DEVELOPMENT OF SILENT AIRFRAME CONCEPTS AND INNOVATIVE CYCLE PROPULSION SYSTEMS FOR REDUCTION IN AIRCRAFT NOISE

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Abstract

This paper will describe a range of innovative airframe configurations and several novel gas turbine cycles; aiming to produce a combination of gas turbine and unconventional airframe technologies, resulting in a low noise viable civil airliner. The combined Airframe and Propulsion technology study is a collaboration of Cranfield University alongside the joint venture of the Cambridge-MIT 'Silent Aircraft Initiative'.

Numerous tools have been used in investigating the low noise aircraft design, emphasizing on performance. Airframe design includes semi-empirical design methods (D. Howe and Loftin performance) with engine design incorporating the TURBOMATCH performance code. The noise analysis focuses on airframe and engine noise, using semi-empirical ESDU codes.

Airframe configurations were down-selected to seven main concepts, each requiring further development to determine an optimum concept for a low noise viable future airliner; requiring high fidelity noise prediction. Noise is critical to engine design, whereby increasing bypass ratio results in reduced jet noise, but increases fan noise unless there is a radical fan redesign. The airframe-engine integration is of utmost importance for performance and noise shielding.

1 Introduction - Vision & Goals

Aviation has recently been targeted as one of the noisiest industries in the engineering sector, and can be related to proximity of airports to residential areas. The growth of aviation has made matters worse as increased flight frequency is a direct result of surges in passengers wishing to travel; leading to expansion of existing airport facilities, such as London Heathrow terminal 5. More passengers and aircraft docking bays would increase the flight frequency, and hence, more community complaints.

Limitations for aircraft noise are governed by international law, as opinions differ on how noise should be controlled. The ICAO has a Committee on Aircraft Noise (CAN), which is the governing body for noise legislation. Limits are being re-assessed to restrict the noise levels, setting strict targets for civil aircraft in-service in 2010. These targets are to be further reduced by 2020, but until new requirements are confirmed, the use of so-called 'noisy' aircraft will still be legal. This emphasis on noise reduction creates a strain on aerospace industries; to generate new solutions to combat noise during early design stages.

Methods to reduce noise from current aircraft configurations are being investigated to tackle noise, so that targets set by ICAO can be met. The main noise source was initially the engine at take-off, but as technology has developed, airframe noise is now considered greater for a landing aircraft. New airframe technologies can be implemented, but only small noise reductions are possible whilst trying to maintain the performance requirements. The emphasis on noise reduction creates a strain on aerospace industries to generate new solutions, in order to try and combat noise at early design stages.

The collaboration of C-MIT 'Silent Aircraft Initiative' (SAI) investigates a radical aircraft change to meet future noise targets. Selection of a BWB airframe and novel technologies to re-design an aircraft is a bold step, focusing not only in reducing noise, but also emissions for a 'greener' aircraft.

The SAI project is supported by a unique Knowledge Integration Community (KIC), where the interaction between industry and research activities is discussed and analysed. The KIC is of great importance to the overall project in terms education, advice and industrial collaborations.

The research conducted by Cranfield University is a parallel study with SAI, focussing on innovative concepts and radical designs to compare the 'most silent' airframe and propulsion system designs. The outcome is to determine whether the most silent airframe is competitive to the current day configuration, whether it meets aviation regulations and is it an economically viable design.

1.1 Scope of Paper and Research Questions

The main Objective of this research is to develop a methodology for novel airframe configurations and innovative propulsion systems design. An important consideration is the integration process between airframe and propulsion system, and has proved difficult. The ideal airframe may not necessarily have the lowest noise, especially with the wrong engine, so another target for researchers is to integrate all possible design concepts to achieve the main goal; a low noise, socially and economically viable aircraft for the future.

The research currently conducted by the Silent Aircraft Initiative (SAI) team permits the authors to acknowledge the importance of this type of study, and how it may affect the future of civil air transport design. Additional research into legislation and future targets has proved useful to set guidelines for the aircraft specification, with the baseline design examined and preliminarily tested using a low fidelity ESDU noise model.

1.2 Airframe Noise

The target to meet noise legislation is an important feature, but the main question aircraft designers must now face is, what is noise? How can it be measured? How can it be isolated? Smith [1], best describes noise as being *"a common parlance for undesirable sound"*.

Fig. 1: Approach configuration, courtesy of 'Science of Flight'.

Noise at the airport perimeter is measured using effective perceived noise scale EPNdB, which was created specifically in order to validate the noise level certification of aircrafts. *"The decibel addresses a wide range of sound intensities by using a logarithmic ratio of the actual sound pressure level (SPL) to a nominal value, the threshold"*, where *"a doubling of sound intensity or noise level is reflected by a change of 3dB"* [1].

Noise isolation is a critical study that requires an aircraft design team to work with an independent authority on noise. Identification of major aircraft noise sources is necessary and can be divided into airframe and engine noise; with further subdivisions under the two groups.

In the history of noise, airframe noise was not considered due to the magnitude of sound from the engines. As noise reductions for propulsion systems progressed, it was found that airframe noise sources contributed a larger amount of undesirable sound than initially expected during landing, and as a result noise tests were conducted.

The sources of airframe noise are mainly due to surface interference or obstructions to airflow. If no surfaces are deflected the aircraft has a clean flight configuration. If all surfaces are deployed, for example, on approach (Fig 1 & 2), then this is a ‘dirty’ flow configuration.

Fig. 2: Landing configuration, courtesy of ‘Science of Flight’.

Main contributors to noise are undercarriage, leading edge (LE) slats, trailing edge (TE) flaps and empennage. Although these provide the majority of noise, additional source are present, for example the wing, wing-fuselage interface, wing-pylon and pylon-engine nacelle joints. These are minor disruptions to the flow, but never-the-less they propagate noise towards the ground. Additional noise sources include hatches, cavities and surface vibrations during flight, for example from the engine components vibrating.

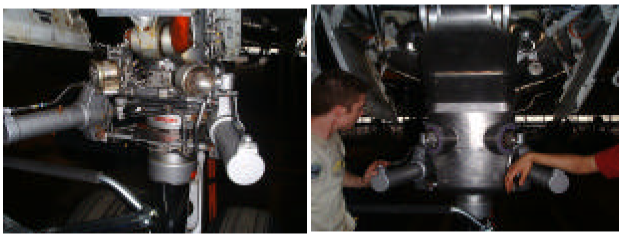


Fig. 3: Fairing undercarriage components, courtesy of SILENCE(R) project.

Noise tests on modified aircraft aimed to lower noise significantly, but only resulted in a slight noise reduction, with modifications such as fairings on the undercarriage (Fig 3), or novel slats and flaps. Newly developed technology for reducing noise on old airframes will suffice to meet legislation requirements, but only for the short-term. Options are limited for reducing noise from the current configuration, and hence, new radical airframe design solutions are required to meet future targets.

