Aviation in a sustainable world

Omega Study No. 8

Integrated Study of Advanced Open Rotor Powered Aircraft

Project Report

Thematic Area: Technology

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Executive Summary

Advanced Open Rotor (AOR) powered aircraft are a technology that could yield significant benefits in terms of fuel savings. However, there is perceived risk to their introduction due to the levels of noise they produce and an objective of this study was to develop a framework that would allow assessment of community noise implications should AORs become widely used in civilian fleets.

This framework has been successfully developed. It has been used to assess the likelihood of AORs meeting noise certification standards and, in line with the ICAO "Balanced Approach", the effect of variations to aircraft operational procedures has been considered.

It was found that for a generic 150 seat aircraft, AORs are capable of meeting the ICAO Chapter 4 Noise Certification Standard if the consideration of noise is made in the design and operation of the aircraft. Given that this result is based upon information that is publicly available, the likelihood is that any commercial design will have a greater margin over Chapter 4.

Industry and government will be able to apply the results and the methods developed in this study to scope the viability of future aircraft operations from a noise perspective. They will also be able to influence the development of open rotor propulsion to a higher technology readiness level at reduced risk.

The framework presented involves bringing together a variety of existing tools in the area of aircraft noise and performance analysis. However, it would not be possible without the development of a new prediction capability for open rotor tonal noise prediction. The method developed for this can be implemented as a "stand alone" programme and is an important contribution to noise prediction capabilities in its own right. (For example, it will be used on behalf of stakeholders to analyse data obtained from rig measurements that form part of the EU FPT7 *Dream* programme.)

This study has made an important first step but further research and model development are required if the full potential and usefulness of this approach are to be realised. Some improvements are straightforward and involve increased fidelity of the methods employed. Others require the methodology to be modified for inclusion in more generic platforms that will allow stakeholders to make a comprehensive range of predictions and comparative studies such as noise contour plots and emissions.

1.0 Introduction

Advanced open rotor powered aircraft (AORs) are a candidate technology for short and medium haul aircraft and are being actively considered by industry as possible power plant on the replacements for the Boeing 737, Airbus A320 150 seater class airframes. The attraction of AORs is their potential for a large reduction in fuel burn and the commensurate reduction in cost and environmental impact via reduced emissions. It is reported that operators are looking for specific fuel consumption reduction of up to 40%.

However, such aircraft face major challenges if their advantages are to be fully exploited. Not least of these is a very significant noise issue, which was one of the factors that led to the rejection of similar propulsion technology when it was previously considered in the 1980s. Significant technological progress has been made over the intervening years and manufacturers are now more confident of achieving the required certification standards. Nonetheless, the lack of models that would allow third parties to make confident predictions for noise levels (and emissions) of such aircraft is an obstacle to informed debate on the likely benefits and disbenefits were such aircraft be introduced.

To fill this gap, Omega has sponsored the current project that has developed a framework for the comparative analysis of AORs with conventional turbofan equivalent aircraft.

Because of the very great differences between AORs and turbofan engines it has been necessary to develop a code specifically tailored for AOR noise prediction. Turbofan noise and airframe noise have been dealt with using existing methods. Input parameters for the noise models have been developed using a commercial aircraft preliminary design tool. It is then possible to make predictions for both turbofan powered aircraft and a alternative AOR operating the same route. The results are presented as differences in Effective Perceived Noise Levels (EPNL).

This report gives an account of the methodology developed for obtaining the results. Most of the methods chosen are in the public domain and references are therefore given to more detailed expositions. However, significant work has been undertaken on the AOR (tonal) noise model and computer code and a detailed account of this is therefore given in a Technical Annex to this report.

The report begins with a detailed overview of the problem and the required objectives. The aircraft design procedure is then discussed. This is followed by discussion of the noise certification procedure and methods used for noise prediction. A description of the comparative study and results is then given and these are discussed along with recommendations for future research requirements.

During the course of this study advice has been sought from industrial and other stakeholders and this has proved very useful. There is, however, a natural reluctance on the part of airframe and engine manufacturers to allow detailed design information to be reported on. Consequently the example calculations presented should be seen as indicative of the methods capability rather than reflecting the true likely behaviour of planned technology.

The principal finding is that AORs are capable of meeting the ICAO Chapter 4 Noise Certification Standard with modest improvement in technology and operational procedure. Given that this result is based upon information that is publicly available, the likelihood is that any commercial design will have a larger margin over Chapter 4 than this.

Essentially due to their more fuel efficient powerplant, reductions in cumulative aircraft certification noise levels of as much as 12 EPNdB, when compared to an equivalent 150-seater, single-aisle, medium-haul turbofan-powered aircraft of the year 2000. These noise savings come as a direct result from: a) specific changes to the engine noise source character (i.e. its spectrum and directivity), and b) possible alterations to the aircraft's operation. These operational changes include increasing both the climb and descent gradients of the aircraft (as part of its 'landing and take-off' (LTO) cycle) as well as a slight reduction in the take-off thrust levels necessary for an aircraft to reach its top-of-climb/cruise altitude.

In addition to the aircraft operation analysis, particular changes to the actual design of an advanced open rotor's powerplant were also investigated. Two designs were compared: 1) an 8 X 8 rotor design (i.e. 8 blades on both the upstream and downstream blade rows) and 2) an 11 X 8 design (i.e. 11 blades on the upstream and 8 blades on the downstream blade rows). It was found that by reducing the blade number ratio between the upstream and downstream blade rows, there is an acoustic benefit of 9.3 EPNdB at cutback, 8.5 EPNdB at lateral and 7 EPNdB at approach certification locations for a 150-seater, medium-haul aircraft. It should be noted, also, that further acoustic improvements to an advanced open rotor engine are expected to transpire as a result of current research and development.

2.0 Overview

2.1 Objectives and Problem Definition

The main objective of this study was to develop the methods needed to undertake a comparison (in terms of a suitable metric) of the noise levels of two different aircraft types (AOR and Turbofan) undertaking similar flight missions (range and passenger payload). It was decided that the comparison of noise levels would be made using the ICAO noise certification standards.

Because the study is comparing different technologies it was decided that the noise models used must be capable of discriminating between different assumptions concerning the airframe and engine architecture. Consequently, generic prediction tools are not sufficient and a number of "noise from source" tools were needed. Further, these tools must be combined to give a whole aircraft prediction for variable flight parameters.

For the purposes of this study the turbofan aircraft chosen was a generic 150 seater year 2000 design. Advice was taken from airframers and engine manufacturers on the best parameters to use in calculations. It should be emphasised that this choice was made because of the ease of obtaining aerodynamic performance information. The AOR chosen for comparison is based on a 1990s design --- again the choice being dictated because of the need to obtain aerodynamic data. This design was somewhat modified to include advances arising from better material technology. (While these choices mean that the comparison is somewhat less than ideal the main goal at this stage is to make a preliminary comparison that proves the fitness of the methodology.)

Given the availability of data on turbofan aircraft design and performance predictions for these aircraft types are relatively straightforward. In the case of the equivalent AOR it has been necessary to undertake a design process for the aircraft from scratch. This however, is an integral part of the project brief as it forms part of the capability sought ---- namely the ability to make meaningful noise predictions from the outset of the design process.

During the course of this study only a preliminary design process has been possible. Details of this are given in section 3 below. Even so, it is not a simple task to redesign an aircraft for replacement powerplant. Apart from the many structural considerations that exist when positioning an engine on an aircraft (due to changes in the centre of gravity etc.), it is the delicate balance and creation of lift and drag that is extremely sensitive to slight changes in the aircraft's total take-off weight and required thrust. The wing configuration of the airframe, in particular, is crucial because it must not only allow a stable low speed flight for approach, but also be able to create enough lift to allow a safe and sufficient climb performance at take-off. The mission information for a particular flight together with any engine operational constraints, therefore, both play a fundamental role in the determination of the necessary on-board fuel weight of an aircraft as well as its required climb, cruise and descent performance properties. All these considerations ultimately trace back to the airframe design.

