Integration of the Silent Aircraft propulsion system

Cesare Hall *

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This talk is a summary of a study completed for the SAI (Silent Aircraft Initiative) aimed at determining whether the propulsion system for a "Silent Aircraft" should be embedded within the airframe body or should be supported on pylons and physically separated from the airframe surface, i.e. podded.

This work was completed earlier this year with many contributors from both Cambridge and MIT. The authors of this presentation are as listed.

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Overview

1   Introduction and summary

2   Qualitative study of podded versus embedded engines

3   Quantitative investigation of key issues
    - Jet noise requirements
    - The design space and number of engines
    - Forward and rearward propagating fan noise
    - Operability and inlet distortion

4   Findings and follow-on work

This slide shows an overview of the talk and the approach to this study.

The presentation starts with a brief overview of the SAI project and the integration study background.
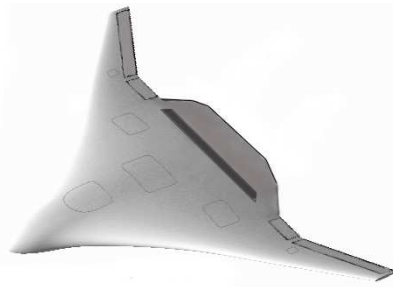
The study started by collecting relevant information from published literature, personal communications and internal documents. This was used in a qualitative comparison of the candidate configurations.

The qualitative comparison was used to identify numerical analysis required in order to quantify differences in the critical criteria between the podded and embedded options. The talk outlines some of these quantitative activities and their results.
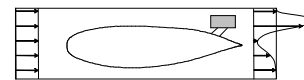
Finally, the findings of the study are summarised and some details of current work underway is described.
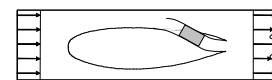
1. Introduction

- The Cambridge-MIT Institute (CMI) is working on a collaborative, multi-disciplinary research project called the Silent Aircraft Initiative.

- The project has a particularly bold objective: to reduce aircraft noise to the point where it is imperceptible in the urban areas around airports.

- This talk focuses on key questions regarding the integration of the propulsion system:
  - Where should the engines on a Silent Aircraft be sited?
  - Should the engines be podded or embedded?

An all lifting body aircraft with embedded engines

a) Podded propulsion system

b) Embedded propulsion system

Options for engine/airframe integration

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All aspects of aircraft noise are being addressed by the SAI project: airframe, engine and flight operations.

The Silent Aircraft requires the total noise emission to be imperceptible within a built-up environment, for this study a peak noise target outside the airport perimeter of 58dBA was used. To achieve this all engine noise sources would have to be reduced.

For the purposes of this talk an "all lifting body" aircraft is assumed for the airframe. This is described in previous SAI talks at the ceas workshop - it is a very efficient shape that generates low self noise and provides excellent shielding of engine noise.

This presentation addresses key questions relating to the packaging of the propulsion system. It is not intended to be a comprehensive assessment or audit of candidate designs, but rather a basis for making a decision on the basic airframe/engine configuration used in future Silent Aircraft design studies.

2. Qualitative Podded vs Embedded comparison

1. Noise - Inlet fan, exhaust fan, jet, turbine, combustion, airframe.

2. Cost - fuel burn, emissions, operability and reliability, maintainability, mechanical integrity, acquisition cost.

3. Design space – total jet area, installation size, number of units, variable cycle and geometry options available.

Qualitative assessment

- A Pugh matrix was constructed for noise, cost and design space.
- Podded and embedded options judged against each of the criteria listed above. Scores assigned between 0 and 3.
- Scoring based on literature, personal communications, task force opinion.
- Quantitative tasks identified to improve confidence in the scores.

The Silent Aircraft must be economically viable as well as quiet. Thus, candidate concepts can be judged by their potential to reduce the total noise emission relative to their total cost when operated commercially. In addition to noise and cost, the chosen configuration must allow for flexibility in the design to overcome technical barriers and mitigate risks.

The key metrics are therefore noise, cost and the design space.

The noise contributions can be divided as fan inlet, fan exhaust, combustion core, jet, turbine and airframe.

The direct operating costs include all factors that ultimately lead to higher price per passenger. This includes the acquisition costs (product design, development, certification, materials and manufacture), the costs incurred to operate the aircraft reliably and safely (maintenance, operability/stability and mechanical integrity) and the costs per flight (fuel burn and emissions - through regulation).

The jet area, the installation geometry, the number of propulsion units, the possible integration with the airframe aerodynamics and the scope for novel engine concepts involving variable cycle were selected as appropriate criteria in relation to design space.