1.3 Propulsion systems

Figures 4 and 5 show the noise distribution during typical take-off and landing conditions, for a current technology aircraft.

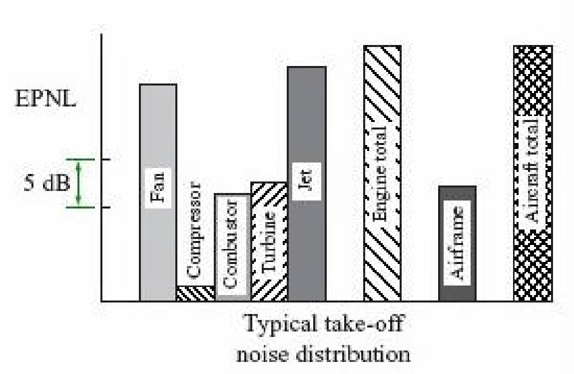


Fig. 4: Noise distributions during take-off, courtesy of ESDU [2].

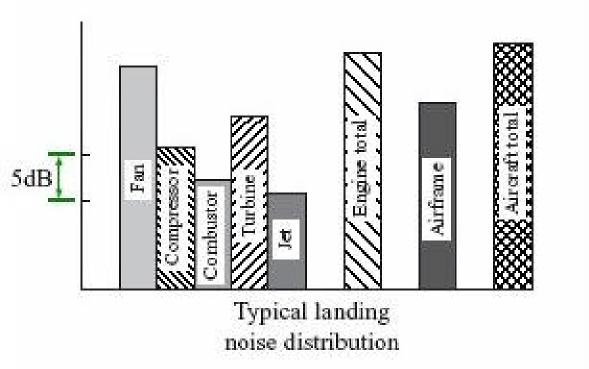


Fig. 5:Noise distributions during landing, courtesy of ESDU [2].

The main noise sources during take-off appear to be the jet and the fan. During landing though, the airframe and fan noise are the two of major importance. Thus, the principal engine noise sources are the fan and the jet.

Jet noise or ‘jet mixing noise’ is the noise produced by the mixing of the high velocity core nozzle jet with the low velocity bypass nozzle jet and the surrounding air. Jet noise is produced by:

- the turbulent mixing of the exhaust gases with the ambient air
- the jet shock noise

- the jet entropy noise caused by the high temperature

Fan noise on the other hand comprises:

- the tonal noise, due to the interaction of rotor wake with stator
- the broadband noise, due to turbulence

1.4 Noise Regulations and Legislation

An important part of the noise conditions is to investigate the noise regulations and keep updated with new requirements, governed by ICAO. It is important to understand how aircraft noise has been reduced over the years, and Fig. 5 depicts the trends and future targets.

The trend in noise reduction shows that minor improvements made to-date have very little effect on overall noise. Legislative cut-backs on noise levels would seriously affect the aviation industry, as no aircraft would meet the 10dB reduction, let alone a 20dB target by 2025.

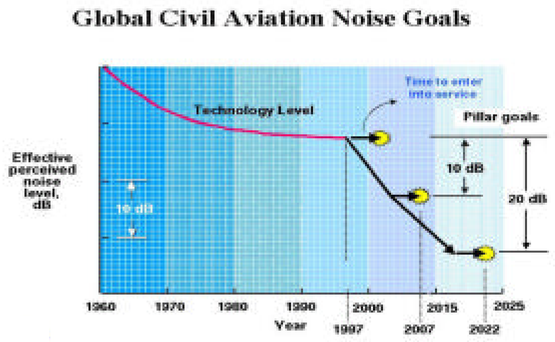


Fig. 6: Future Noise Targets and past trends over Aviation history, courtesy of NASA.

Fig. 6 represents the targets currently being used by NASA, and indicates that within the next twenty years or so the noise limits will be cut back by an estimated 20dB. This is a large cut in the noise, and 50% of this is hoped to be achieved by NASA by 2007, which is a steep reduction given on the noise produced from current airliners.

The Advisory Council for Aeronautics Research in Europe (ACARE) targets are clearer, with emphasis on perceived noise being reduced by 50% in 2020, which results in -10 EPNdB noise reduction for flight operations. This reflects an elimination of aircraft noise outside the airport boundaries to a limit of 65 LDEN; which is the Day-Evening-Night noise indicator.

Discussions with the SAI team during a KIC meeting have established a target of 60 EPNdB. The challenge will be to reduce both airframe and engine noise to approximately 55 EPNdB, so that if the combined noise should fluctuate around the 58 EPNdB mark, with a 2dB margin of error available.

Aircraft noise legislation must be considered, most commonly Annex 16 – Environmental protection, is one of the technical annexes of the ICAO. Alternate requirements are set by Joint Airworthiness Requirements (JARs) and also Federal Aviation Regulations (FARs).

2 Aircraft Design Process

In order to determine the most ideal process for designing an aircraft, basic tools must first be used to understand the design philosophy governing current civil airliners. Howe, 2000, 'Aircraft Conceptual Design Synthesis' utilises parametric analysis to design and optimise a conventional aircraft. The conceptual approach predicts the sizing and performance of certain classes of aircraft, given that a specification is provided.

2.1 Baseline Aircraft

The initial aircraft specification was for a medium range air transport with twin engines, 269 passenger payload, cruise speed of Mach 0.8, and a range of 4,020 nautical miles. A similar aircraft specification was also used by the SAI team focussed around a datum aircraft.

Structures are assumed to be metallic, but in current technology aircraft composites are now used for the majority of applications. A factor is incorporated to estimate a conservative 12% reduction of the metallic structural weight. Howe, 2000, however, states that a realistic value is a 15% weight reduction factor. The factored 'more' composite design estimated a minimum maximum take-off weight (MTOW) of 155,235kg (342,234lb), which is acceptable given the datum aircraft has a MTOW of 156,490kg.

Fig. 7: Baseline Aircraft CATIA model.

Metallic Description	Symbol	Baseline	U
Wing Mass (M)	M w	24,238	kg
Fuselage M	M fus	18,009	kg
Tail plane M	M t	4,847	kg
Landing gear M	M gr	6,435	kg
Powerplant M	M pp	14,168	kg
Systems M	M sys	24,132	kg
Operational item M	M op it	2,762	kg
Operational empty M	M oew	94,595	kg
Payload M	M pay	21,600	kg
M of fuel for range	M f	44,691	kg
Overall aircraft M	Mo	160,886	kg
Wing area	S	245.1	m^2
Wing span	B	44.3	m
Wing aero mean chord	MAC	5.5	m
Wing aspect ratio	A	8	-
Quarter chord sweep	del 0.25	33.0	-
Wing taper ratio	Lambda	0.207	-
Thickness to chord ratio	t/c	0.11	-
Position of wing apex from nose	W apex	15.5	m
Horizontal stab Area	S ht	59.6	m^2
Vertical stabiliser Area	S vt	35.8	m^2
Total static thrust	Stat thr	579,130	N

Fig. 8: Baseline Aircraft design breakdown.

