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Silent Aircraft Initiative

Modelling Minimum Airframe Noise for an All-Lifting-Body

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Outline

- Brief overview of Silent Aircraft Initiative (SAI)
- Airframe Noise Sources
- Trailing-edge noise
  - Brooks *et al.*
  - ESDU
  - Lilley
- Additional noise sources
  - Mild separation noise
  - Wing tip noise
- Implications of results

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Brief Overview of Silent Aircraft Initiative (SAI)

- Design a commercial aircraft with noise as the primary design parameter
- Ideally, noise would barely be heard above the background noise level in a typical urban built-up area outside the airport perimeter, but what sets the limit?
- Project subgroups:
  - AIRFRAME
  - Engine
  - Integration
  - Economics
  - Operations

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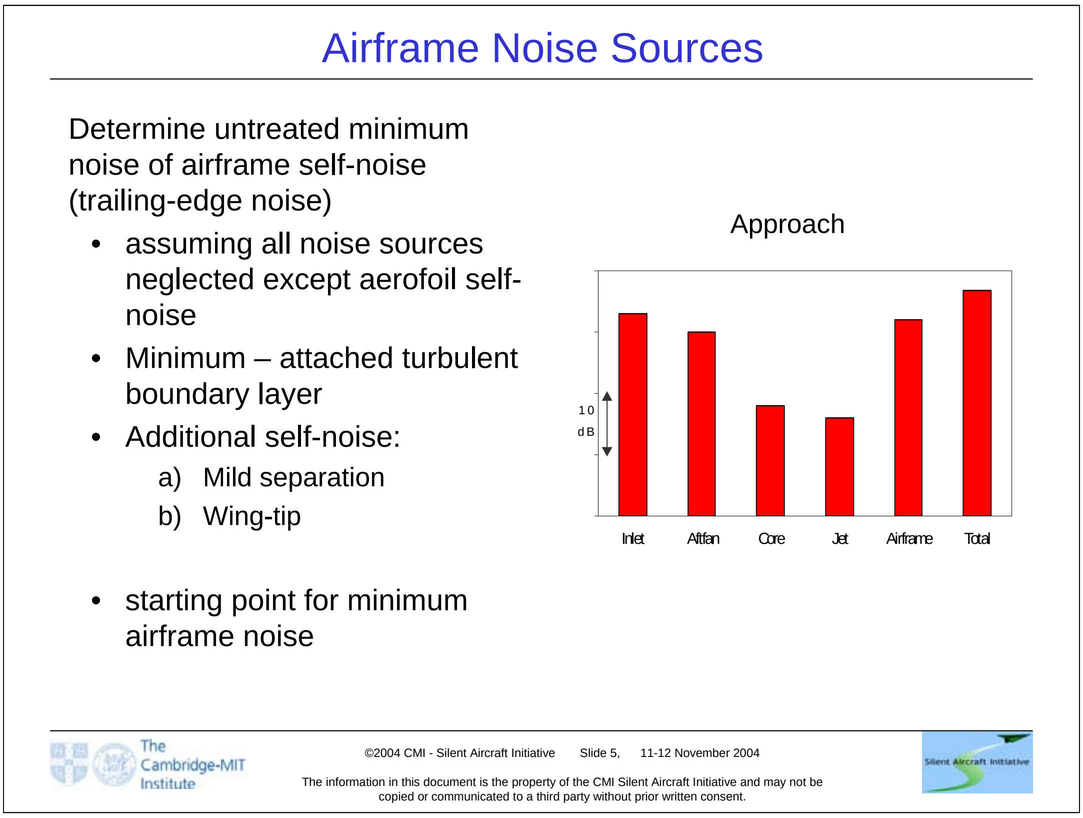

Airframe Noise Sources

Determine untreated minimum noise of airframe self-noise (trailing-edge noise)

- assuming all noise sources neglected except aerofoil self-noise
- Minimum – attached turbulent boundary layer
- Additional self-noise:
    a) Mild separation
    b) Wing-tip

- starting point for minimum airframe noise

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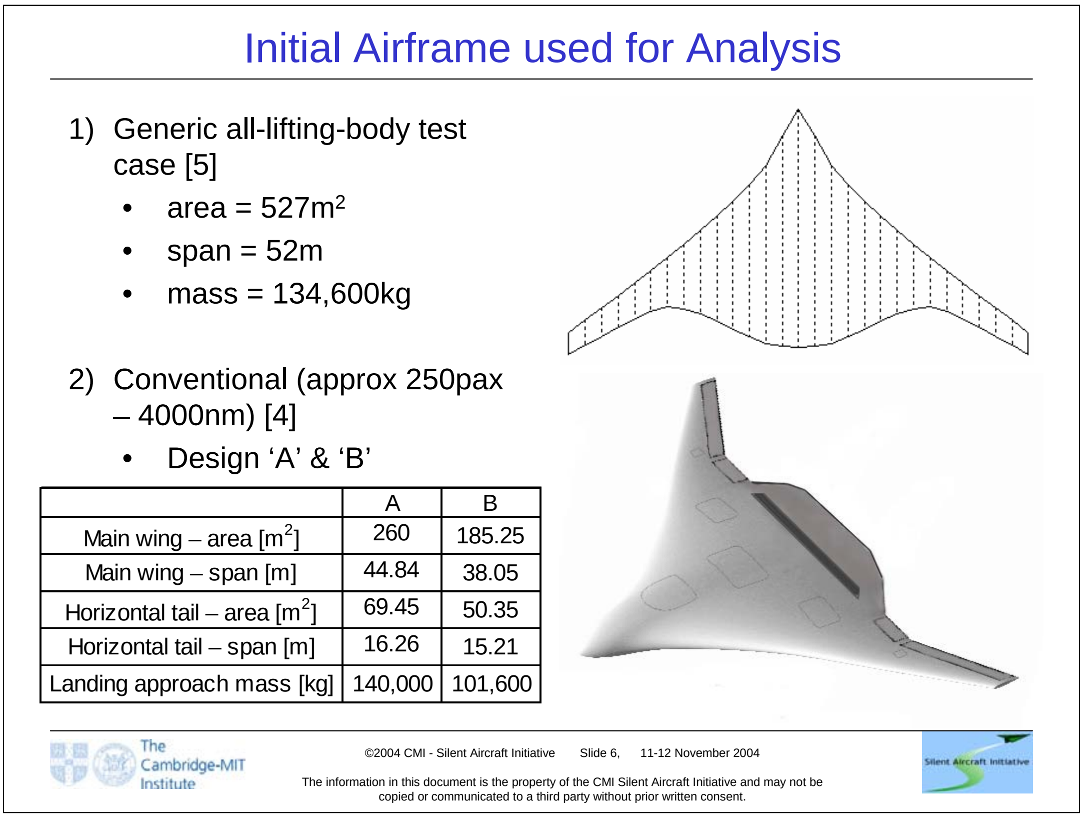
The objective of this work is to determine the minimum untreated airframe noise. It is assumed that the minimum airframe noise source, when other sources are neglected, is aerofoil self-noise.