A Pugh Matrix type approach was used to compare the podded and embedded configurations. In this, the two configurations are judged against each of the criteria identified above and a score is assigned between 0 and 3. This score was based on information derived from published literature, personal communications with industry experts and the views of the SAI team.

Pugh matrix for noise

Comparison criteria			Justification
The potential of each configurations to reduce noise relative to current technology			
Pylon and pod configuration above wing			
Embedded configuration integrated within wing			
Inlet fan noise	2	3	Podded configuration has the wing suction surface for shielding but limited intake space for liners. Embedded can have a long intake duct and therefore more acoustic liner area. More noise is radiated upwards in embedded when the intake is above the wing. This is particularly true for a mail slot type inlet *Task N1 - Calculation of SPL $_{podded}$ – SPL $_{embedded}$ for inlet fan noise*
Exhaust fan noise	1	2	Limited engine length in podded configuration for attenuation, although placement of engine could give some rearward shielding. Scope in embedded configuration to have a long length of acoustic treatment, to optimise rotor/stator spacing for reduced interaction noise, and to dissipate the broadband noise. Embedded could create additional propagating modes due to geometry changes required in the exhaust duct. *Task N2 – Calculation of SPL $_{podded}$ – SPL $_{embedded}$ for exhaust fan noise*
Jet noise	1	2	Largest noise source at take-off. Both configurations can be made larger to increase jet area and reduce jet velocity, within constraints of weight/performance/operability. Embedded has more scope for variable cycle, high aspect ratio jet, and enhanced mixing within the exhaust duct. Both configurations have the potential for jet vectoring and jet-by-jet shielding. *Task N3 – Calculation of SPL $_{podded}$ – SPL $_{embedded}$ for jet noise*
Turbine noise	1	2	Improved liner technologies to reduce turbine noise emission. Longer exit exhaust duct in embedded gives greater attenuation and scope to space rotor/stator rows to reduce noise.
Combustion/core noise	1	1	Improved combustor and new high temperature liner technology can be applied to both configurations
Airframe Noise	1	2	Embedded engine removes airframe boundary layer reducing trailing edge noise. If the jet emerges from the trailing edge, the noise can be reduced further. Jet vectoring could be applied for high lift. If the spool-up time of engines can be improved, the drag requirements on the airframe can be reduced.

Quantitative tasks are shown in italics – some of these are addressed in the next section.

The tasks identified were intended to be quick assessments of the differences in the noise between the configurations using either ESDU tools and correlations or correlations documented in NASA's Aircraft Noise Prediction Manuals.

Note that all noise sources and potential attenuation are expected to be slightly better with embedded. However, the magnitude of the differences are difficult to determine without detailed analyses.

Pugh matrix for cost

	The impact on direct operating costs (0-low → 3-high) relative to present day bypass engines		
	Pylon and pod configuration above wing		
Criteria	**Embedded configuration integrated within wing**		
Fuel burn	3	1	Podded solution has large, exposed frontal area leading to high drag. High BPR and advanced engine cycle used to improve efficiency. Embedded requires higher pressure ratio fan and thus larger core and lower cycle efficiency (inlet and exhaust duct losses), component efficiencies are also lower due to inlet distortion and its variation. *Task C1- Cycle design study of the effect of inlet and exhaust loss on fuel burn and fan parameters* Embedded uses lighter support structure (no pylon), reduces profile drag of wing if boundary layer ingestion can be used and there is potential for reduced thrust requirements if wing drag lowered. *Task C2 – Trade study of weight (core, fan and engine structure), airframe drag and engine efficiencies on overall fuel burn*
Emissions	2	2	Future emissions regulations will increase much quicker than emissions reduce. Silent aircraft size and range chosen for low fuel burn per passenger mile. Research needed to reduce NOx from higher core temperatures.
Operability	1	3	Inlet distortion a big problem for the embedded engine and adequate stall margin may not be possible at all conditions. Variation of the flow conditions into the engine at different points in the envelope is much greater in embedded as a result of the more developed boundary layers. *Task C3 – Study of impact of inlet distortion on the fan design required to maintain stability and mechanical integrity.* Externally generated distortion (airframe wakes and vortices) worse for rear-mounted podded engines. Manoeuvrability with embedding improves - engines are more in line with the centre of gravity, i.e. less trim required. Scope for novel thrust reverser in embedded concept and thrust reversal more easily controlled because it does not pitch the aircraft nose-up. However, embedded reverser could create a hot region close to aircraft surfaces.
Maintainability	1	3	Podded units are easier to monitor, access and repair reducing maintenance time and labour. They are likely to be modular and easier to scale so units have more in common and can be readily swapped with other aircraft. The embedded concept is more integrated and could have fewer parts leading to some lower maintenance costs. However, life cycle issues may be greater with embedded requiring greater support (see next).
Mechanical integrity	1	2	High cycle fatigue of the fan more of a problem with embedded concept because the fan sees more distortion throughout the mission. Foreign object damage during take-off/landing reduced by intakes above the wing. Probability of bird strike reduced for embedded (reduced exposed frontal area). Fan impact damage could be better or worse depending on the trajectory of the bird within the embedded inlet duct and the fan speed. Containment of fan more of an issue for embedded concept where the fan is closer to aircraft components and passengers.
Acquisition cost	1	2	Price per pound of thrust higher for a low-noise engine because of the large static thrust required for low jet noise. Embedded concepts likely to require larger development programme and more new technology. In particular extensive testing and possible redesigns to ensure the operability and mechanical integrity are acceptable.