Mass optimisation is an essential part of aircraft design, to produce the minimum possible weight without compromising performance. The aim of optimising the baseline is to create a datum to compare sizing, performance and noise results with novel designs. The baseline was modelled using CATIA (Fig.7), providing a visual representation as well as numerical results.

2.3 Aft-Mounted Engine (AME) Concept (Fig. 9)

This concept is a favourable design that would generate adequate noise shielding without major re-design of the aircraft or airports, and is an ideal aircraft to launch into the aviation industry.

The AME study is modelled similarly to the baseline with minor adjustments for the propulsion system and empennage. Power-plants are mounted at the rear of the fuselage in-between the main wing and tail plane; providing shielding of forward propagating engine noise. The empennage has a similar role by shielding the jet noise using a C-tail to guard the side and rear; by placing the horizontal tail surface below the engine exhaust ducts to reflect noise, which prevents sound propagation aft and downward.

A long engine cowl is represented for acoustic shielding purposes. Although it is noted that long engine ducts are not ideal and carry a weight penalty, the possibility remains that the ducts could be lined with acoustic material to prevent the propagation of noise fore and aft of the engine. The use of noise acoustic liners is currently being investigated by the SAI team.

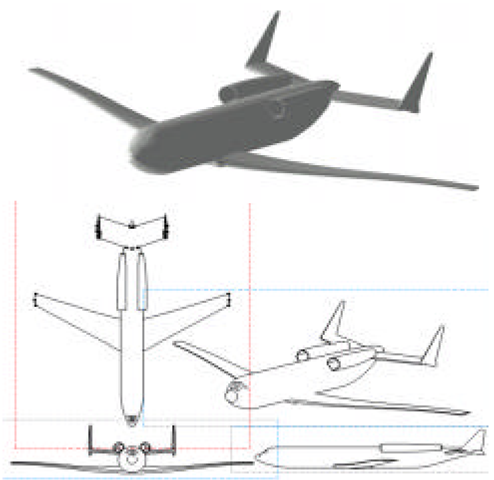


Fig. 9: AME Aircraft concept.

Re-locating the engines pushes the centre of gravity (c.g.) aft and results in the main wing apex moving further forward. The AME configuration has performance disadvantages compared to the baseline, with a 1.4% increase in engine static thrust, resulting in a 0.7% increase in overall mass; the majority of this being additional fuel.

The development of this concept is being investigated by many major aircraft design teams and would be an acceptable solution for the 2010 noise targets, but would not realistically achieve the 2025 goals. The primary reason, being the wing houses standard LE, TE devices, and conventional undercarriage; these being the three main airframe landing noise sources.
This aircraft is not considered to be novel or an innovative concept, and as a result will not be further developed as a solution for a low noise airframe.

2.4 Design Process for Novel Configurations (Fig. 10)

The Design process consists of three main criteria of geometry, loading and performance. Geometry is determined by Howe's [3] design methodology, followed by Loftin [4] analysis, which assesses the performance. Both analyses predict loading and are low fidelity semi-empirical methods, with results compared to a datum aircraft.

The final stage in the concept design analysis is to assess the noise produced from the airframe, and this is achieved using ESDU methods. ESDU data item 90023 [5] for airframe noise is an ideal starting point to determine noise characteristics, as a semi-empirical low fidelity computerised model based on theory, and can be applied to most conventional aircraft configurations.

Aero-acoustic analysis has been investigated for use at a later stage, with the aid of the Von Karman Institute (VKI) for fluid dynamics. The use of the Ffowcs Williams-Hawkings' analysis for unconventional aircraft concepts will primarily focus on trailing edge noise from multiple surfaces.

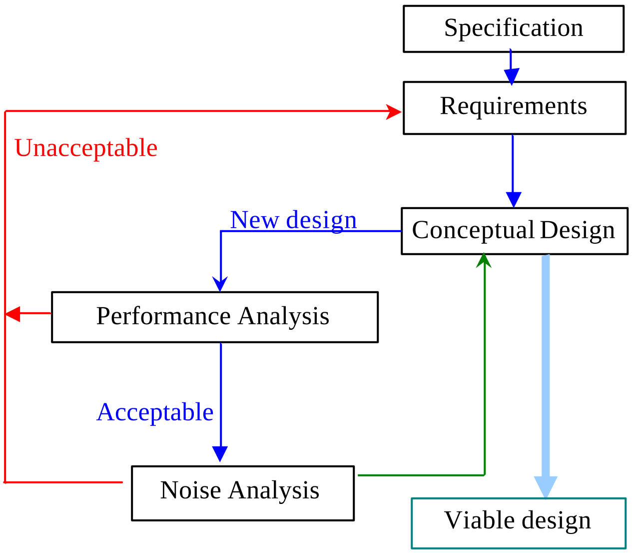


Figure 10: Basic model behind low noise design.

The main intentions for developing a novel airframe conceptual design methodology is to use a simple yet effective model for all aspects of the design, and to combine them into a unified analysis package. The initial low fidelity methods used will form the foundations for more detailed analysis to integrate noise into the concept design stage.

3 Novel Aircraft Concepts

The development of novel designs is more productively achieved through group brain-storming sessions to identify possibilities for multiple configurations. The baseline is an established 'tube and wing' design, of which variations must combat the noise challenge.

3.1 Baseline Aircraft Variations

Rearranging the baseline aircraft by varying the locations of the engines, empennage and wing provide dozens of combinations. In order to understand the true complexity of the problem, comparisons of possible combinations of the baseline are required.

Fig. 11 identifies that a conventional airframe may be modified, like the AME concept, but the main noise sources remain in each design, for example LE, TE devices, wing and empennage. The magnitude of airframe noise does not change, and it is therefore essential to identify alternate configurations which have greater possibilities for reduced noise.

