Required jet area for a Silent Aircraft at take-off

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Overview

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The Silent Aircraft Initiative

The aim of the Silent Aircraft Initiative (SAI) is:

‘To discover ways to reduce aircraft noise dramatically, to the point where it would be virtually unnoticeable to people outside the airport perimeter in a typical built-up area.’[1]

This is an exceedingly ambitious target requiring noise to be considered as **the** primary design goal.

Different groups are looking at the airframe noise sources, engine noise sources and acoustic integration. This presentation is from members of the engine team.

To meet the SAI aim, a considerable reduction in all major engine noise sources will have to be achieved through source reduction, lining and shielding.
Why the focus on jet area?

To significantly reduce jet noise for a given thrust need to increase the jet area and reduce the jet velocity.

Jet noise is directly linked to the engine cycle.

A significant reduction in jet noise therefore requires a significant change in the engine cycle.

Turbomachinery noise requires detailed knowledge of the engine design which follows the engine cycle.

Before other engine noise sources can be silenced, the jet must be silenced through modification of the engine cycle.
Calculating the required jet area

The goal of the SAI can be taken as to reduce peak noise to a set level outside of the airport boundary.

To determine the required jet area to meet this peak noise limit, need to know the departure profile.

In order to optimise the performance at cruise, want to minimise required increase in jet area relative to current trends for optimum efficiency.

To minimise the required jet area, need to optimise the departure profile for low jet noise.

Therefore first step in designing the SAI engines is to optimise the departure profile for low jet noise and calculate the required jet area.
What is an acceptable take-off

The following parameters were used for a reference noise constrained airport:

- 10,000ft runway
- Sea level
- ISA + 12°C
- 70% relative humidity
- Airport boundary of 450m for sideline and runway length + 1,000m for flyover.

These parameters reflect London airports with the temperature set to cover 99% of operating hours at London Heathrow[2].
What is an acceptable take-off

The following key regulated[3,4] areas must be met during take-off:

• **Accelerate-stop**  
  *Max distance to reach V1 based on JAR25.109*  
  \[ s = 3048 - 2V_1 - \frac{1}{\eta g} \int_0^V \left( c_1 V^3 + c_2 V^2 + c_3 V + c_4 \right) dV \]

• **Take-off field length**  
  *Must be 35ft high at runway length / 1.15*

• **Minimum climb gradient**  
  *Min angle of climb allowing for 11% thrust increase on engine out*  
  \[ \theta_{\text{min}} \approx \sin^{-1} \left[ \frac{1}{1.11 \frac{E_{\text{num}}}{E_{\text{num}} - 1}} \left( \frac{1}{L/D} + \sin \theta^* \right) - \frac{1}{L/D} \right] \]

To satisfy the majority of SIDs, average climb angle of 4° (7%) required up to 1000m without exceeding the jet noise limit.

Minimum regulated cutback height of 800 ft[5,6] not enforced as entire take-off profile is low noise optimised with a continuous variation in thrust.
Jet Noise Prediction

- As jet noise will not be the only noise source on take-off, the jet noise limit was set 3dB below the overall noise limit.

- Stone Jet Noise model\(^7\) was used to estimate the 1/3\(^{rd}\) octave SPL
  - Single jet with core and bypass streams fully mixed out
  - Low temperature
  - No corrections for internal forced mixing applied (e.g. Garrison\(^8\) / Tester\(^9\)) as expect engine design to be very high bypass ratio

- Atmospheric attenuation, lateral attenuation and ground reflection corrections made based on ESDU data\(^{10,11}\)

- No aircraft shielding or reflection corrections included
Aircraft Model

Angle of aircraft = angle of thrust

Direction of flight

L = \( \frac{1}{2} \rho c L A_{\text{wing}} V_{\infty}^2 \)

D = \( \frac{1}{2} \rho c D A_{\text{wing}} V_{\infty}^2 + \mu (mg - L) \)

Tyre friction – on ground only

\[
L + E_{num} T_N \sin \beta = mg \cos \theta
\]

\[
m \frac{dV_{\infty}}{dt} = E_{num} T_N \cos \beta - mg \sin \theta - D
\]
Optimised take-off

(Re)Initialise Parameters

Time step on the ground*

NO

V<sub>R</sub> reached

YES

Time step during roll*

NO

Lift > Weight

YES

Time step in the air*

NO

Target height and speed reached?

NO

Increase jet area

YES

Operational requirements met?