Total aircraft noise is fundamentally governed by the airframe and the powerplant sources but it is the operation of the aircraft, which is equally important when considering aircraft certification and the impact each plane has on the community. It is, therefore, important to understand the performance constraints of a specific aircraft so that one can pinpoint the aircraft design parameters most sensitive to changes in total noise level at each certification microphone position.

The questions left, then, are, 'how sensitive are these parameters to total aircraft noise levels?' and, 'which specific advances in future aviation technologies will offer the maximum reduction in noise levels affecting the community?' The study, therefore, shall take two parts. The first will compare two similarly sized aircraft, with the same flight mission, each powered by a different powerplant. The objective, here, is to be able to calculate the possible changes to certification noise levels in order to compare an existing turbofan aircraft with an equivalent open rotor-powered aircraft.

The second part of this study will begin to investigate the specific powerplant design parameters most sensitive to certification noise levels. From this knowledge, better predictions of the noise benefits associated with a particular powerplant design can be made in order to procure effective decision-making early on in future design processes involving new technologies. It is important, however, to appreciate that this study is a first phase investigation aimed to introduce the necessary framework for predicting future noise benefits from any fundamental changes to an aircraft's design and its operation.

2.2 Aircraft Noise Considerations

For comparison purposes, this study uses the standard ICAO certification measurements. This is based on a cumulative measurement over three positions of microphone as shown in Figure 1 below.

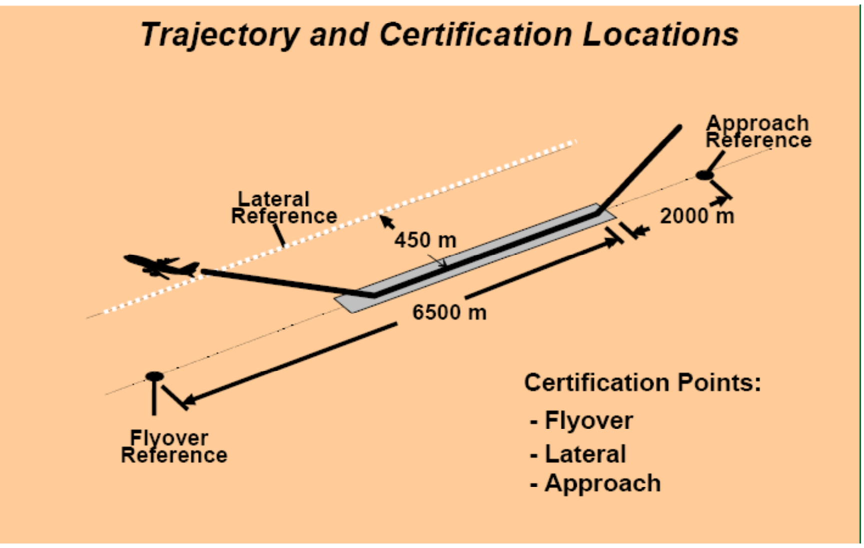

Figure 1 – Aircraft noise certification locations [2]

At the lateral (or sideline) microphone position the noise measured is governed predominantly by the power and directivity of the sound sources from the aircraft's engines. Incidentally, these noise sources must include the particular installation effects due, for example, to the proximity of the engine to the airframe, (i.e. reflection, scattering and jet-wing interaction effects). Typically, the thrust setting of a modern turbofan aircraft is set at 90% as the aircraft passes the lateral position.

At the flyover (or cutback) position, however, the situation becomes much more complicated. In addition to the power and directivity of the engine sources, the attitude and altitude of the aircraft are now important factors. Both the aircraft attitude (i.e. the angle the aircraft is to its flight path) and the actual climb angle (or flight trajectory) of the aircraft will, effectively, alter the directivity (and potentially the strength) of the sound sources heard on the ground. The altitude, however, of the aircraft above the flyover certification microphone is governed by the aircraft's climb performance. It should be noted that this performance is unique to one type of aircraft on a particular flight mission.

Finally, at the approach certification position there are, again, several important factors responsible for the sound measured at the microphone on the ground. As well as the sound power of the engines and their directivity (determined also, as before, by the aircraft's attitude and angle of descent) and the altitude above the microphone (which is determined by the aircraft's angle of descent), the approach velocity and flap operation of the aircraft also become important parameters. This is due to the significant increase in aerodynamic airframe noise above that of the various powerplant sources. The angle of descent is fundamentally linked both to the minimum possible approach velocity and also, therefore, to the maximum possible drag production available from the flaps.

2.3 Holistic Project Considerations

It is clear to see that in order to begin analysing such a problem, a basic understanding of aircraft design and performance capability is essential. For the purposes of this study, the aircraft design analysis and subsequent acoustic predictions are performed at a conceptual aircraft design level. In order to quantify, precisely, the possible changes to an aircraft's performance during its landing-take-off (LTO) cycle, one must perform a detailed design analysis. High-lift device geometry and operation, for example, have important repercussions for an aircraft's climb and descent performance, which then has a direct impact upon noise source levels at the flyover and approach certification noise positions.

Both economic and emission considerations are also closely linked to the amount of noise an aircraft produces at the three noise certification positions. Previous research by Antoine (2000) has found that, under some scenarios, overall NO_x emissions could be reduced by as much as 50%, for an increase in operating cost of only 9%. In terms of noise, however, under particular alternative scenarios, cumulative certificated noise levels could be reduced by up to 15 EPNdB for an increase in operating cost of 26% (see Figure 2 below).

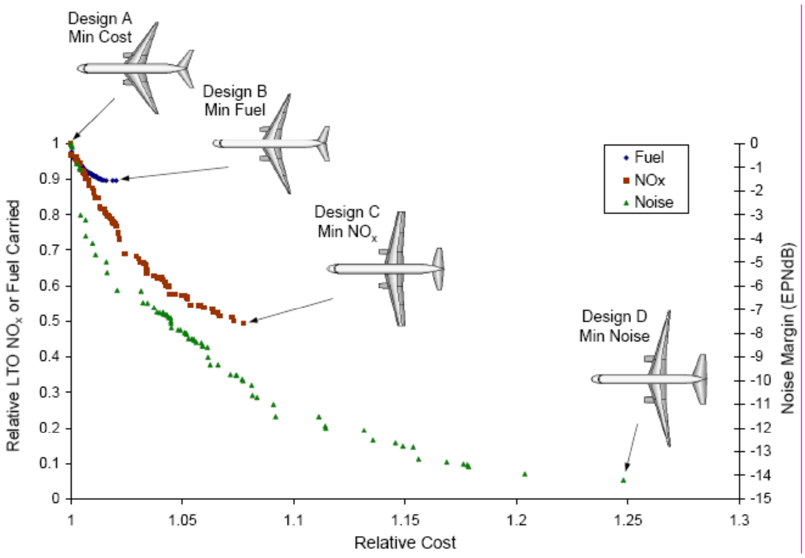

Figure 2 – Pareto-optimization fronts of fuel carried, LTO NOx, and cumulative certification noise vs operating cost [3]

When analyzing the level of NO_x emission and cumulative EPNdB benefits over the LTO-cycle against necessary cost implications (as in the previous figure) pareto-frontal optimization concludes that the inter-relationships here are not trivial.

Figure 3, below, also illustrates the complex trade-offs that exist between these three parameters.

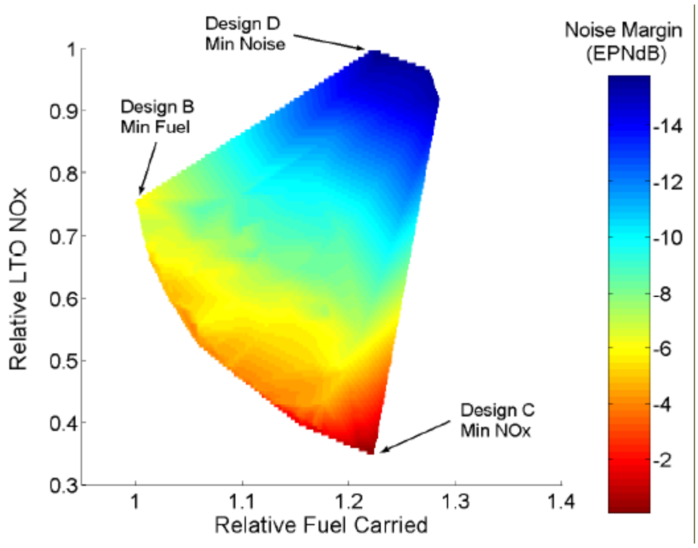

Figure 3 – Pareto surface of LTO NOx vs fuel carried vs cumulative noise [3]

Having said that, it should be noted that this situation is true only of a particular turbofan-powered aircraft whose most crucial variable, in terms of noise, is the bypass ratio of the turbofan engine. We can expect a differently shaped graph when introducing future technologies to the table. The important point to remember is that aircraft noise and emissions are never mutually exclusive variables and so require careful analysis. Detailed thrust analysis specifically, therefore, is required to quantify the exact fuel burn profile, noise source power levels and aircraft speed at each phase of the aircraft's LTO-cycle.

