The Cambridge-MIT Institute

Silent Aircraft Initiative
...a new approach

# Silent Aircraft Scoping Study

Chris Andreou, Will Graham
Cambridge University Engineering Department

CEAS
CONFEDERATION OF EUROPEAN AEROSPACE SOCIETIES
8th ASC-CEAS WORKSHOP NOVEMBER 11+12
BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS, HUNGARY
AAAF AIAE AIDAA DGLR FTF NVvL RAeS SVFW

# Acknowledgements

- This work is supported by Cambridge-MIT Institute (CMI) as part of the Silent Aircraft Initiative.

- The authors would like to acknowledgements Adam Diedrich & James Hileman at MIT for guidance on appropriate values used to obtain our parameters.

# Objectives of the Silent Aircraft Initiative

To design an aircraft that:

- has a noise level that is inaudible outside an airport boundary in an urban environment.
- will demonstrate that the technology is technically feasible.
- is economically viable and desirable from an airlines perspective.
- is scalable to larger sizes and thus,
- will hopefully eventually replace the entire world fleet.

# Scoping Study

- 'Which factors affect airframe noise levels on landing approach?
- This presentation will discuss the results from a scoping study undertaken to estimate the influence of aircraft weight, wing loading, approach angle, approach velocity and lift/drag characteristics on ‘clean’ configuration noise.
- The drag polar is essential in carrying out a noise study of a specific aircraft configuration on landing approach.
- To produce this drag polar, it is necessary to estimate both the zero-lift and lift induced drag as well as the lift coefficient.
- Lift and drag are obtained from a theoretical drag polar of an all lifting body.

# Lilley's Equation

- Lilley [1] and Spakovsky [3] have analysed such issues before, but without taking the requirement for equilibrium flight into account.

- Lilley [2] used a form of the equation developed by Ffowcs Williams-Hall to derive a simple, semi-empirical equation to model airframe noise of a conventional aircraft in "clean" configuration:

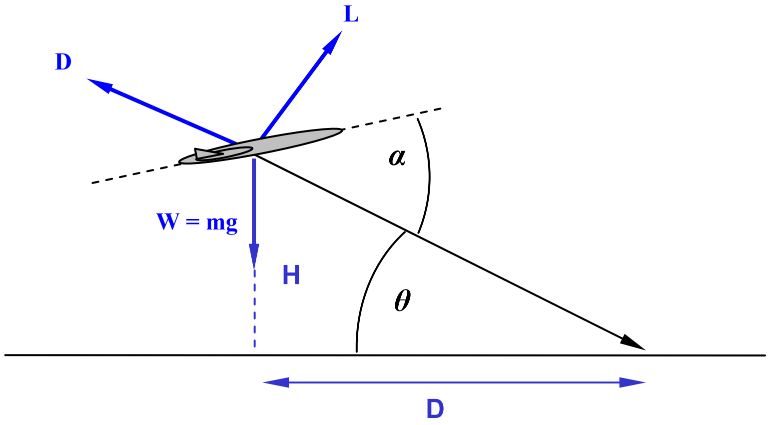
$$I = K\left(\frac{WU_oM^2}{C_LH^2}\right)$$

- The Coefficient *K* provided by Lilley [1] has an approximate value 5.6 x $10^{-7}$.

- We expect the value of *K* to vary with Re, but experimental results suggest it stays more-or-less constant over a wide range?

# Approach Path

- Forces acting on an aircraft during a constant descent approach,



- The component of the weight opposite the lifting force, L, is offset by the generated lift of the aircraft.

$$W \cos\theta = \frac{1}{2}\rho u_o^2 C_L S$$

- H is calculated by assuming a point 2 km from the point of touch down to the reference point at a constant angle of descent.

# Simplified Lilley and Calculation of SPL

- From trailing edge noise analysis the sound intensity is:

$$I = K\left(\frac{\frac{1}{2}\rho S U_o^5}{c^2 H^2 \cos\theta}\right)$$

- The SPL can be calculated from the sound intensity using the formula:

$$SPL(dB) = 10\log_{10}\frac{I(W/m^2)}{I_{ref}}$$

- Using $I_{ref} = 10^{-12}$ (W/m$^2$), it now becomes a relatively simple matter to obtain sound pressure levels for a “clean” configuration.

