Omega Aviation in a sustainable world

UNIVERSITY OF Southampton
Institute of Sound and Vibration Research

Advanced Open Rotor Workshop
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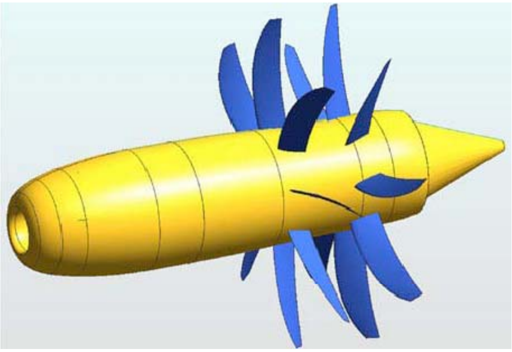
Institute of Sound and Vibration Research
University of Southampton

Advanced open rotor noise prediction methods



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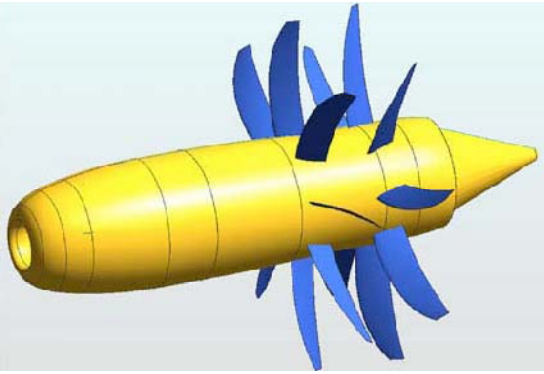
Presentation overview

- Background
  - Advanced open rotor (AOR) architecture
  - Motivation for using AOR aircraft
- Available noise prediction methods
  - To predict sound pressure we need to know the flow over the rotor blades
  - Computational
  - Analytic
- Analytic methods
  - Require induced flow to be expressed as a sum of various ‘sources’
  - Source descriptions
- Whole aircraft noise prediction
  - Installation (radiation and source) effects
  - Propagation effects

Advanced open rotor concept

- Two rows of counter-rotating propellers
  - Swirl off first blade row increases air velocity onto the second blade row
  - Second blade row reduces swirl in wake
  - Much reduced weight and drag compared with a turbofan
  - Unsteady airflow onto the second blade row produces high levels of noise
- Promise significant reductions in fuel burn