It has been suggested that the issue of aircraft noise away from airports (i.e. low-altitude 'en-route' flight) will also be an important future issue for the aviation industry. While this particular problem, however, has fallen outside the scope of this investigation, it is believed that the specific noise predictions from aircraft at altitude will pose no significant problems using the proposed framework.

3.0 The Aircraft Preliminary Design Process

In order to understand the principles behind the subtle operational differences between two similar aircraft, the design process should be broken down into three phases. Phase 1 of the process includes the all-important aircraft weight and sizing calculations (including the minimum wing span, etc.) based upon the specific flight mission and powerplant properties. With this knowledge, phase 2 involves calculation of the minimum distance required to take-off safely (clearing the necessary height regulations, etc.) and the subsequent potential climb performance properties of the aircraft. Phase 3 then deals with analysis of the aircraft's approach and landing process, including calculation of the required minimum landing distance based on safe approach speed and angle.

3.1 Phase 1 – Weight / Mission Sizing

The weight of an aircraft is extremely important when determining its optimum performance capability. The equation used to calculate this weight is the basic Breguet equation, shown below:

$$ds = \frac{VLdM}{cDM}$$

Equation 1 [1]

where,

s = Range (m)

M = Mass (kg)

V = Velocity (m/s)

c = Specific Fuel Consumption (kg/N/hr)

$\frac{L}{D}$ = Lift-Drag Ratio

For the purposes of this study, a typical six-phase mission has been assumed: 1) warm-up & take-off, 2) climb, 3) cruise, 4) descent, 5) 20-minute loiter and 6) landing & taxi. The third phase of the mission is the most important factor in terms of the amount of on-board fuel carried.

The necessary inputs required to estimate the size and weight of an aircraft are listed below:

- Payload (number of passengers, baggage, etc.)
- Range
- Cruise Mach number
- Cruise altitude
- Specific fuel consumption at cruise
  (kg of fuel burned per Newton of thrust produced per hour)
- Aircraft lift-drag ratio at cruise
- Operating empty weight (i.e. the weight of the airframe and engines)

All of the above parameters, except the payload and the operating empty weight, are key players in determining the fuel fraction of the cruise phase of a particular flight mission. It should be noted that, inherently, crude assumptions must be made for a conceptual design level analysis. Here, the main assumption is that the cruise conditions of such an aircraft remain constant. It is, then, an iterative calculation process between the empty weight fraction, the fuel fraction and the total added payload, which will, ultimately, result in a value for the aircraft's gross take-off weight. The other output from this analysis is the minimum necessary wing span required to carry such a weight at take-off. This wing loading will have repercussions later on for required take-off distances calculated in Phase 2 of the conceptual design process. The final maximum value for the wing span is a function of many detailed aerodynamic variables (including properties of the leading and trailing edge devices on the wings) necessary for stable low-speed flight, particularly when landing. For the purposes of this conceptual design process, however, typical factors have been used.

3.2 Phase 2 – Take-off Analysis

There are two methods, here, which need to be investigated to appreciate the level of sound recorded at the flyover certification position. Firstly, and most obviously, analysis of the length of take-off distances between differently-sized aircraft, having the same amount of thrust, will naturally lead to changes in flyover altitude and, therefore, a reduction in total flyover noise. Secondly, and as mentioned earlier, the climb performance is also of particular interest. The aircraft's operational constraints picked up by detailed thrust analysis will determine the altitude of the aircraft at the flyover stage of its flight (i.e. 6500m from the start of roll to the take-off process). The climb performance is both a function of the maximum available continuous thrust required to lift the aircraft to its cruise (or top-of-climb) altitude and a comfort/safety factor imposed by passengers and regulation as to how steeply the aircraft may climb. The important constraint here, therefore, is the aircraft's maximum 2nd segment climb angle. This parameter will be explained later on in more detail.

3.2.1 Take-off Distance

Figure 4, below, defines the regulation take-off distance for today's civil aircraft.

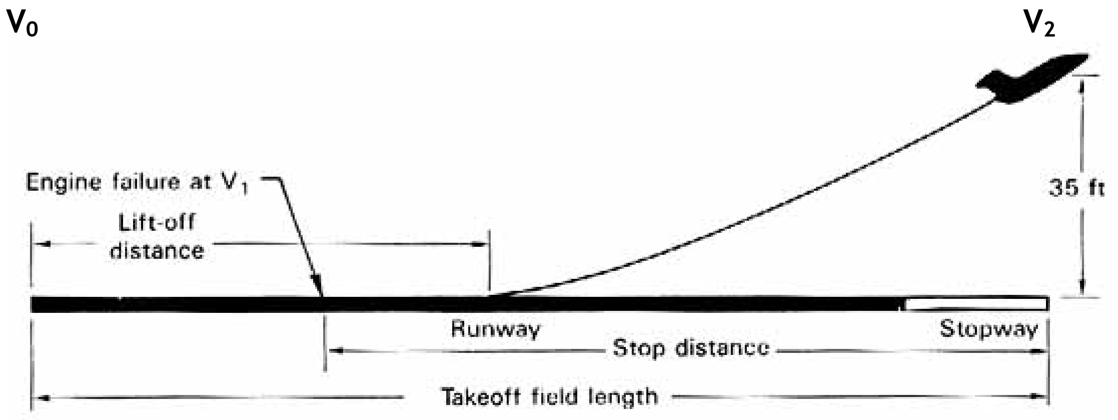

Figure 4 – Regulation civil aircraft take-off definition

V_0 is the zero-velocity of the aircraft at the beginning of roll on the runway and V_2 is the velocity of the aircraft at the safety obstacle height (35ft). V_2 is also the beginning of the aircraft's 2nd segment climb. The total take-off distance is termed, "Take-off Field Length". This distance is a function, essentially, of four main parameters:-

- 1) Max Take-off Weight
- 2) Thrust-to-Weight Ratio
- 3) Unstick Lift Coefficient (an aerodynamic take-off condition, governed by the aircraft's wing configuration, at which point the aircraft can lift off the ground)
- 4) Take-off Wing Loading.

The equation to calculate the take-off field length is written down below:

$$ToL = \frac{k_e}{C_{LUS}} \frac{Mg}{S_0} \left(\frac{T}{Mg} \right)_0^{-1.35} \left(\frac{Mg}{S} \right) \left(\frac{T}{Mg} \right)_0 \; 61201 \; {}^{0.5} \; [\;]$$

Equation 2 [1]

where,

$k_e = 0.1$ (for turbofan-powered aircraft)

C_{LUS} is the unstick lift coefficient (function of aircraft stall speed)

$\left(\frac{T}{Mg}\right)_0$ is the take-off thrust-to-weight ratio

$\left(\frac{Mg}{S}\right)_0$ is the take-off wing loading

So, for making comparisons between aircraft having different weights and airframe designs for the same thrust, this calculation is adequate.