The minimum airframe aerofoil self-noise source is attached turbulent boundary layer. This presentation will present three models used to model this noise source.

Additional aerofoil self-noise noise sources, consisting of mild boundary layer separation and wing-tip noise will also be presented



Initial Airframe used for Analysis

1) Generic all-lifting-body test case [5]
   - area = 527m^2
   - span = 52m
   - mass = 134,600kg

2) Conventional (approx 250pax – 4000nm) [4]
   - Design ‘A’ & ‘B’

	A	B
Main wing – area [m^2]	260	185.25
Main wing – span [m]	44.84	38.05
Horizontal tail – area [m^2]	69.45	50.35
Horizontal tail – span [m]	16.26	15.21
Landing approach mass [kg]	140,000	101,600

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The test case for the aerofoil self-noise models will be a generic all-lifting-body based on an airframe from [5].

Two conventional airframe test cases are also presented to compare an all-lifting-body planform to a conventional tube and wing planform. Also to compare the applicability and differences of the self-noise models to the different planform configurations.

Attached Boundary Layer Turbulence Trailing-Edge Noise (Minimum Untreated Airframe Noise)

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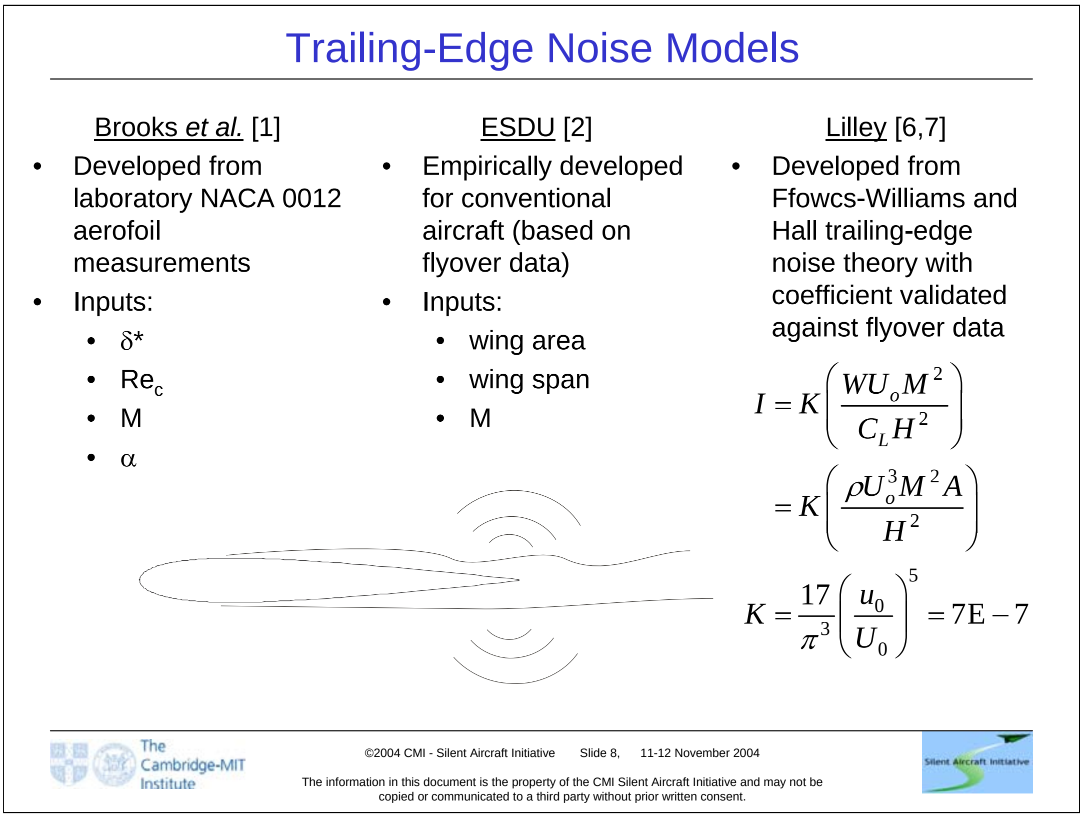

Trailing-Edge Noise Models

Brooks *et al.* [1]

- Developed from laboratory NACA 0012 aerofoil measurements
- Inputs:
  - δ^*
  - Re_c
  - M
  - α

ESDU [2]

- Empirically developed for conventional aircraft (based on flyover data)
- Inputs:
  - wing area
  - wing span
  - M

Lilley [6,7]