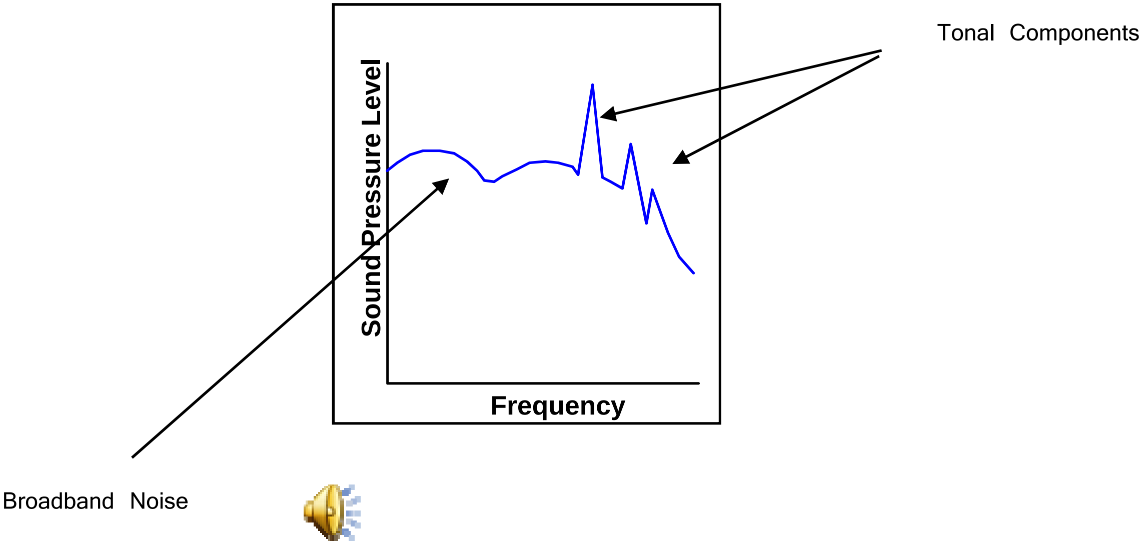


Background

- The AOR concept was considered during the 1980’s in response to high fuel prices at that time because of their good fuel efficiency.
- Development was not pursued for a variety of reasons, however chief among these was that oil prices fell
- Open rotor aircraft are being considered once more because of environmental and economic concerns however, noise is a prominent issue
- The noise spectrum produced by an AOR is expected to be dominated by tones, although there will be a significant broadband contribution
- Tone and broadband noise prediction models are being developed at the ISVR
- Prediction methods can be either analytic or numerical.

Introduction to noise

- AOR's produce both broadband noise and tones



- The human ear responds differently to tones and broadband noise
- Typically noise with tonal contributions are more annoying than purely broadband noise
- Legislation usually penalises tonally dominated noise

Tone Prediction Methods

- Two analytic methods have been identified
  - C. E. Whitfield, R. Mani, P. R. Gliebe (1990) High speed turboprop aeroacoustic study, NASA CR 185242
  - A. B. Parry (1988) Theoretical prediction of counter-rotating propeller noise, PhD Thesis
- Computational schemes (numerous)
  - Time consuming
  - Possibly more accurate
- Experimental validation
  - Extensive NASA report describing experimental validation of Whitfield *et al*. code
  - Some good comparison presented in Parry

Acoustic Radiation Formula

- AOR tones produced by interaction of flow produced by one blade row with the blades on the adjacent row
- An expression for the root-mean square acoustic pressure produced by each interaction tone is given by

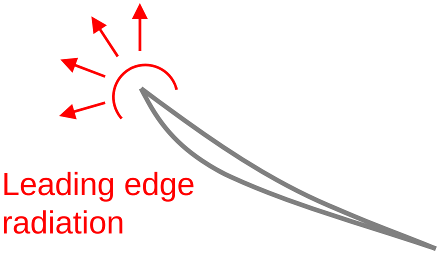
$$p=\frac{BR_t}{2\sqrt{2}\pi r_o\left(1-M_x\cos\theta\right)}\left|\int_{z_h}^{1} S(z)\exp\left\{-i\phi_s\right\}J_\nu\left(\bar{k}mkR_t z\sin\theta\right)dz\right|$$

- ϕ_s is a term due to the sweep of each blade
- J is a Bessel function, whose argument is dependent on observer location and thus greatly affects the 'directivity' of the tone (effectively a directional acoustic efficiency)
- S is a 'source term' which is effectively equal to the unsteady loading on the blade
- In order to calculate the acoustic pressure the unsteady loading terms must be determined for each source

Blade loading

- The unsteady blade loading is estimated using well-known ‘blade response functions’ which express the blade loading as a function of the upwash onto the propeller blades.
- Sears: used for gusts with ‘long’ (relative to the propeller chord) wavelengths

$$\Delta p = -2\rho U_r v_k S(\omega)\sqrt{\frac{c-x}{x}}$$



- Thus the problem reduces to one of finding the velocity field incident onto each propeller blade for each source at any radial location.
- This is done by decomposing the incident velocity produced by each ‘source’ into ‘gusts’ of the form