For a given take-off distance, however, there are two techniques to calculate the required take-off thrust for two different aircraft. Firstly, the above equation can be rearranged to find an iterative solution for the minimum required thrust-to-weight ratio, as shown below,

$$\left(\frac{T}{Mg}\right)_0^{-1.35} = \frac{C_{LUS}}{k_e\left(\frac{Mg}{S}\right)_0}\left[\frac{ToL}{120} - 1 - \frac{6}{k_e}\left(\frac{\left(\frac{Mg}{S}\right)_0}{C_{LUS}}\right)^{0.5}\right]$$

Equation 3 [1]

The second technique is to calculate the required thrust of each aircraft at its respective top-of-climb altitude and to work backwards using a typical thrust lapse rate from a standard atmosphere model. It is important not to forget, however, that the thrust of an aircraft is dependent upon the drag produced by the particular airframe (plus engines), its speed, its attack (i.e. the angle of the engines to the forward flight trajectory), its altitude and the individual type of powerplant it houses. For a typical year 2000 turbofan engine, for example, which has a static sea-level thrust of 25,000 lbs, its equivalent cruise thrust is approximately 20% of that when travelling at 0.8 Mach and at 35,000 ft. It is necessary, therefore, to make another crude assumption in terms of the thrust lapse rate due to the atmosphere. Results from both techniques are presented in this study.

3.2.2 2nd Segment Climb Angle

This parameter is an important one for noise because it essentially defines an aircraft's height above the flyover certification microphone. It is defined as the angle the flight path of the aircraft takes once it has passed the obstacle height (35ft), at velocity V_2. It is only a constraining parameter, however, when one engine fails during take-off. The regulations decree that, for a two-engine turbojet/turbofan aircraft, when one engine fails after the initial take-off, a minimum climb gradient of 2.4% (a climb angle of 1.38^o) must be achievable from position V_2 up to an altitude of 122m (while maintaining a constant speed of V_2). After this height (i.e. the beginning of the 3rd segment climb), all high lift devices are retracted and the gradient requirement is reduced by half.
Currently, the maximum 2nd and 3rd segment angles an aircraft may fly (with all engines operative) is largely determined by passenger comfort and safety, but more so, nowadays, by the economics and emission characteristics of the fuel burned as part of each aircraft's take-off cycle. There is also an Air Traffic Management (ATM) restriction which exists for

particular airports that do not have extensive blocks of free airspace above a generic 4^{o} climb angle, but the angles of concern, here, would correspond to $>20^{o}$, and are, therefore, not an major issue for the conditions imposed by this research. Obviously, there is also a maximum continuous engine thrust constraint for each aircraft (in terms of the maximum achievable speed required to produce enough lift for a given weight and wing configuration in order to reach the top-of-climb altitude), but it is, generally, the passenger comfort and economic (fuel burn) factors, which dictate today's aviation industry protocols.

3.3 Phase 3 – Descent Analysis

Descent analysis is a complicated science in terms of noise. The landing distance, approach speed and approach angle are all inter-related parameters, which demand particularly careful consideration in terms of trade-off analysis when modelled at the detailed design level. Here, they will be broken down individually, to a degree, in order to demonstrate the fundamental sensitivities each has to approach noise measurements.

3.3.1 Landing Distance

The landing distance required for a civil aircraft is dependent upon several parameters. The distance itself is defined as in the figure below,

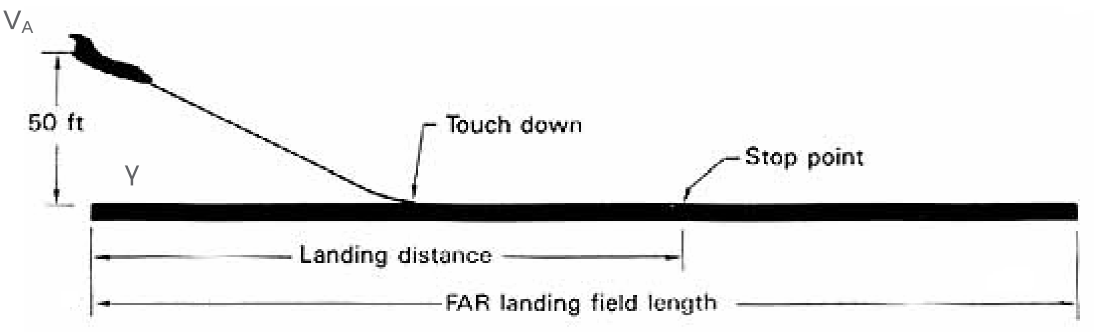

Figure 5 – Regulation civil aircraft landing distance definition

V_A is the aircraft's approach speed, γ is the descent angle and the FAR landing field length is a safety-factored distance. The equation, which links all of these parameters, is written below,

$$\text{Landing Length}\ 4.5\ 0.0255\ \frac{25.55}{\tan\gamma}\ V_a L V_a^{2}$$

Equation 4 [1]

where,

$$L_L = \left[1 + \frac{15.59}{\left(\frac{\mu_G}{0.38}\right)\left\{\left(\frac{\mu_G}{0.38}\right) + 1.2\left(\frac{T}{Mg}\right)_R \left(\frac{M_0}{M_L}\right)\right\}} \right] 20.6\tan\gamma$$

γ is the descent angle

V_a is the approach speed

μ_G is the braking coefficient

$\left(\frac{T}{Mg}\right)_R$ is the thrust-to-weight ratio for reverse thrust

$\left(\frac{M_0}{M_L}\right)$ is the ratio of take-off to landing masses

This equation, therefore, takes into account the runway conditions (in terms of the breaking coefficient, μ_G) and any available amount of reverse thrust, which may be required either for a particularly short airport runway or for a faster/steeper approach. For the purposes of this comparative study, however, these two parameters will be kept constant.

3.3.2 Approach Speed and Approach Angle

Intrinsically, these two properties are closely linked. It is not a simple problem to glide a civil aircraft in to land at a steep angle and at a low approach speed, especially when noise is concerned (more on this later). At a basic level, however, these parameters can be defined individually. Firstly, in terms of the descent angle, the main constraining factor, here, is safety – i.e. the pilot's workload, passenger comfort and the landing conditions (i.e. the weather and runway conditions, etc.). While these factors are also relevant to the maximum allowable approach speed, the fundamental defining parameters, here, are the aerodynamic conditions necessary for stable low-speed flight, which is also termed the "landing stall speed". This speed is determined by two qualities: 1) the aircraft's wing configuration (i.e. its quarter chord sweep angle and high lift devices) and 2) its landing weight, which is a function of the total fuel burned for the distance the aircraft has travelled.

4.0 Aircraft Noise Modelling

4.1 Whole-Aircraft Noise Modelling (SOPRANO)

SOPRANO was developed by ANOTEC as part of the EU FP6 Research programme SILENCE(R). It is a multi-platform program, written in FORTRAN 95, which models sound as it leaves a moving source, or a collection of moving sources (i.e. an aircraft), and travels to a particular microphone, or to a collection of microphones. The program is predominantly used to model aircraft as they travel along a specified geometry/flight path. It is possible to combine source prediction models and measurement databases within SOPRANO, as well as to add new methods. See Appendix A for a list of all the noise prediction methods currently available in the public domain and used in this study. The structure of SOPRANO is shown in
Figure 6, below.