A primary concern when embedding an engine is the effect on operability of inlet distortion. An embedded engine installation inevitably creates non-uniform flow through the generation of thicker boundary layers on the intake duct surface and secondary flow from duct curvature. The engine design must have enough stability margin at all operating points to cope with this distortion, and a low-noise, high bypass ratio engine is likely to be more sensitive.

An objection to the embedded approach is the potential increase in maintenance costs. However, if military applications are considered there are more embedded than podded systems currently in service. The maintenance of these is well established and the methods to access, inspect and repair embedded engines are becoming increasingly automated and therefore cheaper to perform.

In terms of fuel burn and emissions, the embedded option is expected to be significantly better. The engines for a quiet aircraft are expected to be much larger than conventional units and, when podded, will have fully exposed frontal area that leads to high drag and fuel burn (see later).

For a blended wing type of aircraft the manoeuvrability and control is critical and for this the balancing of the aircraft (weight, lift, thrust, and drag) must be carefully controlled. For both embedded and podded options, the engines should be located at the rear for good pitch-wise control. The pitch-wise handling can be significantly improved with embedded engines because the thrust line is closer to the centre of gravity.

Mechanical integrity, in particular fan vibration leading to fan blade and disk cracking, will be more of an issue for the embedded case as a result of greater unsteady forcing from the inlet distortion.

Pugh matrix for the design space

Comparison criteria			Justification
The design space available and the scope for new and novel concepts (0-low → 3-high)			
Pylon and pod configuration above wing			
Embedded configuration integrated within wing			
Total jet area	1	2	Much larger total exhaust area available to the embedded design. Podded engine size is limited by fuel burn implications of large increases in the overall frontal area of the aircraft. The jet from embedded engine can be shaped (rectangular) and integrated with wing trailing edge region. *Task D1 – Quantify limits in available jet at take-off for embedded versus podded*
Installation length	0	2	Much longer ducts possible for the embedded approach. Also, greater scope to vary intake and exhaust duct lengths, area ratios and centreline positions as well as the position on the wing surface of the inlet/nozzle. *Task D2 – Establish volume restrictions for embedded installation*
Number of units	1	2	Embedded approach could incorporate any number of engines to give distributed propulsion benefit, quicker spool-up times, power-plant redundancy, etc. There are fewer advantages for more engines with a podded approach because they are not integrated with the airframe. *Task D3 – Derive the trade-offs in cost, weight, efficiency and operability with engine number*
Variable geometry/cycle	2	3	*Current ideas:* Variable exit nozzle to adjust fan operating point between take-off and cruise Ejectors to increase jet area and reduce effective jet velocity at take-off Variable-pitch, contra-rotating or actuated fan design for ultra high bypass ratio engine Run engine as a turbine to generate drag during approach for low airframe noise Distributed propulsion system with boundary layer ingestion (embedded) Shaft-driven, gas-driven, or electrically-driven auxiliary fans for take-off (embedded) Variable cycle engine with tandem fan, additional combustor/bypass streams, etc (embedded) *Task D4 –Quantify the effects of each concept on noise and cost factors.*

In terms of the space available for the engine installation, an embedded engine will have greater scope for longer ducts with more convoluted geometry, although the size is limited by the free volume available behind the passenger bays in the blended wing (see later). The number of engines parameter is a very important design variable. In the podded case there is no expected benefit for having more than 4 engines (as has been proven by commercial operation). As number of engines increase, the acquisition, maintenance and replacement costs typically rise although this could be offset by lower development and manufacture costs for a smaller, mass produced unit. In addition, multiple engines have greater redundancy - one engine can fail with only limited impact on the overall flight condition. In the embedded case there is the scope for having many more propulsion units. The penalties or benefits of this option in terms of performance, weight and noise are investigated in the later sections.