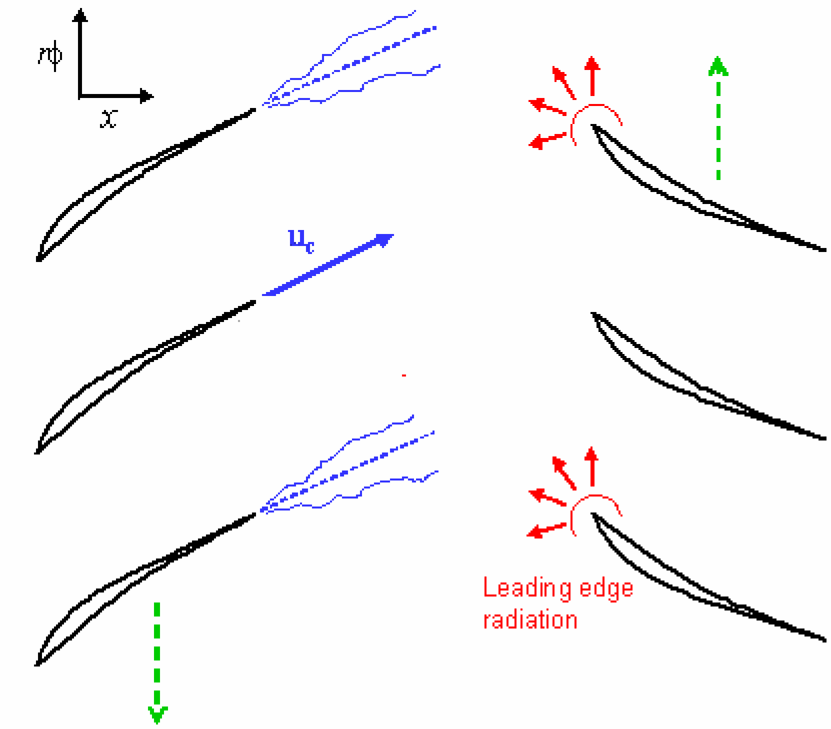
$$v_k \exp\{i\omega t + ikx\}$$

Tone Sources

- There are several sources of noise produced by an AOR…
- Rotor alone tones
  - Produced by rotating thickness and steady loading sources
  - The acoustic source term is calculated directly from the lift and drag data, which is usually provided by the propeller manufacturer, or could be calculated to a moderate degree of accuracy from simple aerodynamic theory

Tone Sources

- Viscous wake interaction tones
  - Produced by the wake from an upstream blade or pylon interacting with downstream rotor blades

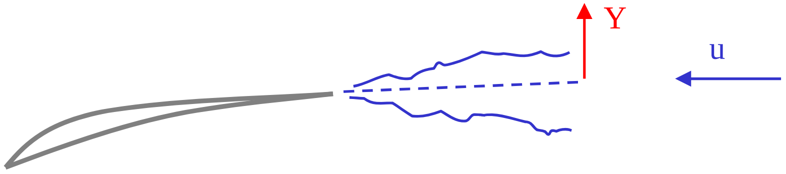


Tone sources

- Viscous wake interaction tones
  - Parry gives several expressions for the wake deficit velocity as a function of upstream rotor drag, chord length and separation distance between the upstream and downstream propellers.