# Drag Polar

- In order to take the equilibrium flight conditions into account, one must have knowledge of the aircraft drag polar and hence we assume it takes the quadratic form:

$$C_D = C_{Do} + kC_L^2$$

- For the flight equilibrium condition with no thrust:

$$\frac{D}{L} = \cot\theta$$

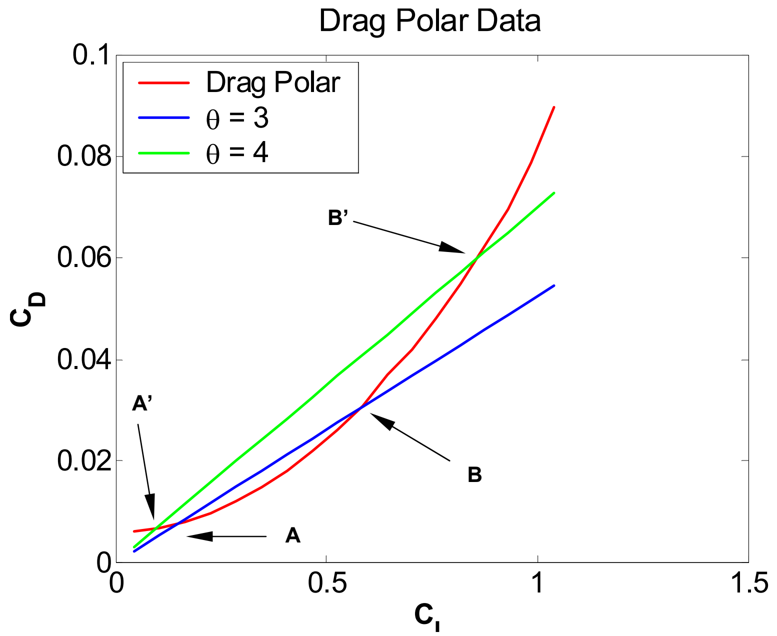
- Re-arranging and substituting $C_D = C_L \tan\theta$, the quadratic equation has the form:

$$C_L^2 - \frac{\tan\theta}{k}C_L + \frac{C_{Do}}{k} = 0$$

- The two solutions to the above equation give two points on the drag polar.

# Solutions to Drag Polar

- Intersection of the drag polar and a line representing $C_D = C_L \tan \theta$, gives the two equilibrium solutions for $C_L$ for a given flight path angle.
- Solution A corresponds to a higher velocity and is speed stable whereas solution B has a slower flight speed and is speed unstable.
- Solution A represents a front-side approach while solution B represents a back-side approach.
- Increasing the flight path angle allows flight at higher $C_L$ and lower velocity.
- The velocities at point A are far too high to consider it as an operating point and further analysis of point A will not be made.



# Aircraft Design Point

The aircraft design point has several characteristics. These are:

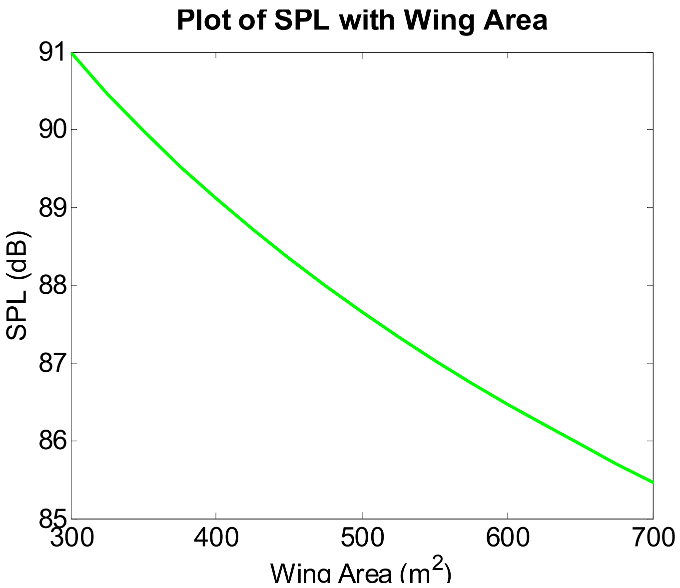
- A wing area of 530 $m^2$.
- A flight path angle of 3º.
- A approach velocity of 83 m/s.
- The height from the observer to the airplane of 104.8 m.
- A zero-lift drag coefficient of 0.0058.
- A lift-dependent drag coefficient of 0.072.
- A landing weight of 135 tons.