The table also lists a number of variable geometry and variable cycle options that could be exploited in order to get low enough noise at take-off and approach as well as reasonable performance at cruise. There are more options available to the embedded system and this can be seen in aircraft currently in service, where variable cycles and powered lift have been integrated within an airframe. Any ductwork or shafts, actuators, etc. for a variable cycle can be accommodated more easily using an embedded system.

The embedded concept has greater scope for noise reduction (12 vs. 7) and this is the key objective of the Silent Aircraft. To reinforce this statement, work is required to approximate the potential noise improvements.

The embedded concept is expected to cost more to develop, acquire and operate (14 vs. 9). Work is needed to assess the differences in fuel burn and the impact of inlet distortion on operability as these issues could rule out one configuration in favour of the other.

Relative to podded, the embedded concept has greater scope for unconventional design in which novel ideas can be included (11 vs. 5). Several variable cycle type concepts aimed at allowing noise reduction without penalising cruise performance significantly have been identified.

Tasks have been identified that require preliminary studies to quantify the differences between the approaches. These are summarised in the next section.

3. Quantitative Investigation

- For the preliminary studies, the propulsion system for an all-lifting body equivalent of a Boeing 767-200 has been considered.
- This aircraft has a range and payload similar to those expected for the Silent Aircraft.

Number of passengers	255 pax
Range	3150 nm
Maximum take-off mass	136.1 tonne
Wing area	283.3 m^2
Cruise altitude	39000 ft
No. of engines	2

Two key design points have been used for the preliminary propulsion system design:
i) peak jet noise and ii) top of climb.

Peak jet noise condition

Jet noise target	55 dBA
Flight speed	80 m/s
Altitude (ISA)	200 m
Climb angle	6 degrees
Angle of attack	4 degrees
Lift/Drag	16

Top of climb condition

Aircraft total mass	133.4 tonne
Flight speed	M = 0.8
Altitude (ISA)	11000 m
Climb angle	0.4 degrees
Angle of attack	0 degrees
Lift/Drag	20

For the preliminary studies, the propulsion system for a Boeing 767-200 equivalent aircraft has been considered. This aircraft has been chosen because it has a range and payload similar to those expected for the Silent Aircraft.

The peak jet noise condition is the point during take-off when the demand on the engines is highest resulting in maximum noise perceived on the ground – i.e. just before cutback occurs. Jet noise is, to a first approximation, a function of only jet velocity and jet area. Once the aircraft thrust requirement is fixed the jet area and velocity are then a unique function of the Silent Aircraft noise target.
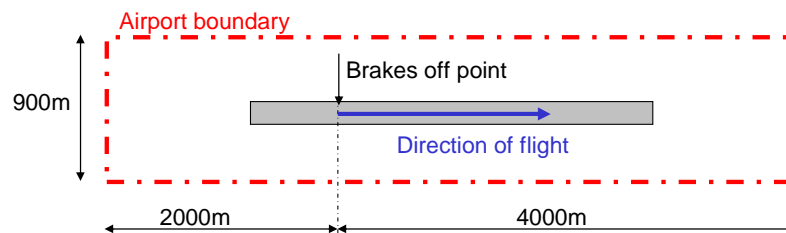
The second table details the flight conditions at the top of climb condition. This point is critical for sizing the engines and for determining the propulsion system performance. The values in the table have been chosen as typical values for a modern 250 seat aircraft.

Calculating required jet area - definition

For the purposes of this study, an acceptable 'silent' take-off was defined as:

- Not exceeding 55 dBA predicted jet noise outside of the airport boundary.
- Ability to silently take-off with a runway length of 10,000 feet.
- Ability to silently climb at 6° prior to cutback.
- Ability to silently climb at 3° after cutback.

The airport boundary was defined as shown in the diagram:

Airport boundary

Brakes off point

900m

Direction of flight

2000m   4000m

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Jet noise depends mainly on the jet velocity and the distance of the observer from the source. The only sure way to reduce jet noise for a given thrust requirement is to increase the exhaust jet area.
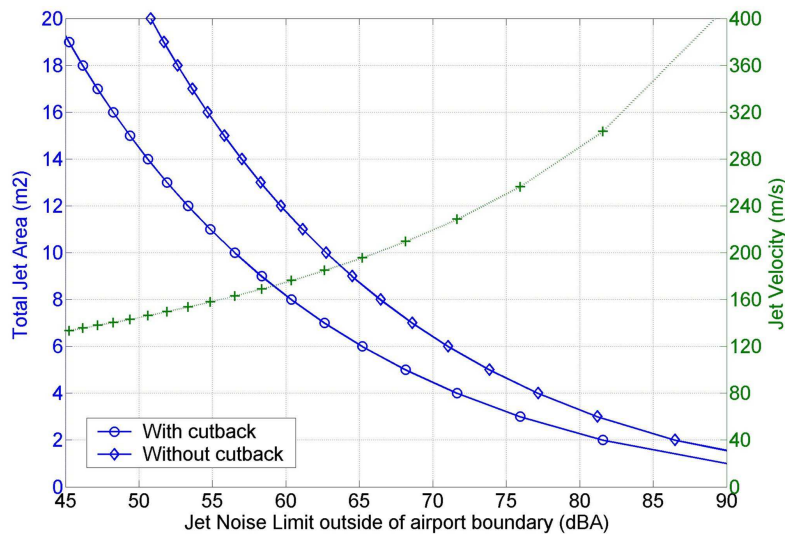
The first quantitative task was to determine the exhaust size required for the noise level to meet the SAI target outside a typical airport perimeter. This can be determined from simple models of aircraft operation during take-off and jet noise correlations (see previous CEAS talk "Required Jet area for a silent aircraft at take-off", D. Crichton et al., 2004)

For the purposes of this document an acceptable 'silent' take-off is defined as:

- Not exceeding 55 dBA predicted jet noise outside of the airport boundary under ISA sea level conditions with no wind.

- Ability to silently take-off on a runway of 10,000 feet (3,048 meters)

- Ability to silently climb at 6° prior to passing over the end of the airport boundary (i.e. before cutback)

- Ability to silently climb at 3° once beyond the end of the airport boundary (i.e. after cutback)

   These parameters are based on standard conditions and requirements at large airports around the world. The jet noise target of 55dBA is based on 'silent' being 58dBA or less and jet noise accounting for 50% of the total noise during take-off.

Variation of required jet area with noise target

- The plot shows that for a jet noise limitation outside of the airport of 55dBA, an exhaust jet area of 11m² is required.

Using the definition of a silent take-off described above, an optimised flight path study was completed to find the minimum exhaust area for a given peak noise level outside the airport boundary.

A MATLAB implementation of the Stone jet noise model was used to predict the noise for this study. This was preferred over alternative models because it predicts noise at lower jet speeds and takes flight effects into account.

The figure presents the resulting variation in the required jet velocity and area to meet the jet noise limit for two flight paths: with and without cut-back.

As can be seen from the figure, a simple cut-back reduces the required jet area for the target jet noise of 55dBA from almost 16m2 down to 11m2 with a small additional benefit from further optimisation.

A jet area of 10.5 metres squared was used for the remainder of this study (this meets the 55dBA target with an optimum take-off flight path). This implies a jet velocity of about 160m/s, which is not practical for cruise, because the engine will not be able to meet the required thrust. Thus, variable cycle/geometry is needed. This enables the aircraft to adapt from a quiet engine at take-off to an efficient engine at cruise.

Airframe geometrical constraints

- The propulsion system placement is limited by structural constraints:
    - Passenger bays at the front of the centre-body with emergency exits behind.
    - The airframe thickness decreases rapidly with wing span.
    - Important control surfaces have to be maintained.
- Thus, the shaded blue region in the picture below indicates the area typically available for the propulsion system in an all-lifting body design.
- For embedded engines, this implies a range of engine number between 2 and 15.

$$H_{duct} \sim 0.9 D_f \qquad L_{duct} \sim 6 D_f$$

$$A_{jet} \propto n_{eng} D_f^2$$

Geometric parameters for an embedded system   *An all-lifting body planform, based on Liebeck, 2001*

The propulsion system placement is limited by the location of passenger bays, emergency exits, fuel tanks and aircraft systems.

The height at 1/3 span decreases rapidly, setting a limit on complete engine integration. In addition, important control surfaces have to be maintained.

Without significant structural modifications, the shaded blue region indicates the area available for the engines in a generic blended wing design.

This gives a range of possible engine number between 2 and 15. The following slides examine the effects of varying the number of engines as well as podded vs. embedded.

The airframe that is currently considered has a maximum available height for embedment of approximately 2.5m. It is estimated that a two engine configuration could only be embedded by approximately 50%. Complete embedding of such an engine would require design changes on the airframe, such as moving the emergency exits forward or redirecting the inlet ducts, both of which would imply a reduction in the number of passengers. On the other hand, with a 50% exposure to the freestream flow the inlet under consideration would have significant setbacks in terms of drag and SFC.