- Developed from Ffowcs-Williams and Hall trailing-edge noise theory with coefficient validated against flyover data

$$I = K\left(\frac{WU_oM^2}{C_LH^2}\right)$$

$$= K\left(\frac{\rho U_o^3M^2A}{H^2}\right)$$

$$K = \frac{17}{\pi^3}\left(\frac{u_0}{U_0}\right)^5 = 7\mathrm{E}-7$$

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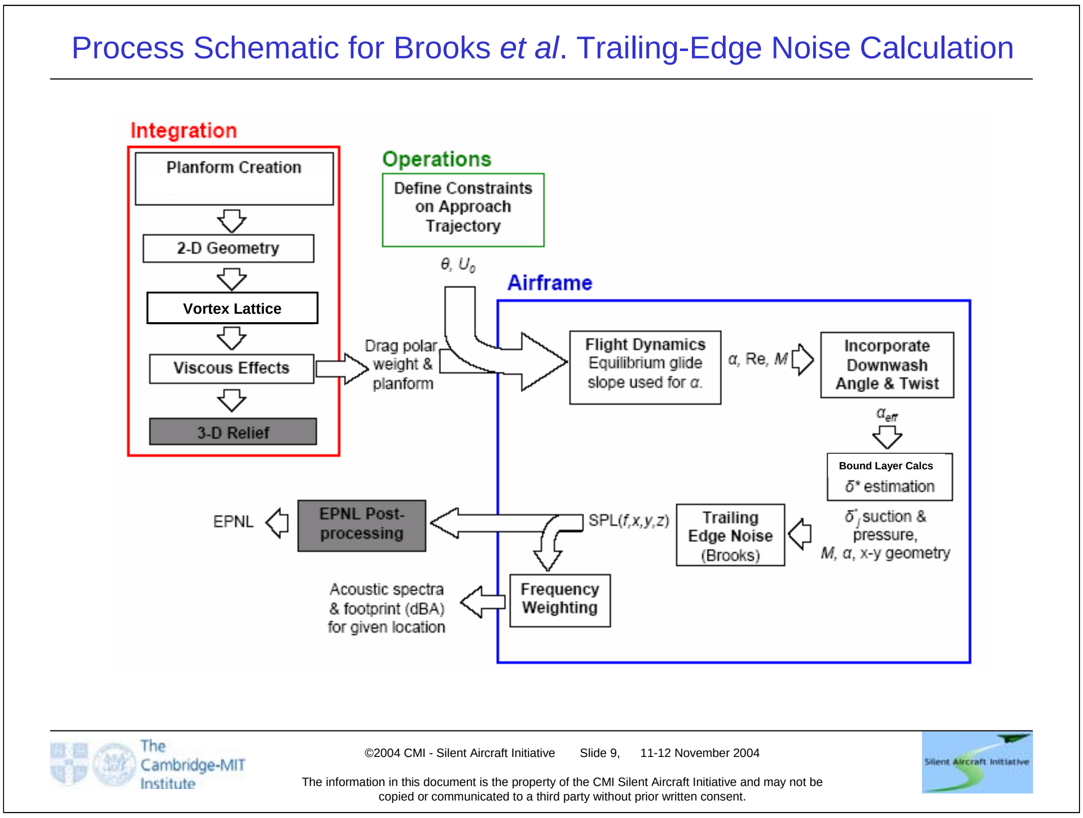
The trailing-edge noise mechanism is due to boundary layer turbulence (acoustic sources) being scattered by the trailing-edge to propagating sound. The trailing-edge noise mechanism is a multipole ($\propto M^5$) noise source.

The models that are compared for use in modelling the minimum airframe noise are:

1) Brooks et al.
   - Semi-empirical model
   - Developed from laboratory NACA0012 aerofoil measurements
2) ESDU
   - Empirically developed and validated with conventional planform flyover data
3) Lilley
   - Semi-empirical model
   - K validated with conventional flyover data



Process Schematic for Brooks *et al*. Trailing-Edge Noise Calculation

Integration

Planform Creation

2-D Geometry

Vortex Lattice

Viscous Effects

3-D Relief

Drag polar, weight & planform

Operations

Define Constraints on Approach Trajectory

θ, U_0

Airframe

Flight Dynamics
Equilibrium glide slope used for α.

α, Re, M

Incorporate Downwash Angle & Twist

α_{eff}

Bound Layer Calcs
δ^* estimation

δ^*_j suction & pressure, M, α, x-y geometry

Trailing Edge Noise (Brooks)

SPL(f,x,y,z)

EPNL Post-processing

EPNL

Frequency Weighting

Acoustic spectra & footprint (dBA) for given location

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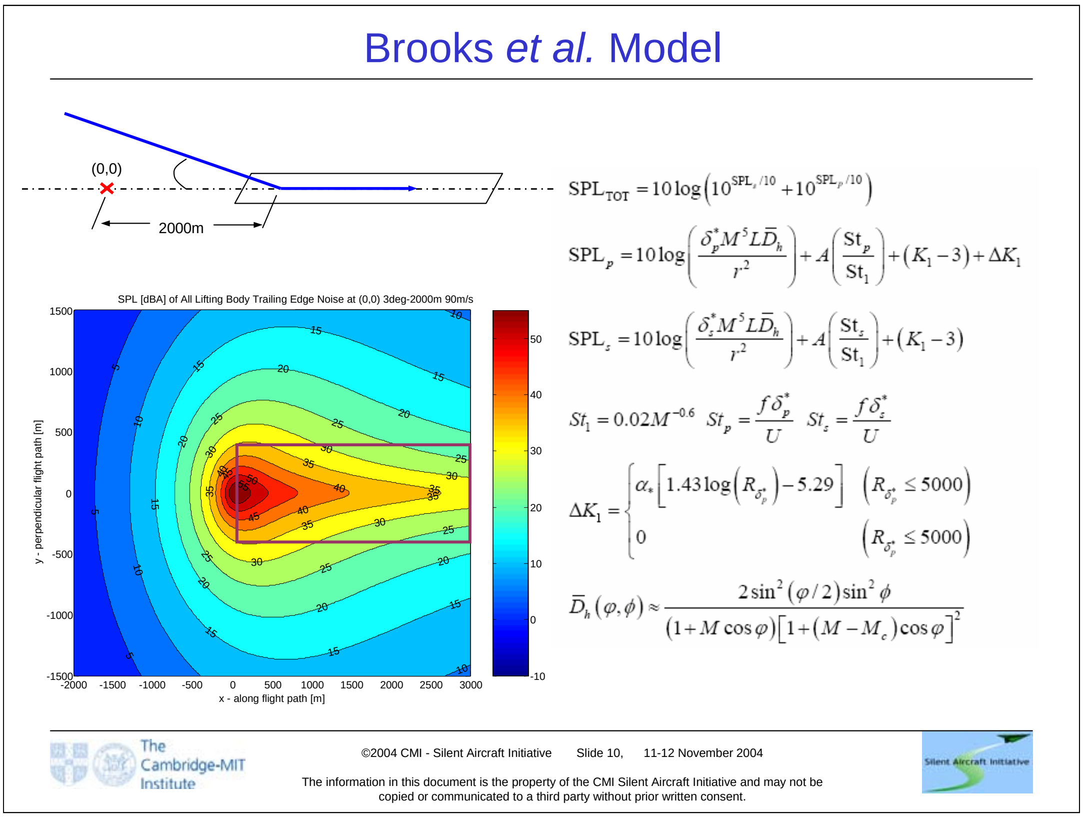
Framework for obtaining Brooks *et al*. model inputs