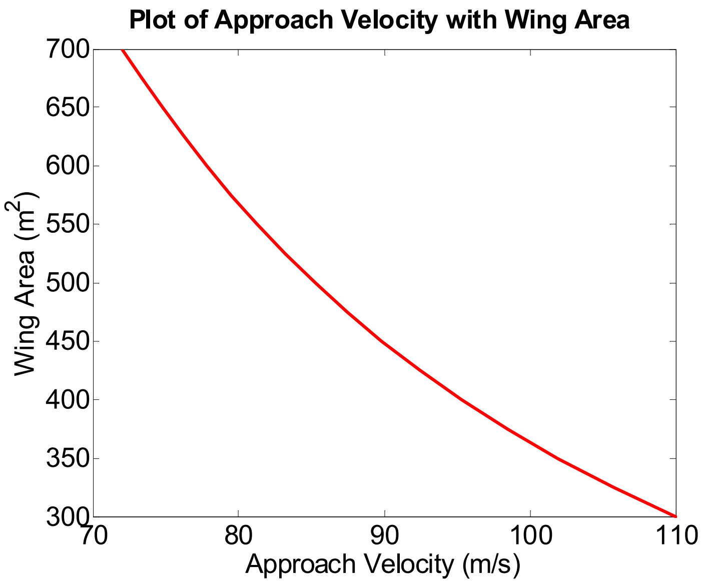
# Aircraft Variations and Changes to Trailing Edge Noise

- How do variations within the aircraft, its drag polar and the approach trajectory affect the noise created by the trailing edge of the aircraft?
- Each slide varies an aircraft parameter (weight, wing area or flight path angle) using the existing drag polar and then determines how this variation affects the noise that is emitted by the aircraft.
- In the following slides changes to the aircraft design point are not made unless stated.
- For excessively high flight path angles, the aircraft cannot achieve equilibrium and additional lift would be required to do so.

# Variations to Wing Area

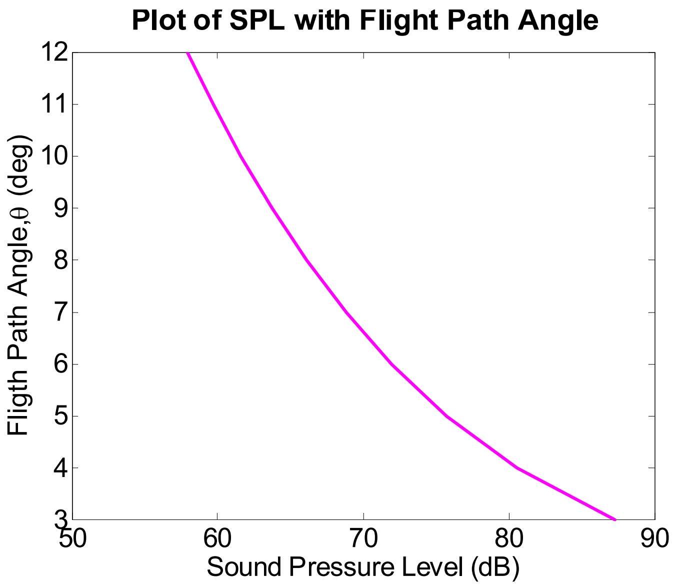
- Wing planform area varied between 300 $m^2$ and 700 $m^2$.
- For a given flight path angle, an increase in the wing area causes a drop in the required approach velocity for equilibrium but this is relatively weak assumption.
- As wing area falls, the approach velocity rises proportionally to $S^{-1/2}$.
- In Lilley's equation, the sound intensity has a velocity dependence to the power of 5. Therefore, the increase in sound intensity is like $S^{-3/2}$.