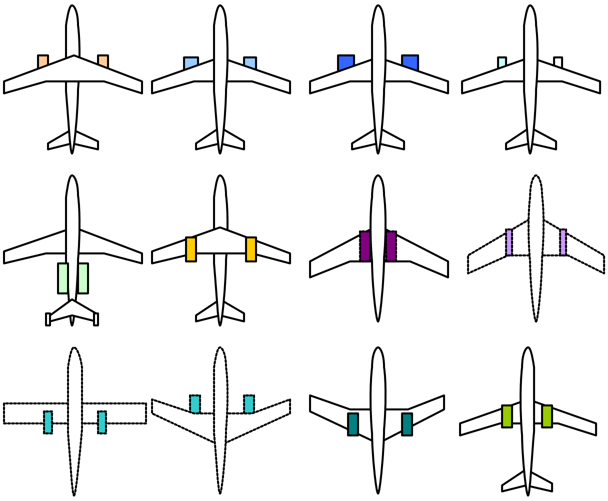


Figure 11: Baseline Aircraft variations.

Aircraft descriptions from left to right:

Row1: High wing Lower Podded Engines (LPE), High Bypass Ratio (BPR)-LPE, Ultra High BPR-LPE, Conventional aircraft LPE.

Row2: AME concept, High wing with Upper Podded Engines (UPE), Engines in wing root, Engines embedded in wing semi-span.

Row3: Un-swept wing UPE, Forward swept wing LPE, Forward swept wing UPE, Aft swept low wing UPE.

3.2 Broad Delta (BD) Concept

Noise benefits of a BD are reduced number of lifting surfaces, where the performance of a low aspect ratio wing, would not require a tail surface to balance moments. This results in the elimination of the need for flaps for pitch attitude control, as there will only be TE elevons for trim.

This is an ideal plan-form for a reduced noise aircraft, because, an additional benefit of a low aspect ratio wing, is a slower approach speed. A main factor governing the noise produced by an airframe is the speed, and a slower speed combined with fewer surface distortions will further reduce the noise.

Other than noise reduction, alternate aspects, such as improved performance and cost can be discussed regarding this new concept group. An initial idea to minimise the cost of this type of aircraft would be to continue using the existing fuselage, and only modify the wing. Adding a delta wing to a fuselage takes you back to a design by Avro for one of their military bomber aircraft. Performance benefits follow the inclusion of winglets to the design, which would lower the induced drag of the geometry; increasing the range and performance. Fig. 12 depicts the variations in geometry for the broad delta concepts with descriptions below.

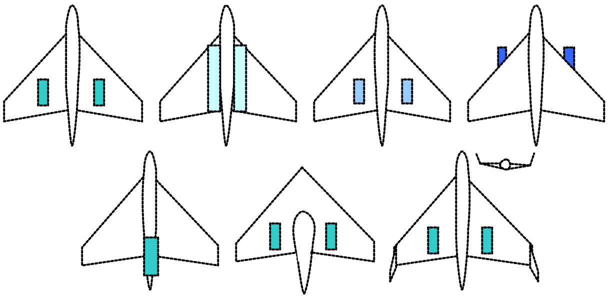


Fig. 12: BD Configurations.

Row1: BD Concept with conventional fuselage, BD with Engines buried in wing root, BD-UPE, BD-LPE.

Row2: BD with buried rear engines, BD wing with rear fuselage section only, BD with winglets and UPE.

Each broad delta design idea has its own merits and the ideal configurations will be stated later as part of the initial down-selection process for the 'most' silent concepts.

3.3 Blended Wing Body (BWB) Concept

The BWB aircrafts are similar to the broad delta family, but the main advantage of this configuration is that the fuselage and wings are fused into a smooth surface. This is also an ideal reduced noise design because it is similar to the broad delta and does not require flaps or a tail surface for pitch control.

Many examples of BWB airframes have been developed, with extensive work carried out at Cranfield University (CU) and are represented in Fig. 13.

The first two designs on the first row represent previous studies for the CU-BWB-98 and the more recent CU-BWB-01 group design projects, with the third being an early SAI planform, and the fourth is a discrete fuselage BWB; with embedded engines in the wing root. The second row incorporates a close coupled canard to a BWB, the CU-BWB-Kestral, and the final BWB has UPE mounted on wing semi-span.

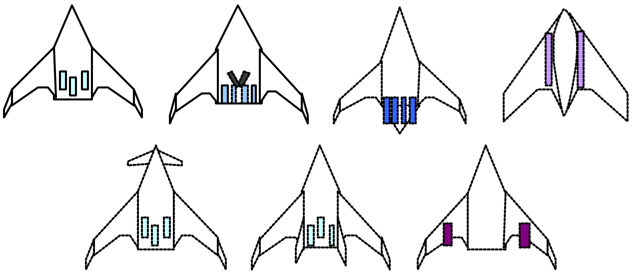


Figure 13: BWB variations.

3.4 Innovative Wing Concepts

The innovative wing concepts have not been explored further than a conceptual design stage, but never-the-less it is worthwhile to explore for noise. The type and variation of innovative wing transports are restricted by choice to symmetrical aircraft, as the viability of an oblique wing or an asymmetric civil airliner is not expected to be easily certifiable.

Fig. 14 represents innovative wing concepts where, the majority of designs are joined wing configurations. The top left concept has engine nacelles at the wing-tip/join region. There are two designs that are essentially 'C-wings', one being similar to a BD, and the other a tail-less conventional aircraft. Whether these concepts would be certifiable, is another concern.

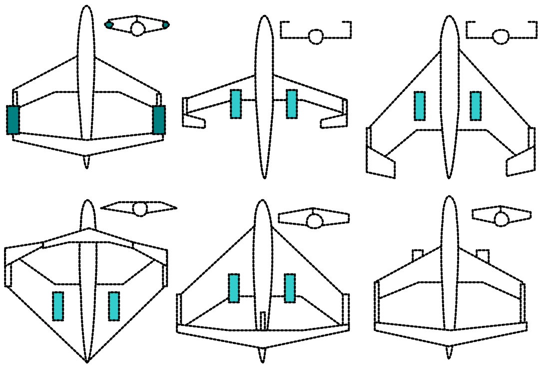


Figure 14: Innovative wing variations

4 Analyses and Down-selection of Concepts

The difficulties in analysing the types of each configuration are that every concept group has either different locations for wings, empennage or engines. There are 9 main engine variations, 7 empennage variations and 3 wing height locations, so with each of these combinations, each group has a maximum of 189 variations!

4.1 Concept Analysis

Purpose of the brainstorm analysis was not only to develop new aircraft concepts, but also to weight each aircraft in terms of design feasibility. A list of critical factors that govern each and every aircraft design were made and a weighting scale set up, as shown in Fig. 15. The weighting reflects the importance of the attribute on a scale of 1-10, with 10 being most important.

Each aircraft was given a score from 1 to 10 for every attribute. This score was then multiplied by the weighting, and the total of these compared to the maximum possible score. This provided an approximate percentage of how well the aircraft would perform given the requirements of each attribute. The weighting process is a good systematic approach that identifies the key areas of noise, performance, integration into existing airport facilities, requirements and maintenance aspects.