Brooks *et al.* Model

$$\mathrm{SPL_{TOT}} = 10\log\left(10^{\mathrm{SPL}_s/10} + 10^{\mathrm{SPL}_p/10}\right)$$

$$\mathrm{SPL}_p = 10\log\left(\frac{\delta_p^* M^5 L \bar{D}_h}{r^2}\right) + A\left(\frac{\mathrm{St}_p}{\mathrm{St}_1}\right) + \left(K_1 - 3\right) + \Delta K_1$$

$$\mathrm{SPL}_s = 10\log\left(\frac{\delta_s^* M^5 L \bar{D}_h}{r^2}\right) + A\left(\frac{\mathrm{St}_s}{\mathrm{St}_1}\right) + \left(K_1 - 3\right)$$

$$St_1 = 0.02 M^{-0.6} \quad St_p = \frac{f\delta_p^*}{U} \quad St_s = \frac{f\delta_s^*}{U}$$

$$\Delta K_1 = \begin{cases} \alpha_* \left[1.43\log\left(R_{\delta_p^*}\right) - 5.29\right] & \left(R_{\delta_p^*} \le 5000\right) \\ 0 & \left(R_{\delta_p^*} \le 5000\right) \end{cases}$$

$$\bar{D}_h(\varphi,\phi) \approx \frac{2\sin^2(\varphi/2)\sin^2\phi}{(1+M\cos\varphi)\left[1+(M-M_c)\cos\varphi\right]^2}$$

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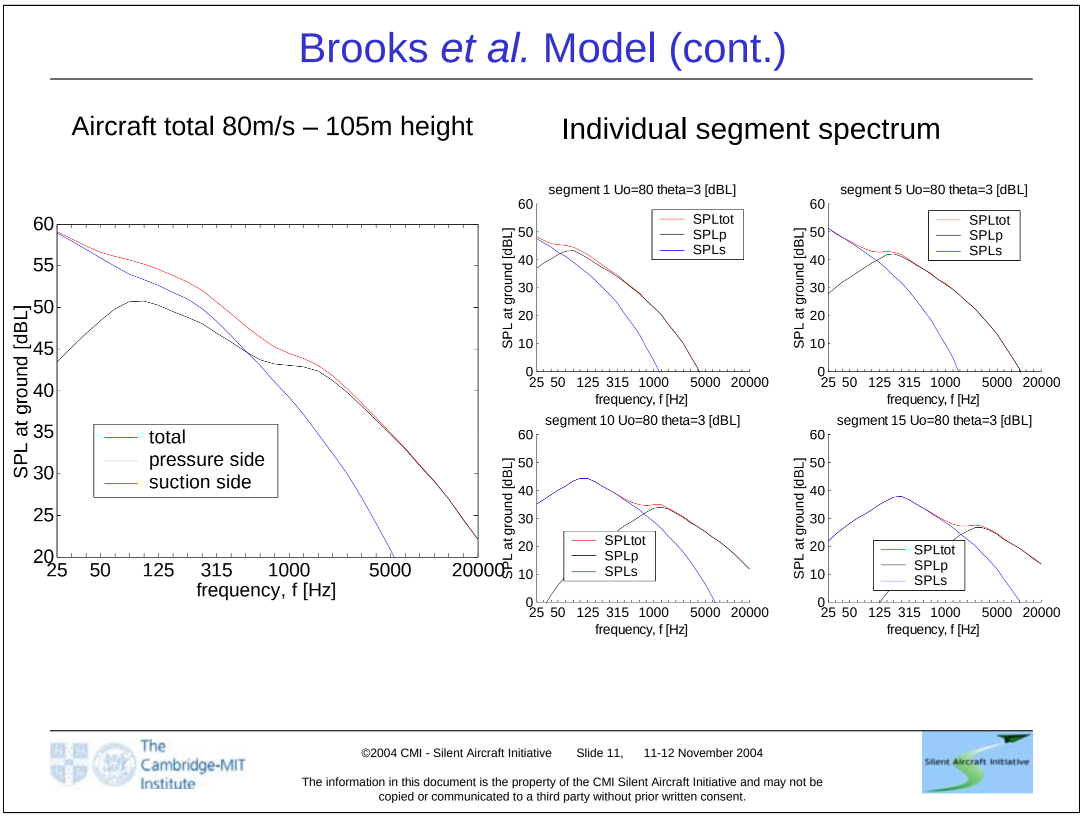
Schematic of comparison point of the models (marked by red X), consistent with current aircraft certification point.

Also this comparison point is the maximum noise point on the ground for a trailing-edge noise source on an approach trajectory outside the airport perimeter, as seen in the ground footprint plot. This is because the trailing-edge noise directivity is maximum below the aircraft (significantly lower as sideline distance is increased) and distance is smallest at this point in the area of interest (outside the airport perimeter).