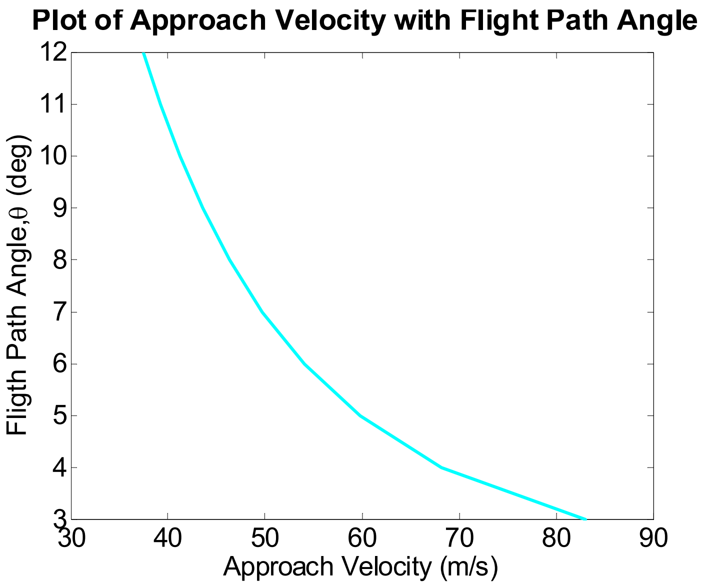




# Variations to Flight Path Angle

- Flight path angle varied from 3º to 12º.
- The SPL in this case changes according to two mechanisms.
- The first is due to that SPL ~1/r$^2$ where r is the distance to the observer.
- The second is due to the fall in approach velocity associated with an increase in the flight path angle for a back-side approach.
- On a front-side approach the benefits are more than outweighed by the associated speed increase.

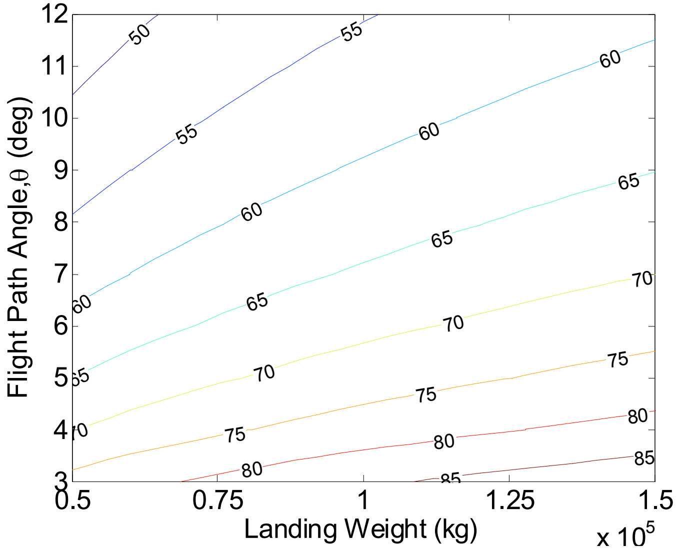




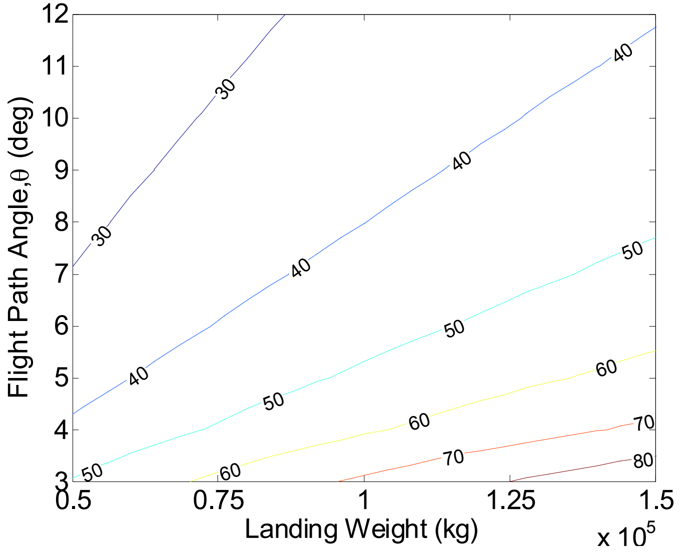
# Variations in Flight Path Angle and Landing Weight

- Landing weight varied from 50 tons to 150 tons.
- The flight path angle is varied from 3º to 12º.
- As the landing weight increases there is an increase in the required approach velocity like $W^{1/2}$.
- This leads to an increase in the sound intensity and SPL.
- The effect is further emphasized due to the direct proportional increases in sound intensity as shown in Lilley's equation.