This is not the final concept selection of course, but the best possible combinations for engine locations and empennage selection are also included in this analysis, and a handful of configurations are set aside for further detailed assessment.

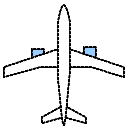
Attribute	Weighting
Far-field Engine Noise	10
Far-field Airframe Noise	10
Cost (development, DOC, etc)	8
Minimum weight	8
Passenger comfort / environment	7
Passenger local internal noise	5
Certification	8
Reliability and Maintainability	8
Crashworthiness / Emergency egress	6
Familiarity / Risks	8
Environmental Effects	9
Airport Infrastructure	6
Maximum possible Aircraft Score	**930**

Figure 15: List of attributes and weighting values

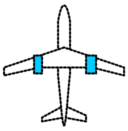
4.2 Rating Analysis

Baseline Configuration

The optimum conventional design was the High BPR configuration scoring 58.7%. The reason for the high score is because it is the most familiar solution, with low development costs, reputable reliability and a good maintenance record, but most of all it is easily certifiable. There is no reasoning behind designing aircraft if it does not meet certification requirements.

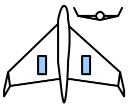


A second configuration with a high wing and UPE closely follows. Engine locations prove ideal for noise shielding, however discomfort to passengers is a concern, as most travellers prefer seeing the wing beneath them and not hanging from it.



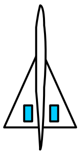
Broad Delta Configuration

The optimum BD concept incorporated winglets and UPE, scoring an impressive 63.8%. This concept scored well in every area and is an ideal configuration; with a large noise shielding benefit from the engines by the long wing chord and winglets.



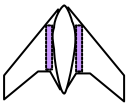
Slender Delta Configuration

The slender delta has a disappointing score of 59.1%. The poor score reflects the overall poor handling performance of the delta a low speeds and for subsonic flight it is extremely uneconomical. This configuration scores well for noise, reliability, maintainability and certification.

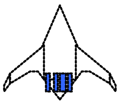


BWB Configuration

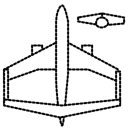
The ideal BWB configuration is the discrete fuselage BWB with a score of 64.3%. It scores very high on the environmental concerns and has a high airframe and engine far-field score; which means that it has the capabilities of being extremely quiet from high noise shielding. The passenger comfort and internal noise has a high score, but for crashworthiness and emergency egress, there are concerns associated with BWBs.



It is beneficial to assess the SAI concept considering it only scored 50.8% on the ratings table. This aim of the study is to determine whether the BWB was the ideal low noise airframe.



Innovative wing Configuration



The innovative wing designs have surprisingly low scores and this is due to the designs being of an unfamiliar nature. Previously the Baseline was a familiar concept, and when products start to become unfamiliar, then everybody becomes cautious. This is the main reason why the innovative wing concept group scored the lowest score, even below the baseline.

4.3 Down-selection of Configurations

The down-selection process begins with analysing the strengths and weaknesses of the remaining aircrafts to see the benefits of each aircraft configuration. Those designs which are considered not worth exploring are noted for specific reasons and the other configurations will be further assessed as the research commences.

The first aircraft configuration that will not be explored further is the slender delta aircraft. This aircraft has advantages of noise shielding but is not an economically viable subsonic aircraft to spend further time developing.

The second aircraft to cease development is the high mounted engine pods on a conventional aircraft with a high wing. This configuration may be ideal for noise shielding, but time should not be wasted redesigning the classical tube and wing configuration.

The baseline aircraft with high BPR engines will be assessed further in order to test the design process and compare with the datum aircraft.

The broad delta and discrete fuselage BWB will also remain to be further analysed, and so too will the SAI BWB with additional investigation into adding a canard to the same planform. Finally the joined wing concept will be added to the group with two possible variations; one with two equal sized wings joined at the tip, and one design with a horizontal stabiliser joined on to the main wing at a semi span location.

Fig. 16 represents the final seven configurations which will be further assessed, one of which is the baseline. These designs will be designed using conceptual design methodologies relevant to each concept, in order to determine the performance, sizing and loading; similar to that initially completed for the baseline. The baseline aircraft will then act as a datum for the novel concepts, so as to compare the performance advantages or disadvantages of each design.

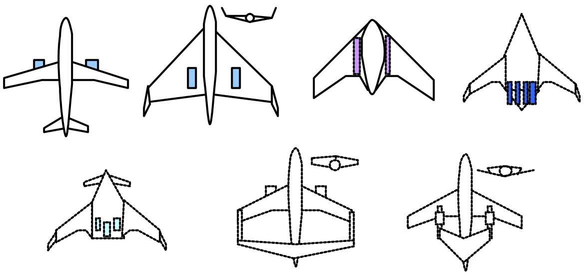


Fig. 16: Down-selection of Aircraft Designs.

The final design aspect for the airframe is as described by Fig. 10, noise analysis. The low fidelity ESDU methodology will initially be used to compare main noise sources, i.e. the wings, undercarriage and trailing edge devices for each concept. This will provide a basic analysis for each concept, which can later be developed through further research into higher fidelity noise codes.

4.4 Engine Configurations

As already discussed, the jet noise suppression is connected with the increase of the BPR of the engine. Some engine configurations that have the potential of high BPRs and low noise emissions are:

- The ultra high bypass ratio geared turbofan. The geared fan allows the reduction of the fan rotational speed, thus low fan noise.
- Variable Pitch Fan/Variable nozzle turbofan. The VPF can replace the thrust reversers, while a variable nozzle can increase BPR during take off.
- The remote fan configurations ideal for distributed propulsion are classified according to the way of the remote fan is powered.
    - Shaft geared remote fans
    - Electric driven remote fans
    - Tip turbine driven fans, shown in figure 17.

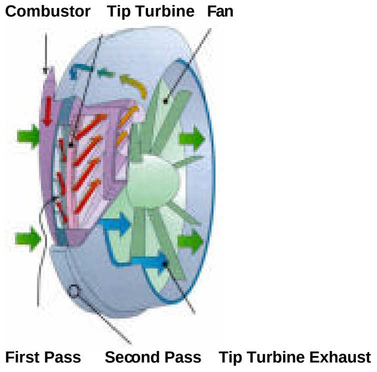


Fig. 17: Tip Turbine Driven Fan.

4.5 Engine airframe integration

The installation of the propulsion system can be of significant importance in terms of noise suppression. In contrast to the current under-wing podded installation, novel airframes provide the chance of different solutions. Such can be the upper podded, semi or deeply embedded engine in order to reduce further the noise emissions. An upper podded installation, on a blended-wing body airframe can provide inlet noise shielding up to 20dB, as discussed in [6] and shown in Fig.18.