Brooks *et al.* Model (cont.)

Aircraft total 80m/s – 105m height

Individual segment spectrum

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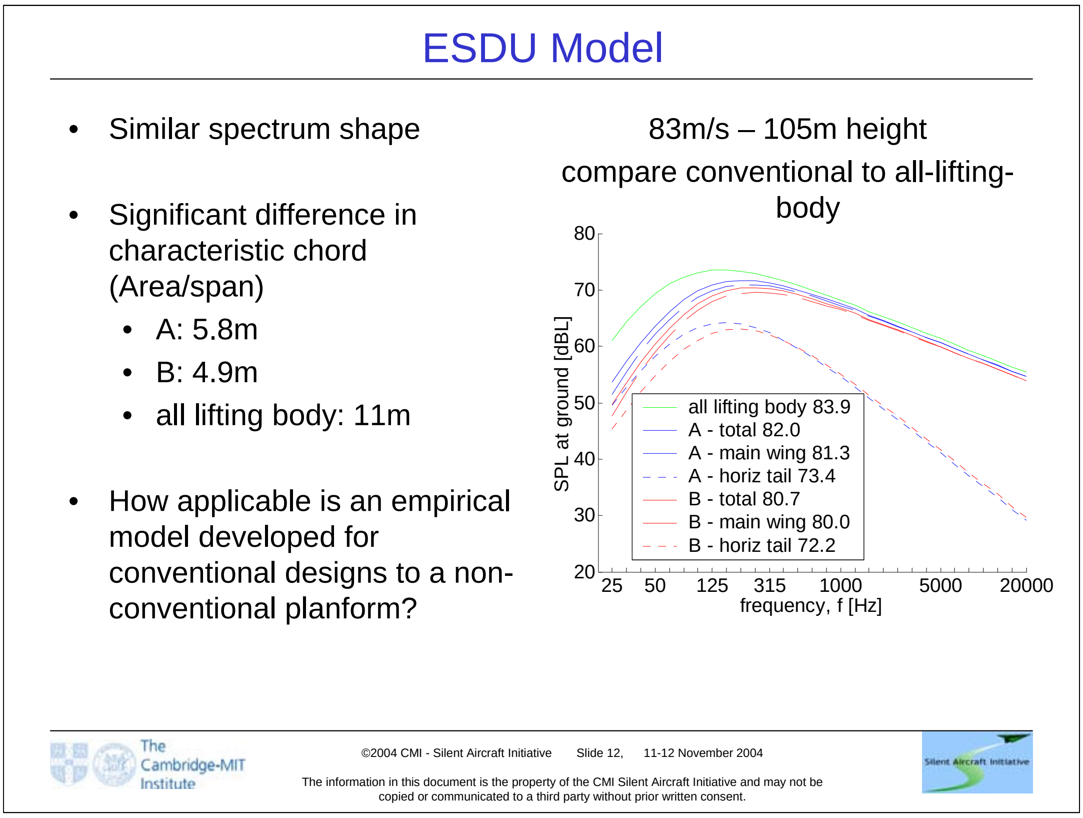
Figures of aircraft spectrum for the Brooks *et al*. model.

The Figures on the right are the individual segment spectrums (segment 1 is most inboard, segment 15 most outboard) which when summed result in the left figure, the aircraft total.

It is evident that the suction side noise source dominates the spectrum and is at very low frequency.



ESDU Model

- Similar spectrum shape
- Significant difference in characteristic chord (Area/span)
  - A: 5.8m
  - B: 4.9m
  - all lifting body: 11m
- How applicable is an empirical model developed for conventional designs to a non-conventional planform?

83m/s – 105m height

compare conventional to all-lifting-body

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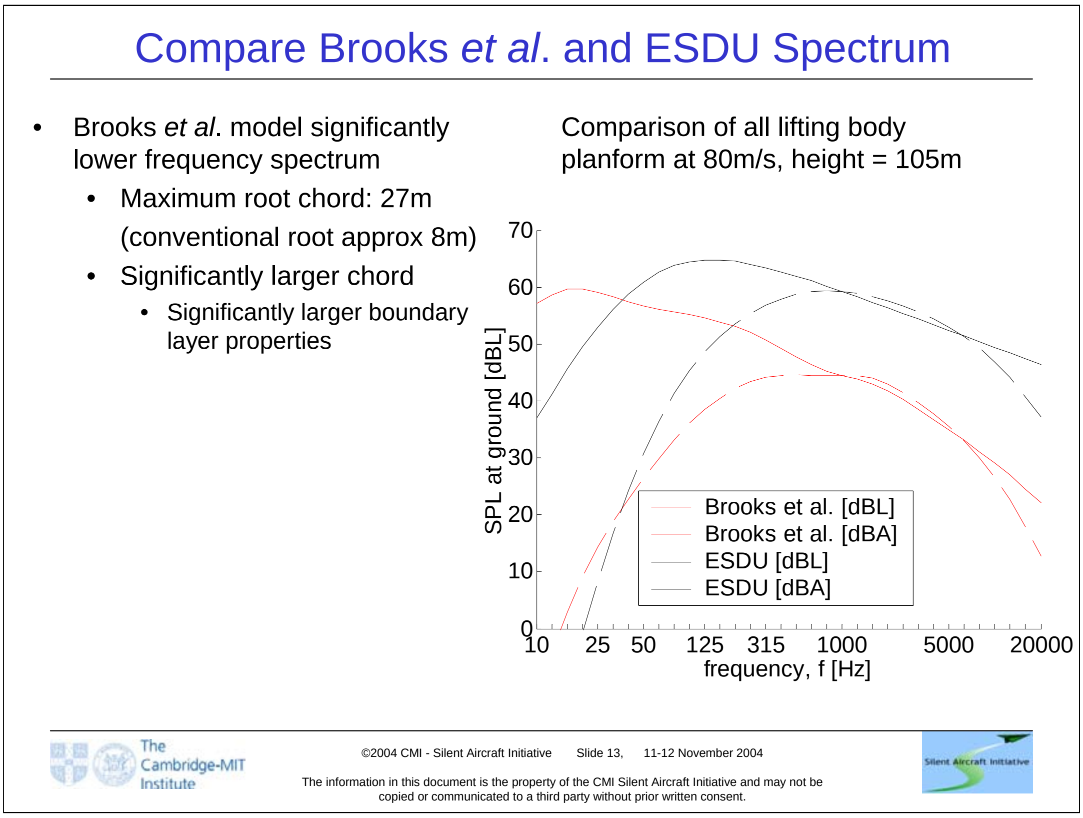
The aerofoil noise of the all-lifting-body and the two conventional planforms are calculated with the ESDU model.