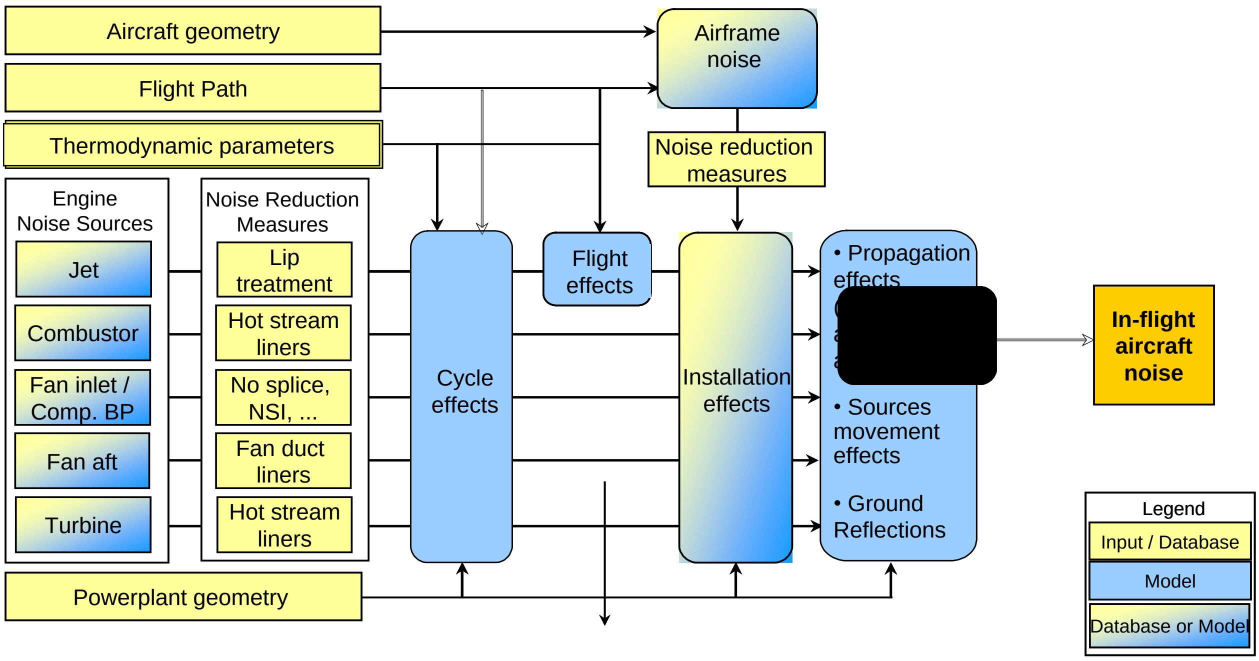

Figure 6 – SOPRANO program structure

SOPRANO will output carpet plots for a single flight from point A to point B along with a source breakdown readout (see
Figure 7), but there are several drawbacks. Firstly, it is not possible to carry out static predictions in SOPRANO. This capability would be particularly useful for detailed comparative analyses of aircraft with different noise identities. Secondly, SOPRANO does not output narrowband results. Third-octave band results are adequate for the current EPNL and L_{Aeq} turbofan predictions, but for noise sources containing many individual tones, like advanced open rotor engines, this averaging metric no longer accounts

properly for the energy present at each key frequency. Further research will determine exactly how significant the repercussions will be for EPNL certification calculations as well as for the wider question of community aviation noise annoyance assessment. The third drawback worth mentioning is that SOPRANO has a 0.1dB rounding error. For EPNL calculation, however, this has negligible repercussions. The final, and most important, drawback with this prediction procedure is that many of the publicly-available noise prediction methods are less than satisfactory for the prediction accuracy required in today's aviation industry. While this is not a crucial hindrance for the purposes of this investigation, any further comparative research will require access to more up-to-date methods (particularly for airframe noise and fan noise prediction).

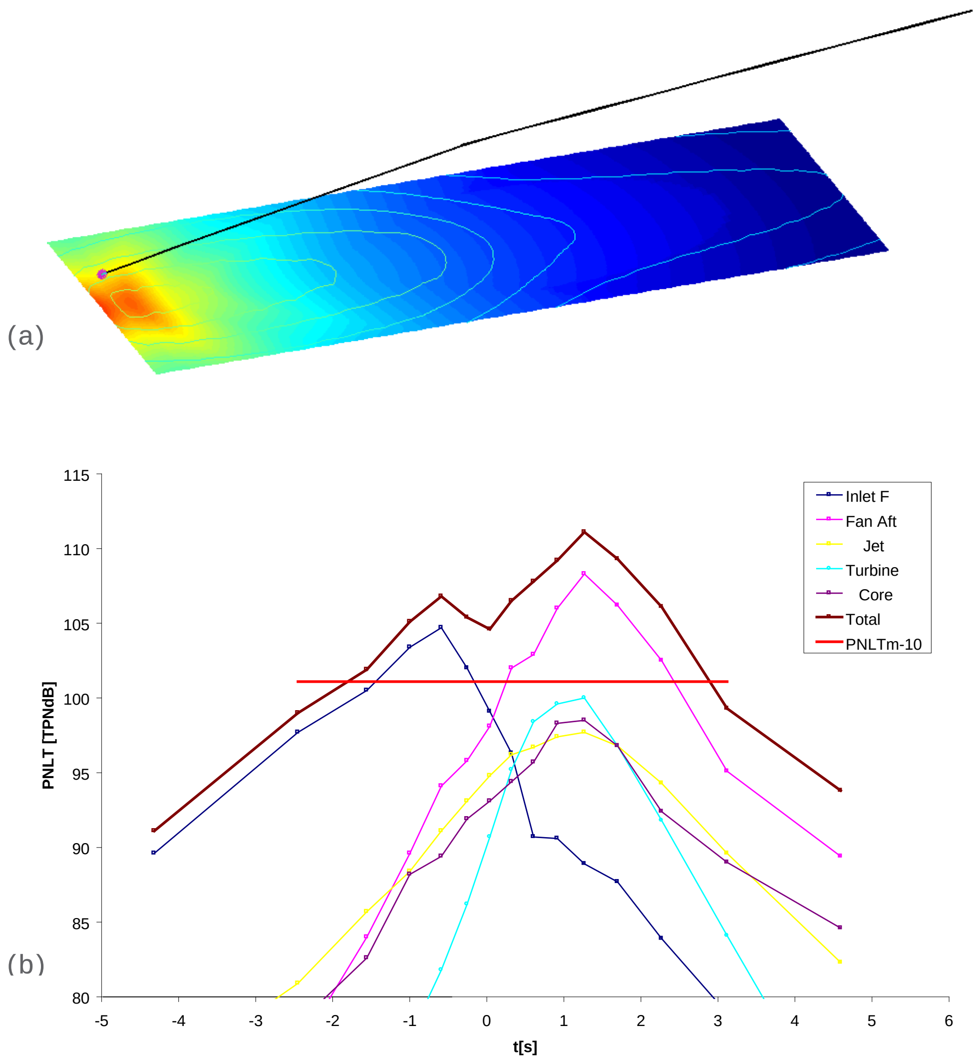

Figure 7 – SOPRANO (a) footprint plot and (b) source breakdown plot

4.2 Special Consideration for AOR Noise

An inability of SOPRANO for the current study is that of predicting noise of counter rotating propellers (CRP). A new code has been developed specifically for this task and this has been used in obtaining results detailed below. This method is fully described in the Technical Annex to this report.

The method uses an analytic expression to calculate the sound pressure in the acoustic far-field and includes the effect of propeller incidence. The analytic formulae require the geometry and operating conditions (forward flight speed, propeller rotational speeds and air density) to be specified. In addition to these parameters both the steady and unsteady loading on the propeller blades must be specified. The steady loading must be determined separately, while the unsteady loading is calculated from the unsteady flow incident on each propeller using standard ‘blade response functions’. Analytic expressions for calculating the unsteady incident flow are detailed in the Technical Annex to this report.

5.0 Aircraft Comparative Study

Once the aircraft design process is understood, it is possible to appreciate the fundamental changes necessary to an aircraft's design and operation given the introduction of a new technology. It is now also possible to compare the amount of certification noise produced from two aircraft with different powerplant technologies. For this investigation, an advanced open rotor-powered aircraft, of the year 1990, will be compared to an equivalent turbofan-powered aircraft, of the year 2000. The term 'equivalent', here, refers to the aircraft having the same mission properties and fuselage size. Table 1, below, lists the properties of each particular case.

Table 1 – Specific mission and performance parameters for a turbofan and an advanced open rotor-powered aircraft used in the comparative study

	Turbofan (Year 2000 Design)	Advanced Open Rotor (Year 1990 Design)
Number of Passengers	150	150
Max (Static) Thrust (per engine)	25,000 lbs	25,000 lbs
Range	5000, 3500 & 1500 km (Max, Mid, Short)	5000, 3500 & 1500 km (London-Lagos, Lon-Cairo, Lon-Rome)
Cruise Altitude	10,668 m	10,668 m
Cruise Mach Number	0.78 M	**0.72 M** [(i)]
Specific Fuel Consumption at Cruise	0.577 lb/hr/lbs	**0.397 lb/hr/lbs**
Climb Angle	4°	4° **- 9°**
Descent Angle	3°	3° **- 6°**

[(i)] Data taken from Hoff, 1990 [4]

In this study, a 150-seater twin-jet turbofan-powered aircraft is compared to an equivalent advanced open rotor-powered aircraft in terms of noise. The range of an aircraft has significant implications for the on-board fuel carried and, thus, its take-off weight. Therefore, a threefold (maximum, mid and short) range analysis was carried out assuming a constant airframe shape with a view to determine 1) the potential savings in thrust and 2) the increase in altitude over the certification microphone provided by a lighter aircraft, which would then result in a change to the certification noise level.