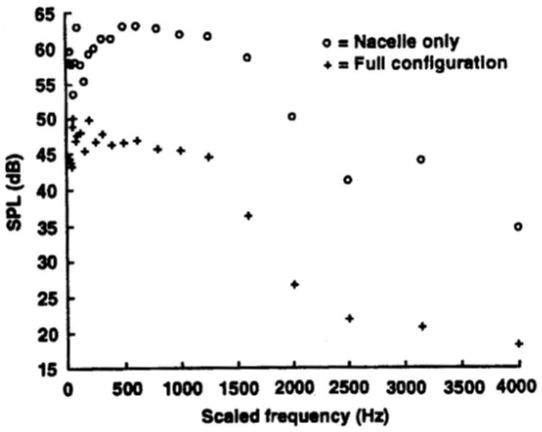


Fig. 18: Inlet noise shielding for the BWB. [30]

A semi or deeply embedded installation is beneficial for the lift to drag coefficient as shown in [7]. In addition to that, such installations can be used for boundary layer ingestion [8] and also for acoustic treatment of the engine jet.

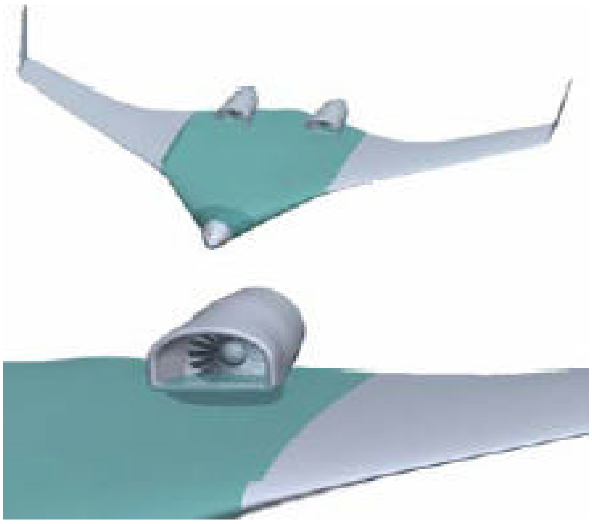


Fig. 19: Semi embedded turbofan, BWB airframe. [9]

5 Aircraft Noise Prediction

Estimating the noise produced from an aircraft is a challenging process, as there are many noise sources and some of these are more difficult to assess than others. The noise prediction method focuses on larger noise sources, neglecting smaller noise sources due to difficulties in isolating their origin.

The primary objective of developing a reduced noise concept is to design the aircraft, so it is imperceptible outside the airport perimeter. The main noise sources relevant to the project therefore, focus on engine noise during the take-off and landing, and airframe noise during the approach and landing phases of flight.

5.1 Airframe Noise

ESDU have developed a low fidelity noise analysis tool to predict the major components of airframe noise, e.g. undercarriage, flaps, slats, wing and empennage noise. The code is part of an ESDU pack titled A90023 [5], Airframe Noise Prediction. This analysis predicts noise from a user defined aircraft (source) onto a stationary observer on the ground. Noise varies dependent on altitude, speed, polar and azimuthal angles from the source to the observer.

Baseline Aircraft Noise analysis

The ESDU noise codes have been tested for preliminary analysis on the baseline aircraft. These results can be directly compared to published noise results to the datum aircraft selected and correlation of these values would certify the methodology used. If the results are of the right order in magnitude, then the low fidelity method can be used on the novel concepts and compared to the baseline to analyse the benefits or disadvantages of each of the six other concepts.

The main noise focus, as described previously, is the landing case for the airframe. In order to determine the observer location and the aircraft flight path it is essential to look at the noise certification requirements published by the JARs. The approach measuring points are taken to be at a 2km distance from the airport perimeter with the aircraft 120m above ground on a 3degree approach flight path angle. There is also a sideline noise measuring point located 450m from the runway that needs to be considered.

The requirements are clear, and landing case can be analysed by using a series of observers located on the ground that covers the 2km distance up until the airport boundary. The range of an observer on the ground only covers a certain distance along the 2km flight path, as shown by Fig. 20, therefore four observers placed directly under the flight path are introduced for analysis. The observers are used to identify the maximum noise angle produced by the total and each individual major source.

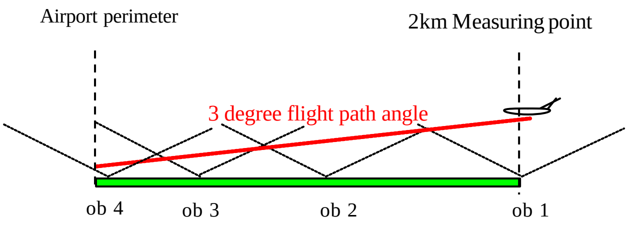


Fig. 20: Observer range on approach flight path

A consideration was to incorporate a similar set of observers to the side of the flight path, so that the sideline noise could be analysed. The sideline observer positions were taken as 100m, 200, 300m, 400m and 450m to make sure the requirements were satisfied, and to produce a broader view of how the noise varies over distance.

Utilising the ESDU methodology and the initial concept design performance analysis, the maximum approach velocity for the baseline aircraft was calculated at 72.5m/s (141 knots), with the ideal landing velocity of 70.9m/s (138 knots). The maximum approach velocity is used in order to provide the upper noise limits; as noise is a function of velocity.

The airframe geometry from the concept design is set to an approach configuration, where:

- Slats fully deployed
- 2-wheel nose gear retracted
- 4-wheel main gears (x2) retracted
- Double slotted flaps set to 42 degree deflection
- Main wing with high aspect ratio
- Empennage

The above mentioned are considered to be the main contributors to airframe noise; the results of which are, each source noise being identified and added, producing an overall noise total for a particular geometry.
The noise prediction case is confirmed to satisfy the certification points and with all aircraft settings determined.

Fig. 21 represents the results of the noise run for the baseline, where noise is measured in Over-All Sound Pressure Level (OASPL). Results of the noise run depict noise trends as the baseline passes over a single observer, at a height of 120m with a 3degree glide path angle. As the airframe approaches the observer (noise receiver Rx), double slotted flap noise is the dominant noise source, closely followed by slat noise. As the airframe passes Rx, flap and slat noise still dominates, until a region where undercarriage noise starts to take over.

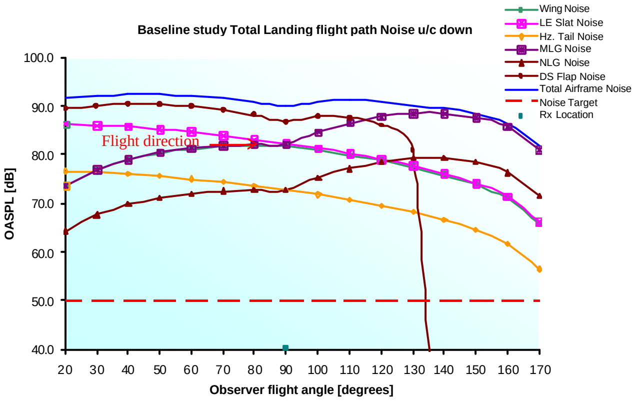


Fig. 21: Airframe noise Components on approach.