The noise of the all-lifting-body is larger than the two conventional planforms and the spectrum of the all-lifting-body also peaks at a lower frequency. This is expected because the larger characteristic chord of the all-lifting-body results in a larger boundary layer and consequently lower frequency.

The ‘A’ airframe has approximately 60% of the all-lifting-body area and is 1.9dB quieter.

The ‘B’ airframe has approximately 40% of the all-lifting-body area and is 3.2dB quieter.



Compare Brooks *et al*. and ESDU Spectrum

- Brooks *et al*. model significantly lower frequency spectrum
  - Maximum root chord: 27m (conventional root approx 8m)
  - Significantly larger chord
    - Significantly larger boundary layer properties

Comparison of all lifting body planform at 80m/s, height = 105m

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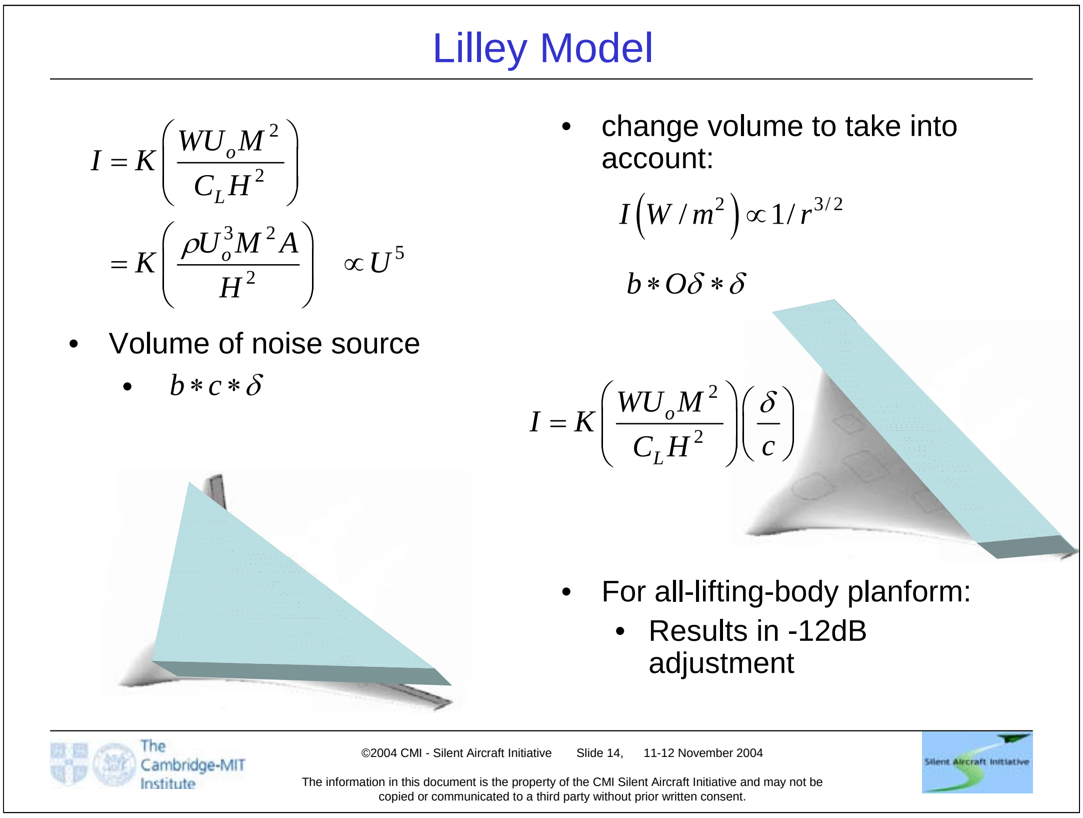
There is a significant difference of the Brooks et al. and ESDU spectrum of the all-lifting-body.

The Brooks model has a significantly lower frequency spectral peak than the ESDU model. This may be due to the drastic departure (I.e. much larger) maximum root chord of the all-lifting-body from a conventional airframe. The ESDU model was developed for conventional airframes and consequently applying it to an all-lifting-body planform may be exceeding it limits of applicability too far. Alternatively the Brooks *et al*. model is also being pushed possibly beyond its limits in being applied to an all-lifting-body when it was developed from laboratory sized aerofoils.



Lilley Model

$$I = K\left(\frac{WU_oM^2}{C_LH^2}\right)$$

$$= K\left(\frac{\rho U_o^3M^2A}{H^2}\right) \quad \propto U^5$$

- Volume of noise source
  - $b * c * \delta$

- change volume to take into account:

$$I\left(W/m^2\right) \propto 1/r^{3/2}$$

$$b * O\delta * \delta$$

$$I = K\left(\frac{WU_oM^2}{C_LH^2}\right)\left(\frac{\delta}{c}\right)$$

- For all-lifting-body planform:
  - Results in -12dB adjustment

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Two forms of the Lilley model will be presented:

1) Original

The original Lilley model was developed from Ffowcs-Williams and Hall trailing-edge noise theory and uses a volume of acoustic sources equal to (span) * (chord) * (boundary layer thickness). This matches flyover data well.