Gathering detailed and reliable information about the properties of future technologies, especially engines, is always a very difficult and sensitive process. Because Omega is a publicly-funded organisation, all data is provided from, and calibrated against, Hoff's NASA report (1990) on counter-rotating blade concepts. For the purposes of comparison and analysis, it has been assumed that a nominal 30% reduction in specific fuel consumption is achievable from an open rotor-powered aircraft compared to an existing turbofan aircraft. This may not strictly be true of future engines once they are attached to the airframe and are operating at cruise conditions, but this precise percentage is not a crucial assumption for the purposes of building a framework to predict the noise benefits.

To highlight the potential noise savings from future technology, the different performance properties of the new aircraft must also be appreciated. For this study, it has been assumed that the advanced open rotor engine is capable of steeper climb angles than existing turbofans. It is too early, however, in the development of this technology to be confident in an exact maximum angle. Results from climb angles, ranging from the minimum regulation 4^o up to 9^o, shall be presented. Similarly, the potential capability for steeper angles of approach is accounted for. Values of descent angle ranging between 3° and 6° have been investigated here.

5.1 Take-off Thrust Analysis

As mentioned in section 3.2, there are two techniques for analysing the potential noise benefits possible at take-off from lighter aircraft (due to a smaller fuel fraction calculated in phase 1 of the aircraft design process) in terms of thrust: 1) by reducing the take-off distance and 2) by reducing the minimum take-off thrust setting required for the whole aircraft to satisfy the regulation safety take-off height and then to ascend to its top-of-climb altitude. Results from the first analysis can be seen in

Figure 8, below.

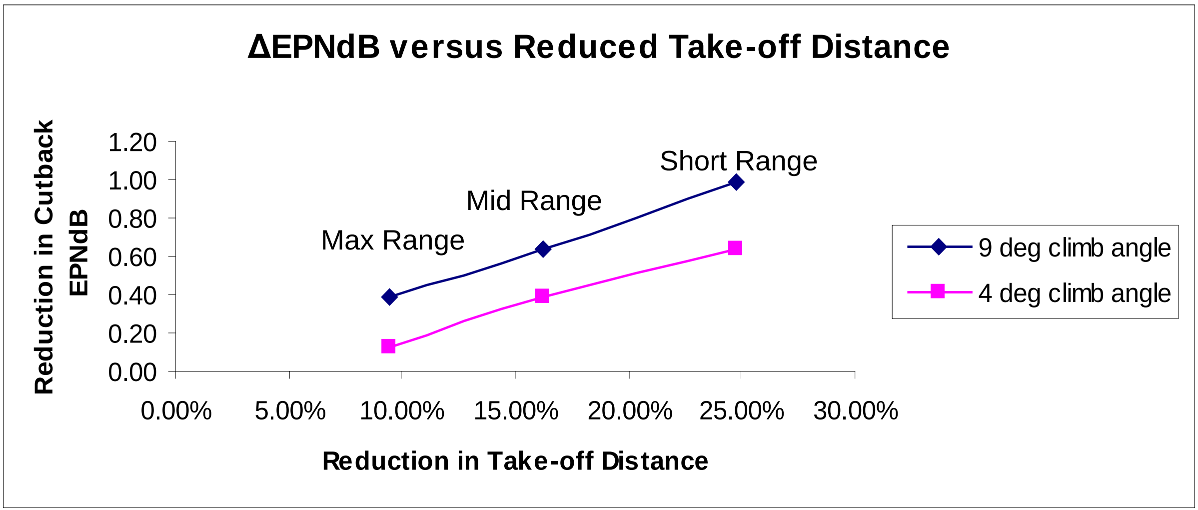

Figure 8 – Noise savings seen at the cutback certification location due to a reduction in take-off distance

As expected, more significant savings in noise measured on the ground can be seen as the aircraft travels less far (and so is lighter) and is also able to climb more steeply. These operational benefits, however, are only seen at the cutback certification location. For the

second thrust analysis method, the total reduction in thrust setting achieved from the same aircraft but this time optimised to reach its top-of-climb altitude (less quickly), allows potential noise savings both for the cutback and for the sideline certification locations. The results can be seen in
Figure 9.

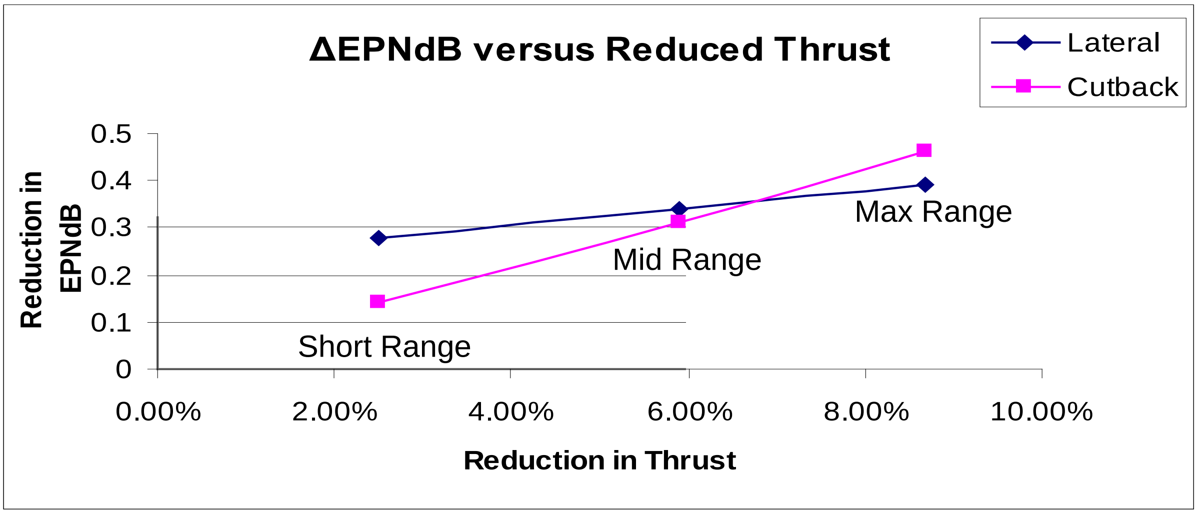

Figure 9 – Noise savings seen at the cutback and sideline certification locations due to a reduction in the required take-off thrust

For this case, the most significant noise savings can be seen by the heavier or longer range aircraft, which see the greater reduction in their minimum required take-off thrust-to-weight ratios.

5.2 Climb Performance Analysis

To illustrate the potential noise savings due to the operational climb performance changes of an aircraft equipped with future technology, two different advanced open rotor engine designs have been compared. The first is called the “8 X 8 AOR” and has eight blades on both the forward and rear blade rows. The second has eleven blades on the upstream and eight on the downstream blade row – the “11 X 8 AOR”. Essentially the 8X8 AOR is a ‘bad’ design and the 11X8 AOR is a ‘better’ design (in terms of noise). By increasing the 2^{nd} segment climb angle of the aircraft’s operation, achievable from such future technologies, the following results are seen, in
Figure 10.