Thus, only a larger number of engines can be fully embedded.
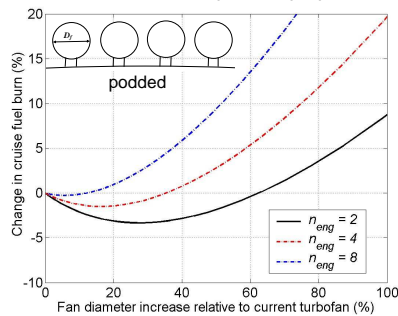
Effect of engine configuration on fuel burn

- The overall efficiency and rate of fuel consumption can be expressed as follows:

$$\eta_o = \eta_{th}\eta_p = \frac{useful\_power}{thermal\_energy} = \frac{X_N V_o}{\dot{m}_f.LCV} \qquad \Rightarrow \dot{m}_f = \frac{X_N V_o}{\eta_{th}\eta_p.LCV}$$
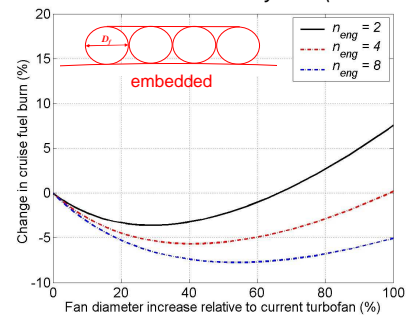
- The variation in fuel burn can be determined from the reduction in jet velocity and the increase in wetted area caused by an increase in fan diameter:

$$\eta_p = \frac{2V_0}{V_j + V_0} \qquad X_N = \rho_j A_j V_j (V_j - V_0) = D_{airframe} + D_{engines}$$

Fuel burn variation for a podded propulsion system

Variation for an embedded system (without BLI)

The overall efficiency can be expressed as useful power out over energy input, i.e. thrust times flight speed over fuel burn times calorific value. Thus the fuel burn is proportional to the thrust and inversely proportional to the engine propulsive and thermal efficiencies.

For a given cruise condition, as jet area increases, jet velocity reduces and propulsive efficiency improves. The drag of the engines can also be related to the engine size, thus the balance between propulsive efficiency and external drag can be approximated from the variation in exposed wetted area, assuming a constant engine thermal efficiency.

The podded case shows that as size goes up the fuel burn first improves then rapidly gets worse. With more podded engines the drag is greater, and the fuel burn rises faster.
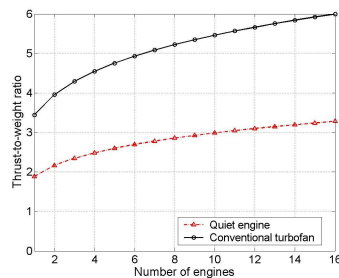
In the embedded case, the reverse is true. Fuel burn can reduce as engine numbers go up (although engine thermal efficiency may reduce – see later). In the embedded case the fuel burn varies less with engine size.

If we consider a conventional engine that is 3* in size, the fan will be 70% bigger, suggesting a much higher fuel burn if podded. This pushes us towards embedded multiple engines.
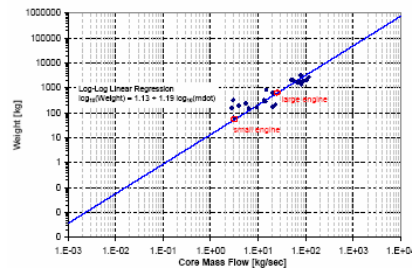
The total weight of the propulsion system has a direct impact on operating costs, either through a reduction in payload or an increase in the fuel load.

As the fan diameter increases the engine weight rises. This is mainly a result of the "square-cube law". In reality, this relationship is not as pronounced due to the hollowness of parts, etc.

Once the propulsion system size is fixed by the aircraft thrust and the jet noise limit at take-off, the weight can be reduced by increasing the number of engines.
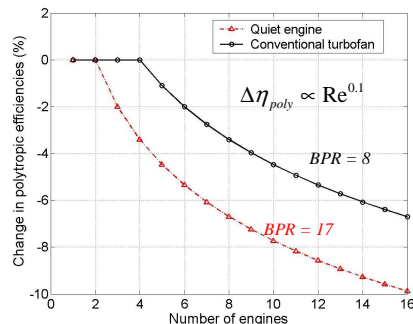
The main weight changes in going from a two engine podded configuration to embedding the same engines lie in the removal of the support structure, which usually make up 20 to 30% of the engine weight and the instalment of the inlet ducts.
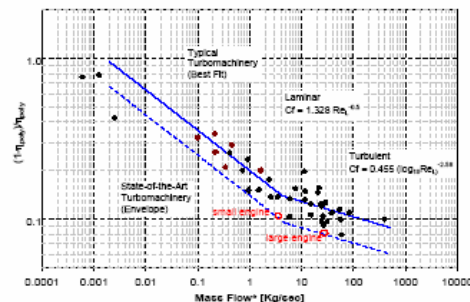
Variable cycle also reduces weight.