2) Modified

The proposed modified Lilley model makes an adjustment to the volume of acoustic sources. This is hypothesized to take into account the relation that the far-field acoustic intensity of trailing-edge noise varies with the distance of the acoustic source from the trailing edge (*r*) according to:

$$\text{Intensity} \propto 1 / r^{3/2}$$

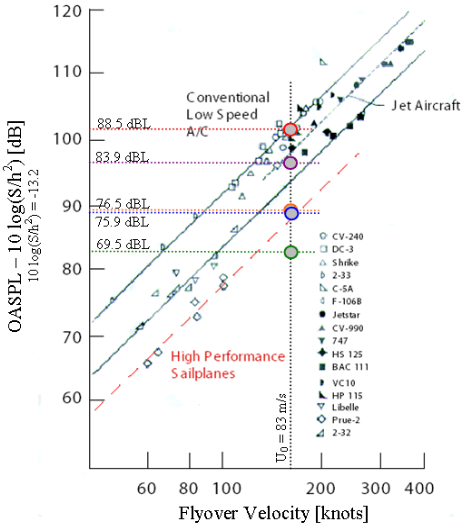
It is proposed that a volume of acoustic sources equal to (span) * (order of boundary layer thickness) * (boundary layer thickness) be used. The distance of the order of a boundary layer thickness is thought to take into account that acoustic sources (boundary layer turbulence) at distances larger than of the order of the boundary layer thickness will not contribute significantly to the noise because the factor $1 / r^{3/2}$ will be sufficiently small with *r* equal to a value of the order of a boundary layer thickness. For the all-lifting-body this results in an adjustment of -12dB.

Comparison of Trailing-Edge Noise Models

All-Lifting-Body Planform Comparison

	Trailing-edge noise (dBL)	Color
Lilley Semi-Empirical Airframe Model	88.5	red
ESDU Empirical Airframe Model - Conventional Wing	83.9	purple
Modified Volume Lilley Semi-Empirical Airframe Model	76.5	orange
ESDU Empirical Airframe Model - Glider Wing	75.9	blue
Brooks et al. Self Noise Model	69.5	green

S (area) = 527m^2, h (height) = 105m, span = 52m, flyover speed = 83m/s



modified from [3,8]

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Additional Aerofoil Self-noise Noise Sources

1) Mild Separation
2) Wing Tip Noise

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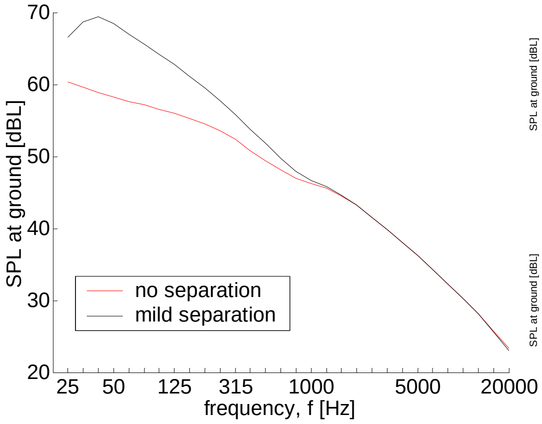
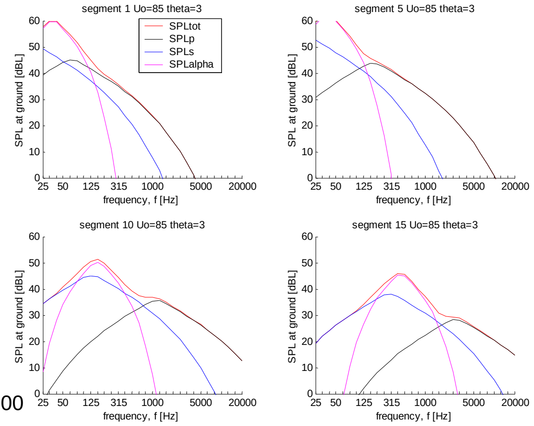
Mild Separation Noise

- Aircraft total 85m/s – 105m height
    - with and without mild separation



- Individual segment spectrum



$$\mathrm{SPL}_{\alpha} = 10\log\left(\frac{\delta_s^* M^5 L \bar{D}_h}{r^2}\right) + B\left(\frac{\mathrm{St}_s}{\mathrm{St}_2}\right) + K_2$$

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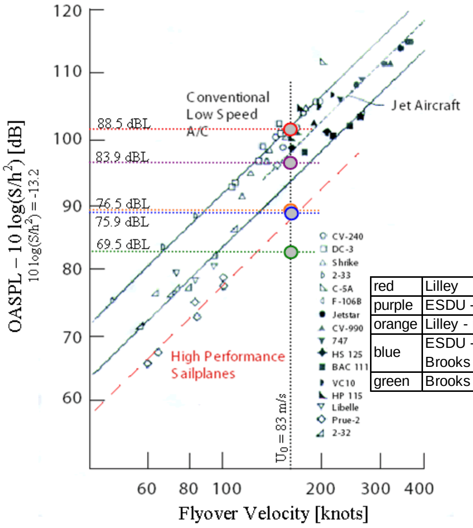
Mild Separation Noise (cont.)

noise with mild separation: 75.9dBL (Brooks *et al*. model)

- same point (blue) as ESDU glider

Models that agree with ‘Fink glider line’:

- ESDU glider
- Brooks *et al*. with mild separation
- Modified Lilley



red	Lilley
purple	ESDU - conv
orange	Lilley - mod vol
blue	ESDU - glider Brooks w sep
green	Brooks et al.