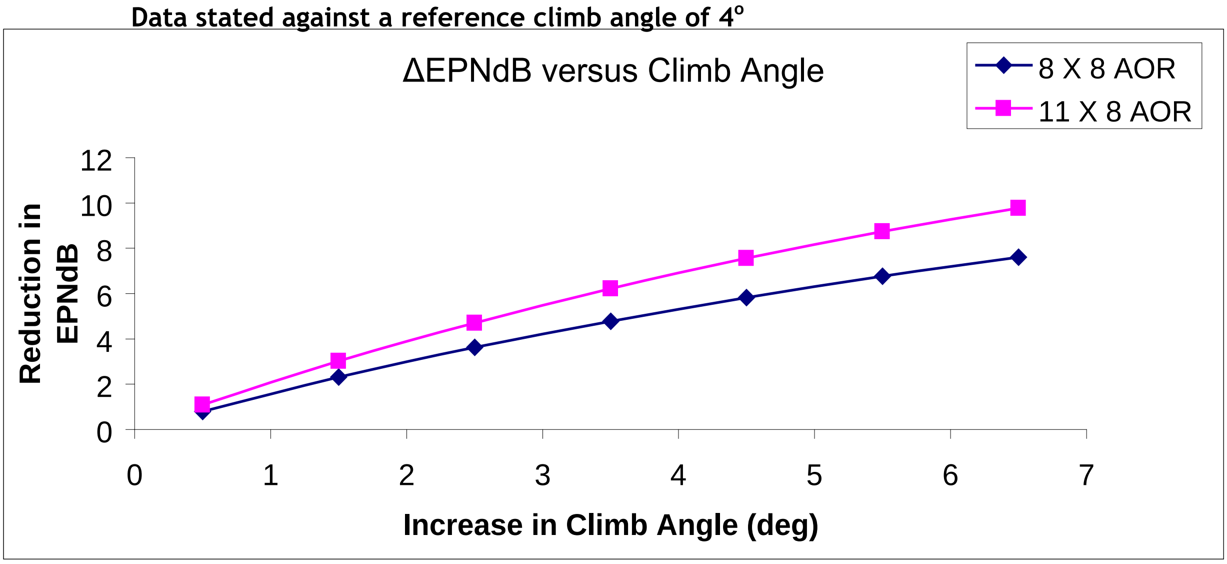

Figure 10 – Noise savings seen at the cutback certification location due to an increase in an aircraft's 2nd segment climb angle

Apart from the expected noise benefit received from the increase in aircraft altitude above the cutback certification microphone, there is another interesting feature to this graph. The additional point to note, here, is that not only does the 11X8 AOR design perform better than the 8X8 AOR design, but the 'better' design actually performs progressively better with increasing climb angles. This may be due to the more directional, or beaming, character of the sound sources present from the 11X8 design compared to the more omni-directional source nature of the 8X8 'bad' design. Any future improvements to powerplant aerodynamic and acoustic design, therefore, can now be predicted and assessed.

5.3 Descent Analysis

The same two advanced open rotor engine designs were used to illustrate the noise benefits due to steeper aircraft descent gradients.

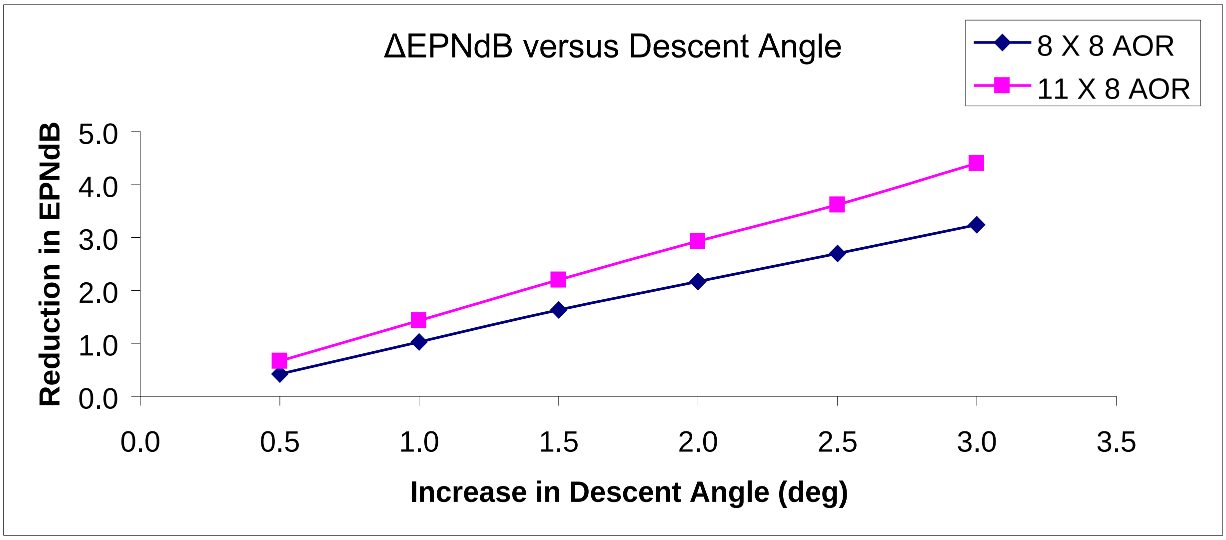

Figure 11 – Noise savings seen at the approach certification location due to an increase in an aircraft's descent angle

Again, the directivity effects from the two powerplant designs can be seen clearly, from Figure 11, in addition to the altitude effects. It should be noted, however, that increased approach angles will also increase the approach speed of the aircraft. There are various issues which now surround this descent analysis. Firstly, based on previous research (Rhodes, 1998), it has been found that increasing an aircraft's speed on approach may serve to reduce the noise observed by the approach certification microphone. Increasing the approach speed by +5 kts, for example, will allow a reduction in flap angle from 30^o to 25^o (whilst maintaining an adequate stall margin), which in turn will reduce both the drag and thrust by 1.5%. This will yield a net reduction in approach EPNL of -1 EPNdB. However, increasing the approach speed by more than 15 kts will actually serve to increase the sound measurement by +1 EPNdB. This is due to the rise in source strengths of the airframe noise, which begin to dominate the benefits achieved by the drag and thrust reductions. The paradox, however, is that if one attempts to reduce the airframe noise (through streamlining, for example), the aircraft loses its ability to create the drag necessary to control its approach. So, an aircraft's approach speed is fundamentally constrained between a minimum, from the aerodynamics of the wing configuration and landing weight necessary for stable low-speed flight, and a maximum, from the airframe noise source, which starts to dominate the certification measurement on the ground.

In addition to these problems, it should also be noted that an aircraft in descent is more susceptible to atmospheric turbulence and, therefore, 'over speeding'. Any increases in approach velocity and angle will obviously serve to increase a pilot's workload, which will lead to an increased safety risk (and extra pilot training certification). It may be, therefore, that any changes to descent protocol are subject to very stringent weather and runway conditions, perhaps, in addition to some degree of flight deck automation.

5.4 Powerplant Design Analysis

This final piece of analysis concerns a more in-depth assessment of the two different advanced open rotor engine designs – the 8X8 AOR and the 11X8 AOR. From acoustic source data produced by the advanced open rotor tone prediction algorithm (See the technical annex), it was possible to compare the two different designs assuming a particular thrust value for each of the three certification locations. The aerodynamic predictions of the lift and drag coefficients on each of the blades, necessary to calculate the thrust of such an open rotor configuration, were developed through NASA's CRPFAN script (1990). More up-to-date aerodynamic models would, therefore, ideally be required for any further valued progression of this study. The results, however, are still interesting for comparative analysis.