**Contours of Sound Pressure Level**



**Contours of Approach Velocity**

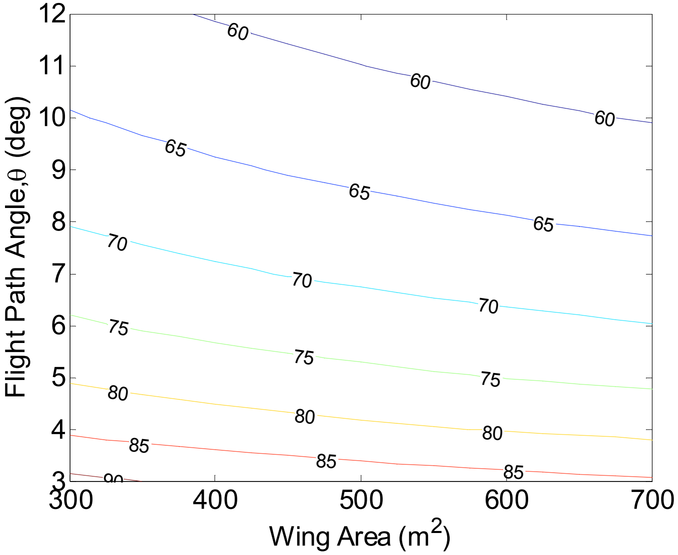


The Cambridge-MIT Institute

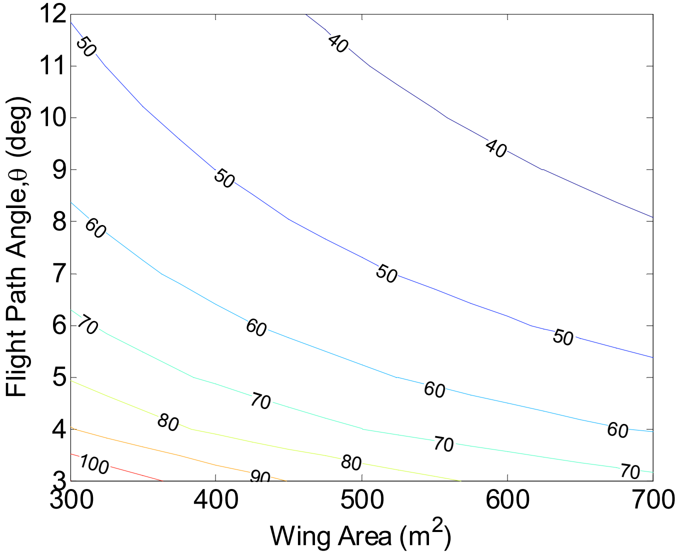
Silent Aircraft Initiative

# Variations in Flight Path Angle and Wing Area

- Wing planform area varied between 300 m$^2$ and 700 m$^2$.
- The flight path angle is varied from 3º to 12º.
- An increase in wing area brings about a decrease in approach speed and a follow on decrease in SPL.
- As the approach angle increases the approach velocity falls and pulls the SPL down as well.