Effect of core size on polytropic efficiencies

- A smaller core operates in lower Reynolds number regimes, leading to higher viscous losses. Tip clearance gaps relative to the component dimensions are also larger.

- The core size reduces as the engine bypass ratio increases and as the number of engines increases at a fixed thrust.

- A regression analysis based on Protz (2004) estimated a 3.3% decrease in polytropic efficiency for a 15 versus a 2 engine design.

Variation in component efficiencies with engine number

Compressor efficiency versus engine size

$$\Delta \eta_{poly} \propto \mathrm{Re}^{0.1}$$

$BPR = 8$

$BPR = 17$

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Core size is lower for a quiet engine because the bypass ratio is much higher, thus the core operates in lower Reynolds number regimes, thus incurring greater viscous losses.

Tip clearance gaps increase relative to the blade dimensions, leading to increased secondary flows.

Increasing size of current manufacturing tools relative to blade dimensions adds to inaccuracies in the shape.
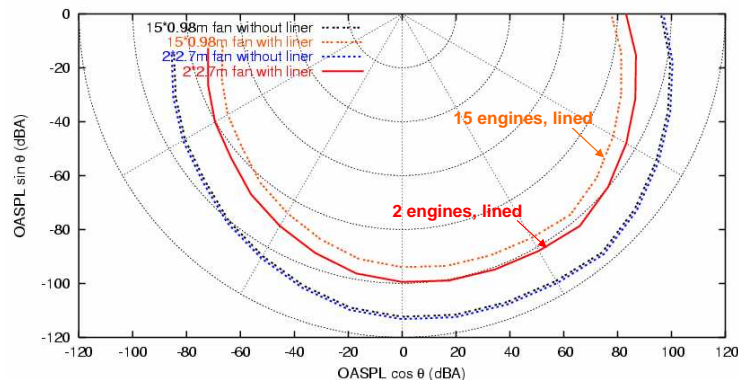
For a fixed aircraft mission and noise requirement the Reynold's number effect can be approximated using simple correlations based on core size.

The benefits of multiple engines could be maintained without a reduction in core size, if a single core is used to drive multiple fans in separate ducts.

Exhaust duct fan noise in multiple engines

- Forward propagating noise shielded by the airframe.
- Acoustic liners required to absorb rearward propagating noise. Exhaust duct L/D increases with number of engines.
- Thus, absorbent liners are more effective in multiple smaller engines.

Variation in emitted rearward fan noise with number of engines (prediction using ESDU, 2003)

With an all lifting body aircraft, provided the engine intakes are on or above the upper surface, forward propagating noise will be significantly shielded.

To eliminate rearward noise, a large area of acoustic liners is required. Basic ray theory indicates that the liner attenuation (in dB) is proportional to L/D. This increases as the number of engines increases (assuming a fixed length available for the engine).

Thus, absorbent liners are more effective in multiple smaller engines.

The prediction shown uses a modified ESDU fan noise prediction model (Hiedmann's method), combined with locally reacting acoustic liner module. Necessary assumptions:

      Liner impedance is independent of the angle of incident sound

      Uniform energy distribution between all propagating modes

      The mean duct flow is uniform within a constant area cylindrical duct

      End effects are neglected

Comparison between 2 big and 15 small embedded engines completed

      Duct lengths of 4.0m intake and 4.0m exhaust for both cases

      Fan diameter of 2.7m for the 2 engine case

      Fan diameter of 0.98m for the 15 engine case

      21 rotors, 56 stators, PR = 1.2, M_{tip} = 1.3

      Liner impedance values from Bielak (1999).

Operability of an embedded design

- For an embedded S-duct inlet:

    - DC60 ~ 0.1 - 0.3, Anabtawi et al., 1999.

    - PR ~ 0.95 versus 0.997 for a podded inlet, Seddon and Goldsmith, 2003.

$$DC_{60} = \frac{p_{02} - p_{02,60}}{p_{02} - p_2}$$

p_{02} and p_2 are the area weighted average total and static pressures at the engine interface plane (Pa)

$p_{02,60}$ is the area averaged total pressure for the 60° segment with the lowest mean total pressure (Pa)

$$PR = \frac{p_{02}}{p_{01}}$$

P_{01} is the total pressure at entry to the inlet (Pa)

- Parallel compressors method indicates significant surge margin loss for an embedded system and worse fan performance.

- Performance loss is recovered from drag reduction due to wetted area reduction and airframe boundary layer ingestion.

- Variable cycle can be used to recover surge margin and to optimise fan condition.