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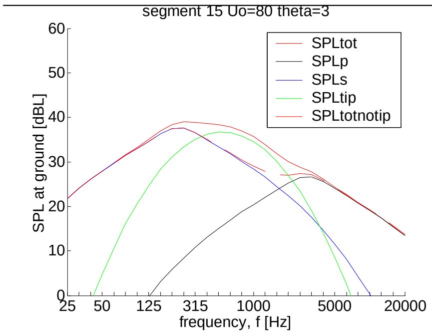
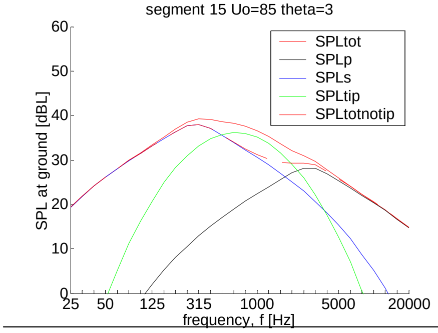
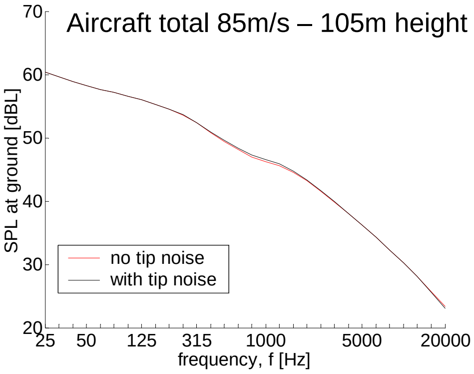
Wing Tip Noise







$$SPL_{TIP} = 10\log\left(\frac{M^2 M_{\max}^3 \ell^2 \bar{D}_h}{r^2}\right) - 30.5\left(\log St_{TIP} + 0.3\right)^2 + 126$$

$$St_{TIP} = \frac{f\ell}{U_{\max}}$$

$$\ell / c \approx 0.008\alpha_{TIP}$$

$$M_{\max} / M \approx \left(1 + 0.036\alpha_{TIP}\right)$$

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New Trailing-edge Noise Model Required

- Uncertainty exists in the previous models for application to an all-lifting-body
  - Substantially larger chord
  - Other noise sources included in other trailing-edge noise models
    - ESDU
    - Lilley
      - Installation noise
      - Engine noise
      - Mild separation
- At limit of current models – models are unable to give insight into possibilities to reduce noise

- Need model that is based on physical trailing-edge noise sources
  - Actual boundary layer turbulence properties
  - Applicable for non-conventional airframe configuration analysis and design
- A model with these characteristics will allow:
  1) better understanding of minimum airframe noise
  2) investigation of noise reduction possibilities

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Implications of Results

- Discrepancy between trailing-edge noise models
  - 2 of 3 models are validated empirically and most likely include additional noise sources
  - All three models are being extended dramatically from design realm for which they were developed to be applied to an all-lifting-body
  - A model is required that is specific/applicable for all-lifting-body design space
- Mild separation noise is visible within entire aircraft noise spectrum
  - elevates Brooks *et al*. to Fink boundary
- Tip vortex noise is visible for tip segment but not visible in entire aircraft noise spectrum
- Indications are that the minimum **untreated** airframe noise (aerofoil self-noise / trailing-edge noise) is the Fink ‘glider’ line
  - all-lifting-body seems to adhere to this limit

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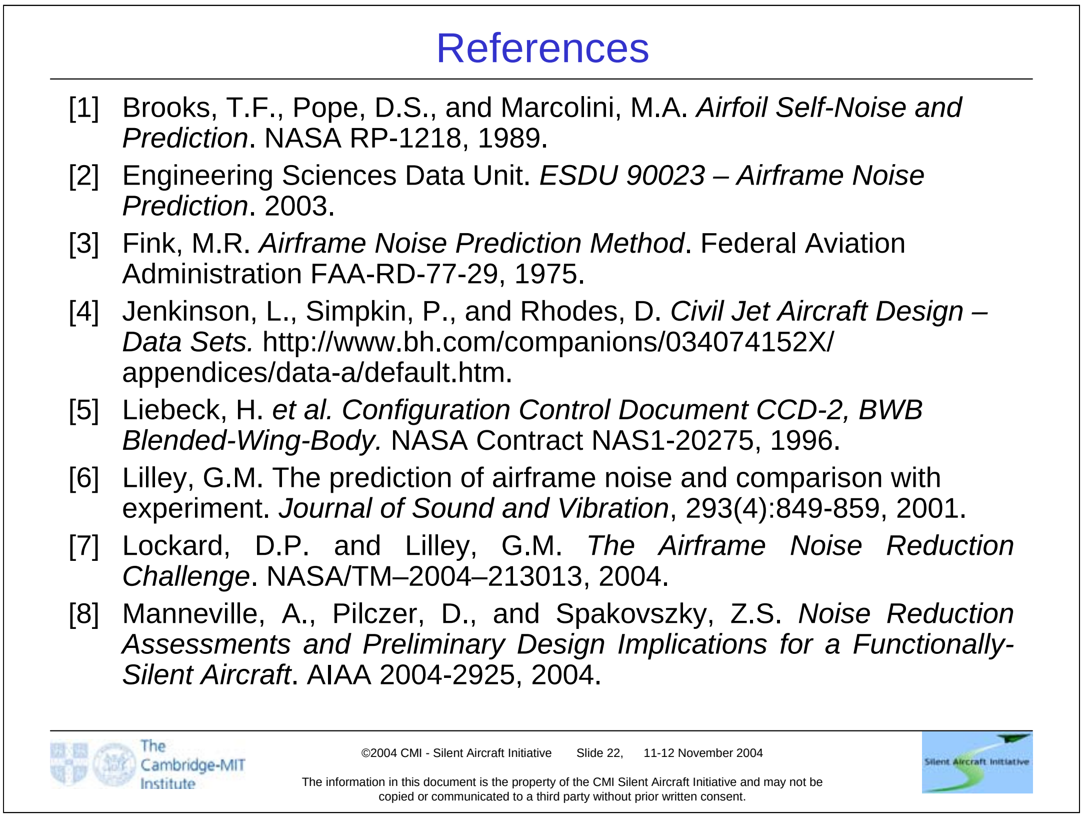

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