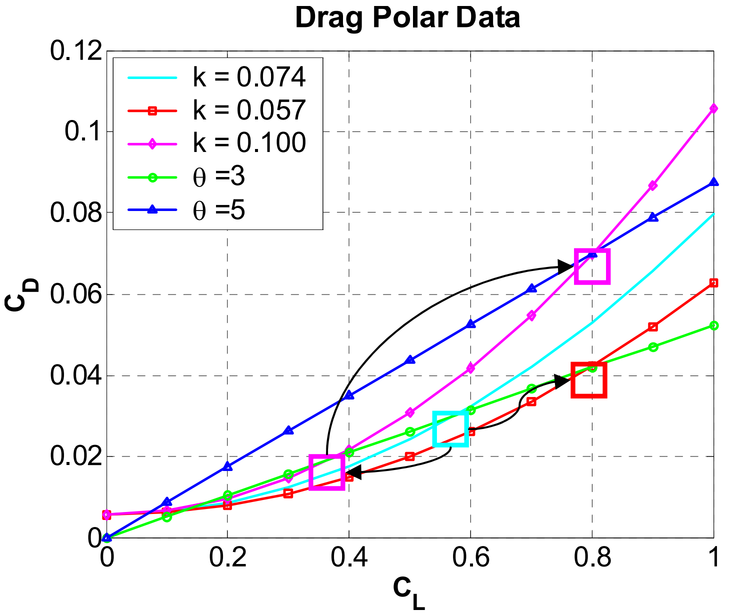
**Contours of Sound Pressure Level**

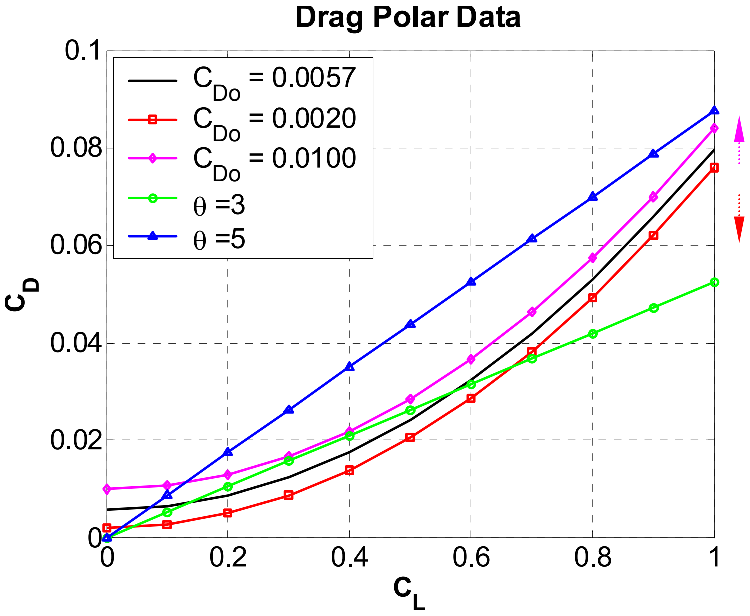


**Contours of Approach Velocity**

# Drag Polar Variations and Changes to Trailing Edge Noise

- The previous subsections described how variations within the aircraft and the approach trajectory affected the noise that was created by the trailing edge of the aircraft for a given drag polar.
- The next section examines how changes in the drag polar affect the sound emission.
- The drag polar is modified by changing the zero-lift drag constant and the lift-dependent drag constant.





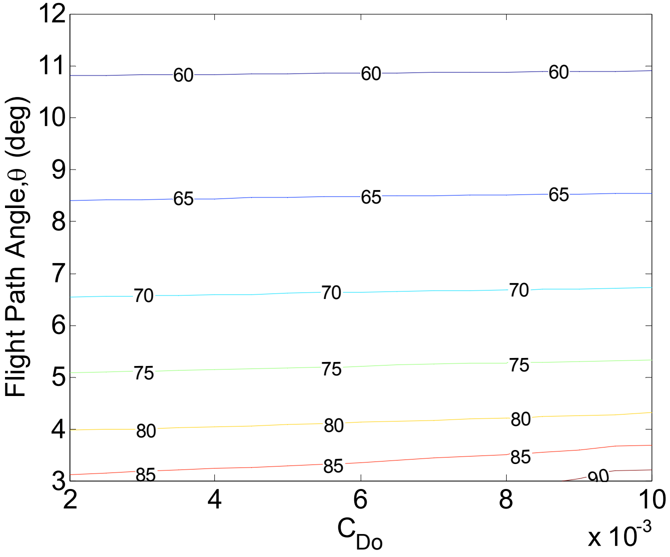
The Cambridge-MIT Institute

Silent Aircraft Initiative

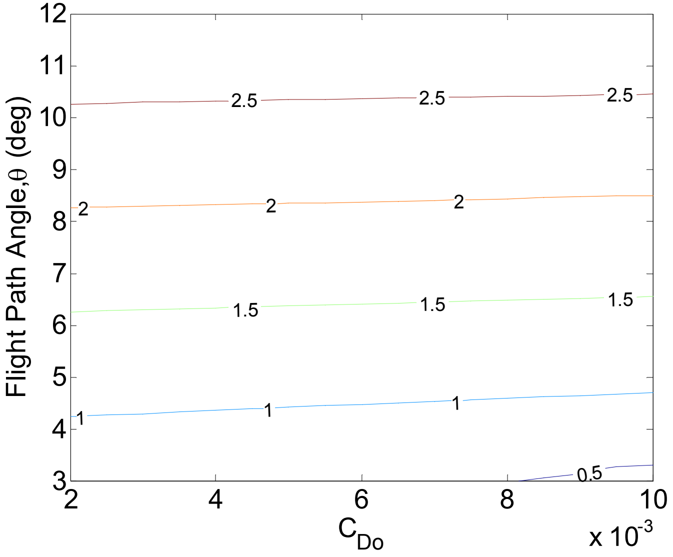
# Variations in Flight Path Angle and Zero-lift Drag