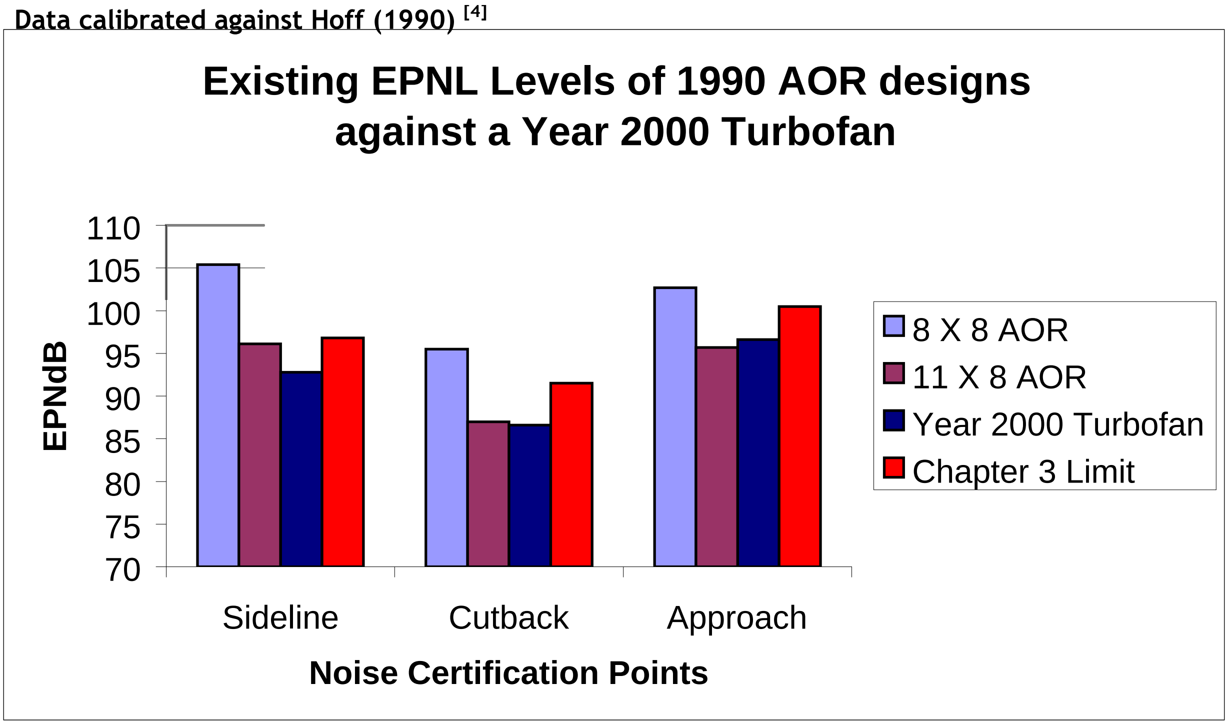

Figure 12 – Noise certification value comparisons between a year 2000 73.5tonne MTOW 150-seater turbofan-powered aircraft and two equivalent advanced open rotor-powered aircraft

It is quite staggering to see the effect increasing the ratio between the number of blades on the front and rear blade rows has on the certification noise levels. A saving of 9.3 EPNdB can be had at cutback, 8.5 EPNdB at lateral and 7 EPNdB at approach. These kinds of acoustic benefits are all the more encouraging when one considers the age of these AOR designs (circa 1990).

6.0 Conclusions & Future Research Needs

It has been shown that with changes to an advanced open rotor's operation, compared with that of an existing turbofan, significant benefits in cumulative EPNdB certification noise levels can be seen. From a 1990s based design of advanced open rotor aircraft, at least a 12 EPNdB benefit is possible from a 5 degree increase in 2^{nd} segment climb angle, a 3 degree increase in descent angle and a 5% reduction in gross take-off mass, compared to a year 2000 73.5 tonne (MTOW) turbofan-powered aircraft.

This study has focussed solely on noise at the takeoff, cutback and approach certification points. These measurement points are acceptable for evaluating the impact of noise on the community for conventional aircraft. However, future aircraft with different noise levels, noise characteristics and operational procedures may be audible at ground level while en-route. Thus the significance of en-route community noise for advanced open rotor powered aircraft needs to be assessed. Because of the potentially large propagation distances of this en-route noise, this will be a complex problem which will require considered analysis.

Acoustic improvements to advanced open rotor engines are expected to continue as the design process deepens. Particular tonal sources (such as the wake & tip vortex interaction tones), for example, are expected to be reduced significantly relative to the broadband noise sources.

The most important outcome of this research is the development of a working framework to assess the noise benefits and disbenefits of fundamental changes to aircraft design due to advances in engine technology together with the effects of varying airacraft operation.

There are two important caveats associated with this method as currently employed. However, neither of these is insurmountable. Firstly, is the access to up-to-date noise prediction codes to replace the public domain methods employed (i.e. a replacement for the Fink airframe noise method, the Heidmann fan noise method and the SAE codes for jet noise). Secondly, predictions that are apposite to current industrial thinking require access to the latest advanced open rotor powerplant geometry, location and performance information. Both of these are largely a problem of IP and can therefore be overcome by stakeholders.

Detailed design and performance modelling of aircraft using heavy duty computer packages (such as PACELAB) should next be completed to feed into the acoustic prediction models before accurate and useful results for industry can crystallize. Again however, the proprietary nature of much of the necessary data, which surrounds future technology, will always be a problem for any publicly available version of the methodology. It is up to the aviation stakeholders to appreciate the importance of such a tool for allowing the assessment of future aviation noise in the community. They can then help to clear the way for a more open system of knowledge transfer. Ultimately, these methods should not only be used to inform effective procurement of regulatory policies, but also to prepare society for the introduction of any such like future technologies.

Assuming such information was made available both noise and emissions models can be fed with accurate data. With access to this information together with the latest noise prediction methods, the path is clear for detailed assessments of the environmental impacts due to this future technology.

An important issue not addressed in this study is that of en route noise. It is known that turbofan aircraft can produce audible noise emmisions while at high altitude [6] and it is believed that AORs would be a more efficient source (due to the tonal dominance of the noise emmisions). Consequently, there is a need for further research in this area to quantify the likely risk that en route noise represents to the public acceptability of AOR aircraft.

Some preliminary studies were undertaken by NASA in the late 1980s and early 1990s (see e.g. [7]) indicating that the levels of noise on the ground varied significantly with propeller design and blade numbers. This suggests that there is the potential of minimizing en route noise through design -- but clearly this requires the development of necessary modeling tools early enough to be of use in the engine and airframe development process. These tools must be able to account for the more complicated propagation problem of sound from sources at altitude, understand the relationship between sources and received sound, and must also reflect the how such noise is perceived. This latter may require the definition of a new metric.

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[6] Weir, D.S., "The prediction of en route noise levels for a DC-9 aircraft", AIAA Paper 88-0268, AIAA 26th Aerospace Sciences Meeting, January 1988

[7] Proceedings of the FAA/NASA En route noise Symposium, NASA CP 3067, 1989

Glossary

Advanced open rotor (AOR): Aircraft engine consisting of two coaxial, counter-rotating propellers. Typically the propellers have high blade numbers and are swept – in contrast to conventional propellers

Climb: Portion of the flight where the aircraft is ascending to the cruise altitude

Community noise: Noise from aircraft which reaches people on the ground – typically people in the 'community' surrounding an airport

Cruise: Portion of flight after takeoff and before landing procedures begin. Typically at a constant altitude

En-route noise: Community noise produced by an 'en-route' aircraft

EPNL: Effective perceived noise level: a measure of aircraft community noise with a tone and duration correction

ICAO: International civil aviation organization

ICAO chapter 3 & 4 : Aircraft noise certification standards

NO_x: A generic term for the various nitrogen oxides produced during combustion

Payload: The mass carried by aircraft (including fuel)

Powerplant: The aircraft engine – provides the thrust used by the aircraft

Range: The distance (point to point on the ground) an aircraft travels on a particular mission. Also refers to the maximum possible distance and aircraft is capable of travelling

Specific fuel consumption: The ratio of the 'mass of fuel burned per second' to the output power of the engine

Thrust: The force provided by an aircraft engine.

Turbofan: An aircraft engine which provides thrust from a fan driven by a gas turbine. This form of engine is most commonly used on current large commercial aircraft.

Appendix A1 – SOPRANO Input Methods (Public Domain)

Fan Noise - Heidmann 'Interim Prediction Method for Fan and Compressor Source Noise' (NASA Technical Memorandum X-71763, 198)

Airframe Noise - Fink (FAA RD 77 29, 1979)

Jet Noise - 'Single Jet Noise Prediction' (based on SAE ARP 876 Rev D)

Turbine Noise - S.B. Kazin and R.K. Matta 'Turbine Noise Generation, Reduction and Prediction' (Paper 75-449 at the AIAA 2nd Aero-Acoustics Conference, 1975)

Core Noise - SAE ARP 876D

Atmospheric Absorption - 'Atmospheric Absorption' (based on SAE ARP 866 Rev A)

Ground Reflection – Chien-Soroka 'Ground Reflections Factor' (based on NASA Tech Memo 83199, Feb 1982)