.

At present arrays of up to one hundred microphones are not uncommon in all of the above applications. The cabling of such arrays, particularly in a hostile environments such as an engine test cell, becomes a serious issue. There is a great opportunity to develop robust, autonomous devices that can transmit data wirelessly, perhaps using ‘scavenged’ acoustic power. This would have a major impact on further developments in this area.

9. CONCLUSIONS

- Significant progress has been made over the last decade in reducing aircraft noise in line with the ACARE noise target for 2020.
- Jet, fan and airframe sources all contribute significantly to whole aircraft noise of current aircraft designs, and further reductions will be needed in all three areas to achieve significant reductions in EPNL.
- While many potential avenues for noise reduction in current airframe and engine configurations have now been exploited, further incremental improvements will be realized by applying flow control methods in fans and nozzles, and by fully integrated optimization of acoustic treatment in engine ducts.
- Significant improvement of the noise environment near airports could be achieved by the acceptance of new operational procedures at takeoff and landing.
- In the longer term, entirely new airframe and engine configurations must be considered to satisfy noise and other environmental criteria. The task of predicting noise for such designs will require advances in current prediction techniques and the accumulation of new databases.
- Novel concepts which carry a noise penalty may be needed in future to reduce specific fuel consumption. Contra-rotating propellers are an important case in point, and these will pose particular challenges for noise control.

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