- Zero-lift drag coefficient varied from 0.002 to 0.010.
- Flight path angle varied from 3º to 12º.
- The contours show that changes in $C_{Do}$ have a relatively small effect on the equilibrium $C_L$ and $C_D$ for the back-side solution.
- Hence, the SPL does not change by a large degree.

**Contours of Sound Pressure Level**

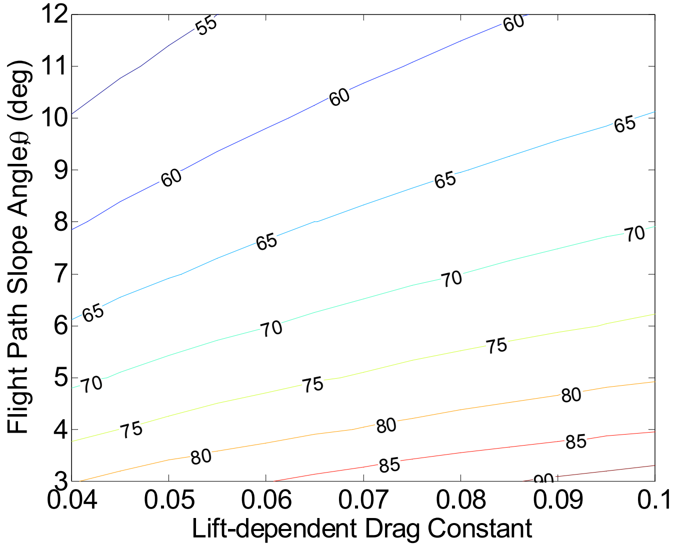


**Contours of Coefficient of Lift**

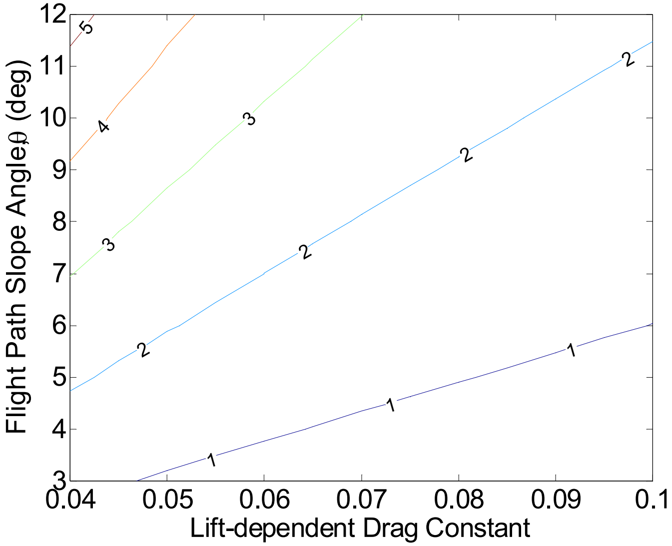


# Variations in Flight Path Angle and Lift-dependent Drag

- Lift-dependent drag constant varied from 0.04 to 0.10.
- Flight path angle varied from 3º to 12º.
- At large values of lift-dependent drag a decrease in SPL is achieved through higher glide slope angles possible for the same $C_L$ values.
- A negative effect is primarily attributed to the increase in velocity brought about by an decrease in $C_L$ for the same glide slope.
- The noise effect is neutral at a combination of a rather higher glide slope and lower $C_L$.