If single set of point sources above each observer are considered, then the magnitude of noise should vary proportional to 1/r; with ‘r’ being the distance of source from ground. This is represented by Fig. 22, where ESDU data item 94036 [10] is also incorporated into the results showing effects of ground reflection on the receiver. Ground reflection occurs when the observer is located at a height off the ground level.

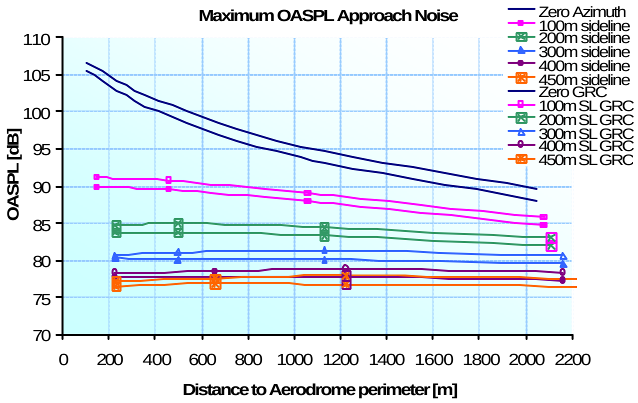
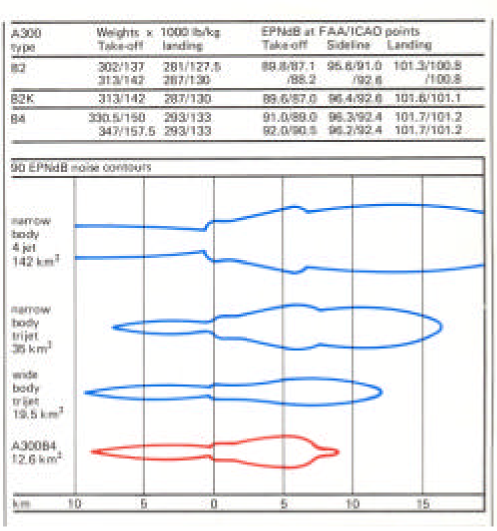


Fig. 22: Ground reflection and Noise trend

The sound wave reflects off the ground and back to the receiver, so the noise result at the receiver is greater than the actual noise from the aircraft. The maximum point noise has been taken from the four observers and plotted in to show the increase in noise measured due to ground reflection can be from 1dB to 2dB (OASPL). The OASPL can be converted to a linear decibel scaling dB(A), and to the EPN(dB) scaling to compare with the new aviation noise limits. This however, will be completed once the final noise limits for 2010 are confirmed.



A300 type	Weights × 1000 lb/kg Take-off	landing	EPNdB at FAA/ICAO points Take-off	Sideline	Landing
B2	302/137 313/142	281/127.5 287/130	88.8/87.1 /88.2	95.6/91.0 /92.6	101.3/100.8 /100.8
B2K	313/142	287/130	89.6/87.0	96.4/92.6	101.6/101.1
B4	330.5/150 347/157.5	293/133 293/133	91.0/89.0 92.0/90.5	96.3/92.4 96.2/92.4	101.7/101.2 101.7/101.2

Fig. 23: Noise contour plots, courtesy of Airbus.

The main advantage of analysing the sideline noise for this 2km range is to use the results to estimate a noise contour plot for an approaching aircraft. Many aircraft companies now include such plots to illustrate the noise issue to potential customers. The industrial plots combine the noise from take-off and landing along-with sideline for the aircraft, the results of which are shown in Fig. 23.

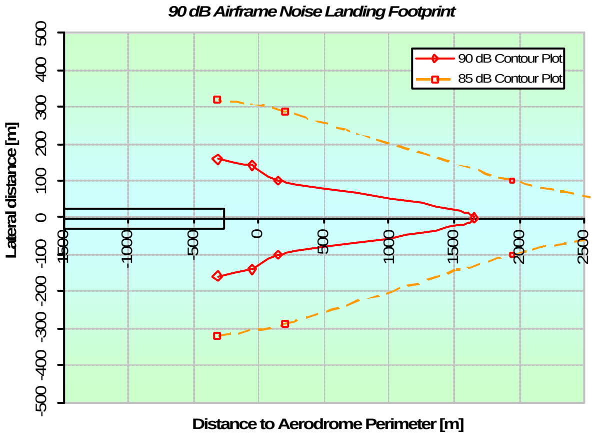


Fig. 24: Airframe noise landing footprint

The airframe landing case can also provide a similar plot to that shown in Fig. 23, represented by Fig. 24. However, it is noted that to generate a complete plot, many more observer locations are necessary and a complete airframe take-off and sideline assessment along-side results for the engine in each case are required.

5.2 Further Research

Development of airframe noise prediction methodologies is essential for analysing the novel concepts. Future research includes investigation into aero-acoustic methods, such as Lighthill's analogy and application of the Ffowcs Williams-Hawkings' analysis [11].

Investigation into airframe noise has led to the baseline airframe results above, however they cannot be directly compared to the datum aircraft at present due to insufficient data for the noise test case. Once the flight test case inputs are confirmed for the datum aircraft, the ESDU noise test will continue and a conclusive comparison will be made, including the noise generated by the engines.

Apprehension in using a low fidelity noise model, along with the possibility of erroneous results reinforces the need for a higher fidelity noise prediction method.

5.3 Engine Noise

Jet Noise Reduction Technologies

The main noise reduction strategy is the increase of the bypass ratio. That leads to reduced exhaust jet velocity; thus reduced turbulent jet mixing and less shock waves.
In addition to the 'by design' noise reduction, various mixing devices can be used as the chevron nozzle shown in Fig 25. Figure 25 demonstrates, also, the noise spectra of the chevron nozzle compared to a baseline nozzle. There is considerable noise suppression up to 5dB as discussed in [12].

Another mixing device is the one presented in [13], utilizing the deflection of the bypass stream in order to suppress the noise directed to the ground. In [13] a noise reduction of 5dB is shown.

Bevelled nozzle can, also, result in a 5-7 dB noise reduction as discussed in [14].