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Typical DC60 values measured in the embedded case range from 0.10 to 0.30, see Anabtawi et al. (1999). This applies to cruise with a well designed installation. A pressure recovery of 0.95 is appropriate for an S-ducted inlet (as opposed to 0.995 for a podded inlet).

The impact of inlet distortion on stability margin can be predicted (very crudely) with a parallel compressor model using the expected pressure rise characteristics of the fan.

This method predicts that for a fan operating with *PR = 1.2* in a duct with *DC60 = 0.24*, 25% of surge margin is lost.

To recover lost surge margin for an embedded design with a low pressure ratio fan, the parallel compressors method suggests a fan speed increase of 15% and a peak efficiency decrease of 5% is necessary relative to the podded engine.

However, this analysis assumes a fixed cycle turbofan. Variable cycle can alleviate the loss of surge margin and allow the fan performance to be optimised (see variable exhaust design later).

4. Findings of podded vs. embedded study

1. To reach the Silent Aircraft noise target at take-off a large jet area is required (about 2.5 - 3 times greater than for equivalent conventional engines).

2. The exposed wetted area in a podded configuration results in excessive drag, which can be mitigated by embedding the engines.

3. The large jet area at take-off requires a variable cycle for acceptable cruise performance and this is easier to implement within an embedded system.

4. If two engines are embedded, the overall weight, fuel burn and noise benefits relative to podded are marginal. If multiple engines are used, the weight, fan noise and fuel burn are all expected to reduce significantly. This approach could also improve aircraft balancing and control and reduce spool-up times, leading to lower approach noise.

5. The disadvantage of multiple embedded engines on acquisition, maintenance and repair costs has so far not been considered.

An embedded propulsion system is recommended as the preferred option for the Silent Aircraft.

Jet noise predictions combined with operational considerations during take-off suggest that a total jet area of 10.5 m2 is required to reach the Silent Aircraft noise target. This is about 3 times greater than conventional engines for a similar size aircraft. It is expected that this jet area will be easier to accommodate within an embedded configuration and that an embedded system will be more amenable to additional jet noise reduction methods.

For acceptable cruise performance the engine needs a variable cycle so that sufficient thrust is maintained at altitude. There are more possibilities for achieving this cycle change using an embedded configuration.
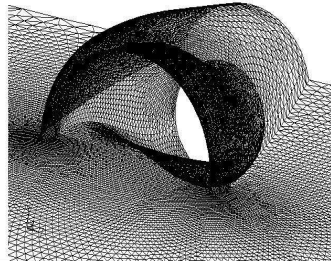
Embedding the engines reduces the frontal area exposed and hence the total aircraft drag. This effect is much greater for the Silent Aircraft because the engines are much larger. Embedding the engines reduces the total weight of the propulsion system. If multiple embedded engines are used the mass reduction is greater.

For both configurations forward propagating fan noise will be shielded by the blended wing upper surface. Acoustic liners in the exhaust duct have a much greater effect on noise reduction for multiple, smaller embedded engines.

Embedding the engines presents additional challenges in terms of inlet distortion. An important additional advantage of embedding the propulsion system that has not been quantified is the benefit to the overall aircraft balancing and pitch wise control. The most important disadvantage that has not been accounted for in embedding the engines is the impact on direct operating costs of the greater replacement and maintenance demands. This is expected to increase as the number of units rises.

Further work

- Development of variable cycle low-weight engines that are quiet at take-off as well as highly efficient at cruise: i) variable nozzles ii) ejectors iii) auxiliary fans
- Study of embedded installation configurations with variable engine number, with and without boundary layer ingestion that also enable simple variable geometry and effective noise attenuation.

CFD mesh for candidate 4-engine design   *CFD mesh for 8-engine design with common inlet*

The use of some form of variable cycle is essential for the Silent Aircraft to be both quiet and economical in terms of fuel burn and therefore emissions. Several variable cycle options have been identified and the design of candidate variable cycle engines to the point where comprehensive audits of noise, weight and performance can be completed .

A detailed study on improved aircraft/engine integration, including full 3-D optimisation of airframe centre-body and engine packaging to minimise overall drag and to maximise shielding/airframe noise absorption. This includes the application of boundary layer ingestion to minimise total airframe drag.

Other studies:

Detailed design of the LP system for low turbomachinery source noise.

Optimisation of the inlet design for minimum inlet distortion and forward-propagating noise emission.

Design of the engine exhaust to minimise rearward propagating noise using improved acoustic liner and mixer technology.

An investigation of thrust vectoring to allow steeper and slower approaches. The impact on noise, aircraft control and safety will be assessed.

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