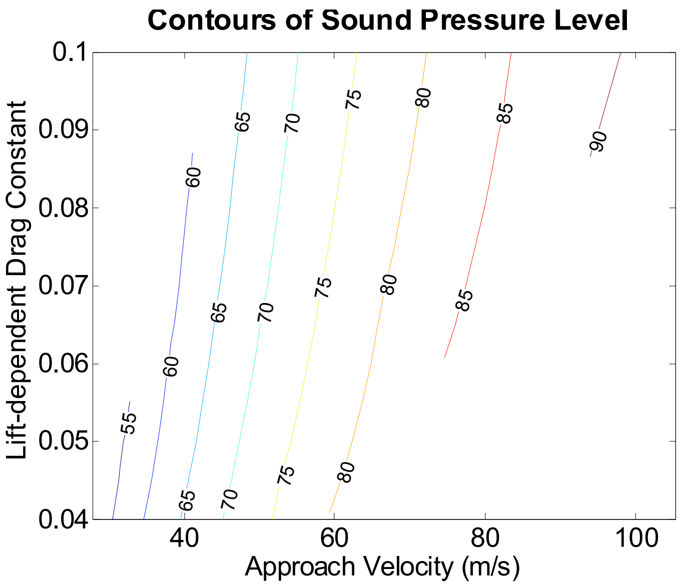
**Contours of Sound Pressure Level**

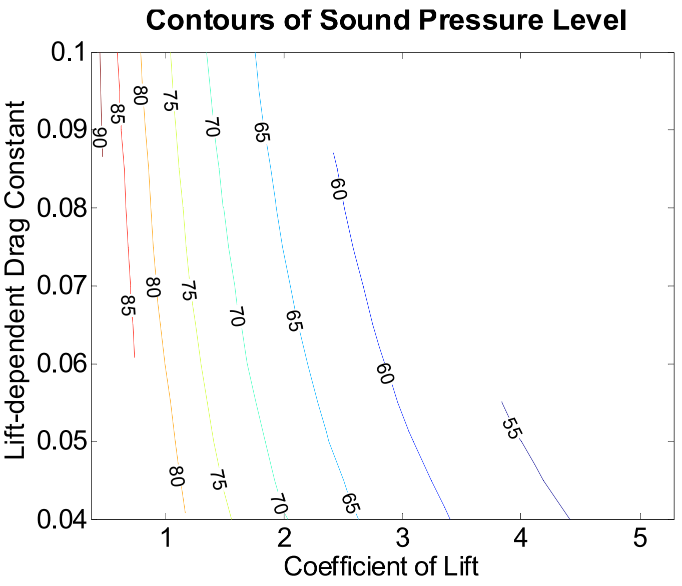


**Contours of Coefficient of Lift**

# Variations in Approach Velocity, $C_L$ and Lift-dependent Drag

- The contours below show the velocity cut-off points due to the flight path angle.
- The edge of the contours are the edges of the flight paths plotted in the previous slides.
- An increase in lift-dependent drag pulls the $C_L$ down, increasing the approach velocity, which in turn causes a significant increase in the overall SPL.
- A benefit of increasing k is that equilibrium flight at larger flight path angles can be achieved, thus increasing the height to the observer and reducing the noise level.





# Conclusions

- Point A is a front-side approach with large velocities. No benefits for flying higher.
- Increasing S reduces speed ⇨ **REDUCES NOISE.**
- Increasing W increases the required $U_o$ ⇨ **INCREASES NOISE.**
- $C_{Do}$ has a minimal effect on the equilibrium $C_L$ and $C_D$ ⇨ **CONSTANT NOISE.**
- Increasing *k* produces higher $\theta$ for constant $C_L$ ⇨ **REDUCES NOISE.**
- Increasing *k* with constant $\theta$ will lower $C_L$ and increase the $U_o$ ⇨ **INCREASES NOISE.**
- $U_o$ is the dominant contributor, so the recommendation is to fly as slow as possible and thus the key requirement is to be able to generate high $C_L$.
- Increasing drag beneficial as this enables flight at large $\theta$ ⇨ **REDUCES NOISE.**
- Paramount that this drag increase needs to be at a high $C_L$

# References

[1] Lockard, D. and Lilley, G. M., "The Airframe Noise Reduction Challenge," Langley Research Centre, Hampton, Virginia, Technical Report, TM-2004-213013, April 2004, pp. 26.

[2] Lilley, G. M., "The prediction of airframe noise and comparison with experiment," *Journal of Sound and Vibration*, Vol. 239, No. 4, 2001, pp. 849-859.

[3] Manneville, A., Pilczer, D., and Spakovsky, Z., “ Noise Reduction Assessments and Preliminary Design Implications for a Functionally-Silent Aircraft,” AIAA 2004-2925, 10 – 12 May 2004.