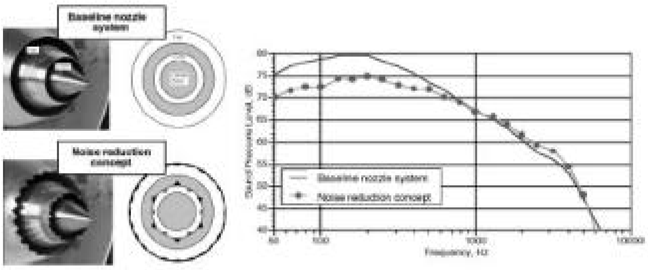


Fig. 25: Noise reduction concept noise spectra,[12].

Fan Noise Reduction Technologies

The increase of BPR makes the fan the primary noise source, as the mass flow through the fan increases. That can be offset by the reduction of the optimum fan pressure ratio (FPR), combined with reduced rotational speed. A low rotational speed results to reduced relative inlet tip Mach number and when that goes under 1 reduced tonal noise is achieved, due to the no formation of shocks. Additionally, liners at the inlet and the exhaust duct add in the direction of fan noise suppression. The tonal and broadband noise can be suppressed, also, by increasing the rotor-stator spacing. However there is a limit for that solution, as the increase of the spacing leads to increased cowl length, leading to increased wetted area, thus drag. The use of leaned and swept stator vanes, as shown in figure 6, can reduce further the tonal and broadband noise levels.

Engine Noise Calculation

For the prediction of fan and jet noise, ESDU codes [15], [16] have been used. The data needed have been produced by the in-house gas turbine performance code TURBOMATCH [17].

Figure 26 shows the design methodology focused on minimum specific fuel consumption (SFC) and noise levels.

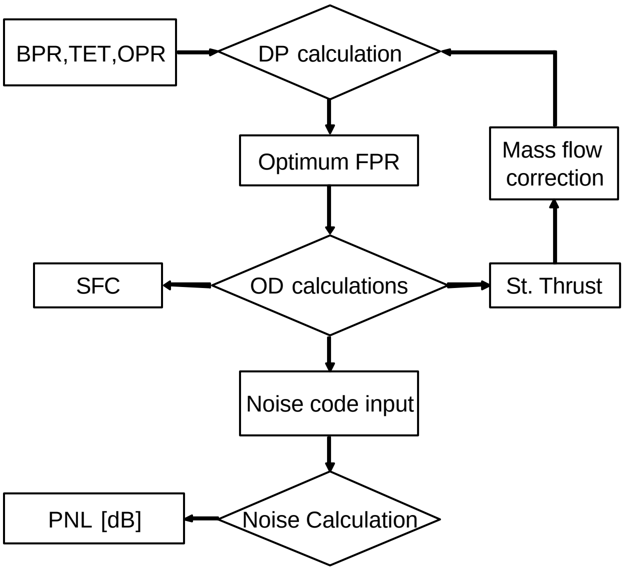


Fig. 26: Engine design flow diagram.

For each row of calculations BPR, Turbine Entry Temperature (TET) and Overall Pressure Ratio (OPR) are defined by the user. Calculations at design point (DP) (Top of Climb (TOC)) condition give the optimum FPR. The off design (OD) calculation gives SFC at cruise, static thrust and take off data (fan rotational speed, Mach numbers, temperatures, jet velocities, areas) that are needed for the noise calculation. Static thrust needs to cover airframe take-off requirement, thus a mass flow correction takes place. The final result is the SFC and the perceived noise levels (PNL).

Initial Engine Noise Results

Some initial calculations have shown the noise reduction obtained by increasing the BPR of the engine. Results are shown for the baseline 8:1 BPR turbofan, a 24:1 BPR turbofan, and a tip turbine driven fan of 24:1 BPR.

Calculations were performed for the take off condition; with altitude set at 100 meters, flight Mach number 0.3, with the observer placed at a distance of 100m. The engines were set at full throttle, and the data is shown in Fig. 27.

Figures 28 and 29 show the noise spectrum for maximum perceived noise levels, for the four engine configurations. The increased BPR leads to significant noise reduction, as was expected. The high BPR configurations give similar sound pressure levels.

Engine	Baseline	High BPR	TTDF
BPR (TOC)	8	24	24
Mass Flow(TOC)[kg/s]	295	700	530
FPR (TOC)	1.6	1.3	1.31
OPR (TOC)	40	35	42
Static Thrust[kN]	290	275	276
Cruise SFC [mg/N/s]	16.7	15.3	14.5

Fig. 27: Engine Data.

The fan noise calculation was performed keeping the same design principals for the fans of the three engines.

The relative tip inlet Mach number was kept the same for the three fans. Fig. 29 shows effects of increased mass flow on fan sound pressure levels. Technologies that have already been mentioned can be used to reduce the fan noise of an increased BPR engine.

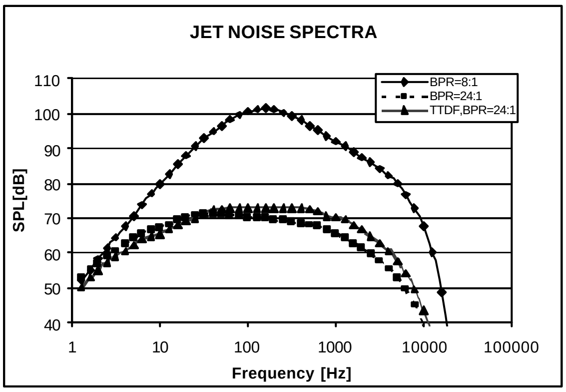


Fig. 28: Jet Noise Spectrum analysis at max PNL.

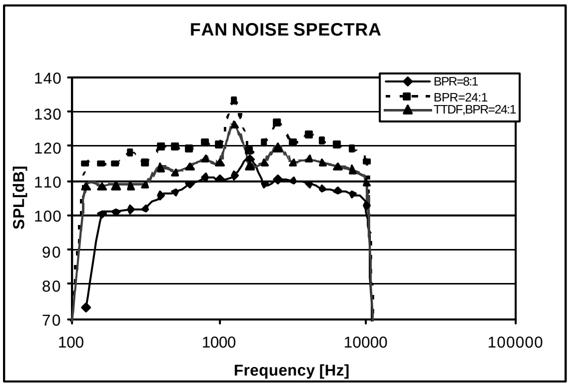


Fig. 29: Fan Noise Spectrum analysis at maxm PNL.

6 Conclusions

This paper has described a range of innovative airframe configurations, of which the BD appears as the most promising design. Alternate concepts were investigated and seven have been chosen to further develop and analyse for noise.

Initial noise analysis for the baseline aircraft have shown the dominant sources of airframe noise as the LE and TE high lift devices, closely followed by undercarriage.

Novel gas turbine cycles have been investigated for unconventional propulsion systems. Emphasis of increasing the BPR showed radical reduction on jet noise. The increase in fan mass flow resulted in greater fan noise, identifying the requirement for a novel fan design.

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