NO

Complete

YES

* Accelerating as quickly / climbing as steeply as possible without exceeding noise limit
Baseline case

- TOW = 200,000kg
- L/D = 16
- \( V_r = 70 \text{m/s} \)
- 2 & 4 engines variants

Total jet area of
- 17.4m\(^2\) for 2 engines
- 15.6m\(^2\) for 4 engines

![Graph showing height (ft) vs. distance from brakes off (km) for 2 and 4 engine variants.](image)
Baseline case

**CRITICAL POINT**
Peak jet noise contours on ground (dBA) – 4 engines
Peak jet noise contours on ground (dBA) – 2 engines
Variation with aircraft mass

\[ A_{jet} \propto m^{1.1} \]

- 4 engines
- 3 engines
- 2 engines

Aircraft mass (tonnes)

Required total jet area (m²)

NEXT GEN AIRCRAFT
CURRENT AIRCRAFT
Variation with jet noise limit

\[ N_{jet} \propto 10 \log_{10} \left( A_{jet}^{-4.2} \right) \]

- Required jet area relative to baseline (%)
- Delta Peak Jet Noise outside airport (dBA)

Lines represent:
- 4 engines
- 3 engines
- 2 engines

Areas labeled:
- NEXT GEN
- CURRENT
Variation with aircraft L/D

Change in required jet area (%)

Aircraft L/D

-4 engines
-3 engines
-2 engines

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Variation with aircraft take-off velocity

Change in required jet area (%)

Aircraft Rotation Speed $V_r$ (m/s)

- 4 engines
- 3 engines
- 2 engines

Accelerate-stop distance critical

Take-off distance critical
Impact on the engine

• For baseline aircraft (200,000kg, L/D=16), if jet area set to meet jet noise requirement for a fixed cycle engine

• For 4 engines;
  • $A_{\text{jet}} = 3.9\text{m}^2$
  • ToC EPR = 1.23
  • ToC BPR = 28
  • Fan diameter = 2.6m

• For 2 engines;
  • $A_{\text{jet}} = 8.7\text{m}^2$
  • ToC EPR = 1.20
  • ToC BPR = 32
  • Fan diameter = 3.9m

• This compares to a Fan Diameter of 2.8m and BPR of 11 for the Trent1000\textsuperscript{[12]}, two of which will power a 9% heavier aircraft\textsuperscript{[13]}.

• To meet take off jet area requirements whilst maintaining cruise efficiency requires innovative cycle designs.
Impact on the engine

To obtain an efficient cruise engine that is ‘silent’ at take-off requires variable cycle technology. Three areas under current consideration include:

- **Variable area nozzle**
  - Increases the BPR and lowers the overall pressure ratio
  - Moves fan working line away from stall.
  - Can be used during entire mission to optimise efficiency

- **Ejection**
  - Uses a high velocity jet from the engine to entrain additional fluid resulting in higher mass flow and lower overall velocity
  - Would require forced mixing to achieve significant benefit

- **Auxiliary fans**
  - Single core and fan for cruise attached to gearing to drive additional fans for take-off
  - Would allow large increases in BPR at expense of complexity and weight
Conclusions

• For the SAI with noise taken as the primary design parameter, jet noise reduction drives the engine cycle requirements.

• A 200,000kg aircraft with take-off L/D of 16 and $V_r$ of 70m/s requires a total jet area of
  • 15.6m$^2$ for ‘silent’ departure if 4 engine
  • 17.4m$^2$ for ‘silent’ departure if 2 engine
This is 2.5 to 3 times the area of equivalent current aircraft.

• For the range of parameters considered here, the min climb angle after cutback is the critical requirement for most cases. This results in different required jet areas and departure profiles for 2, 3 and 4 engine aircraft.

• At higher take-off speeds, take-off distance and then accelerate-stop requirements become critical.

• To achieve the required jet area without adversely impacting cruise fuel burn requires the application of variable cycle technologies such as variable area nozzles, ejection or auxiliary fans.
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References

Equation of fit

With the critical angle after cutback being calculated as follows:

\[
\theta_{\text{min}(>400\text{ ft})} \approx \sin^{-1}\left( \frac{1}{1.11} \frac{N_{\text{eng}}}{N_{\text{eng}} - 1} \left( \frac{1}{L/D} + \sin \theta^* \right) - \frac{1}{L/D} \right), \quad \theta^* = \begin{cases} 
0.69^\circ \ (1.2\%) & \text{if } N_{\text{eng}} = 2 \\
0.86^\circ \ (1.5\%) & \text{if } N_{\text{eng}} = 3 \\
0.97^\circ \ (1.4\%) & \text{if } N_{\text{eng}} \geq 4 
\end{cases}
\]

Starting with the assumption that jet noise is a function of \( V_{\text{jet}}(V_{\text{jet}} - V_\infty) \) and \( A_{\text{jet}} \), rearranging for net thrust with added coefficients results in the following:

\[
N_{\text{jet}} = 46.4 \log_{10}\left[ mg \left( \frac{1}{L/D} + 0.5 \left( 0.1 + \sin \theta_{\text{min}} \right) + 6 \times 10^{-20} V_{r1}^{9.1} \right) \right]
- 42.15 \log_{10} \left( A_{\text{jet}} \right) - 147.2
\]

Rearranging for the required jet area gives:

\[
\Rightarrow A_{\text{jet}} = \left[ mg \left( \frac{1}{L/D} + 0.5 \left( 0.1 + \sin \theta_{\text{min}} \right) + 6 \times 10^{-20} V_{r1}^{9.1} \right) \right]^{1.1}
\]

\[
3107 \times 10^{0.0237N_{\text{jet}}}
\]