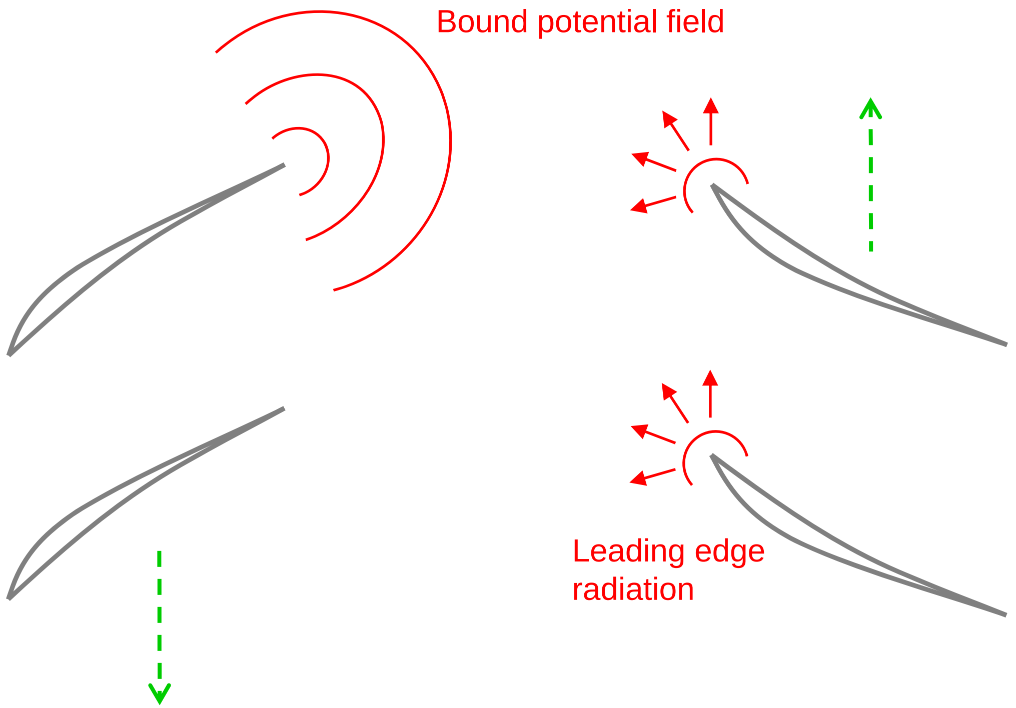
$$u = 2U_\infty \left(\frac{\ln 2}{\pi}\right)^{1/2} \left(\frac{cC_D}{X}\right)^{1/2} \exp\left\{-\frac{\ln(2)Y^2}{b_{1/2}^2}\right\}$$

'Gaussian' velocity profile



Noise sources

- Bound potential field interaction tones
  - Produced by the bound potential field (due to thickness and circulation) on a blade interacting with passing blades on the adjacent rotor



Bound potential interaction tones

- Parry gives expressions for the upwash onto an adjacent blade produced by the bound potential due to thickness and circulation. A general expression describing the upwash onto the propeller blade is given below

$$v = \sum_{n=-\infty}^{\infty} v_n \exp\{i\omega t - \gamma(X - iY)\}$$

- Note that the upwash decays with streamwise coordinate X, this indicates that increasing the propeller row separation distance will drastically reduce this noise source
- This is different from the wake interaction noise source which decreases far more slowly with propeller row separation distance

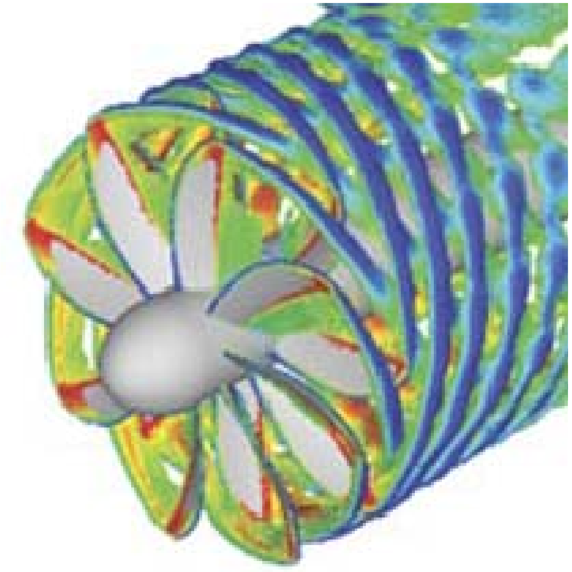
Tip vortex interaction tones

- Tip vortex produced by large lift gradients close to the propeller tip which produce airflow 'across' the blade tip
- Produced by the tip vortex shed from the upstream rotor interacting with downstream rotor blades

Tip-vortex simulation for contra-rotating fans – courtesy DLR

Noise sources

- Tip vortex interaction tones
  - Difficult to predict tip vortex parameters, although an empirical model is available from a NASA study.
  - This is where CFD simulations (such as those being undertaken at Cambridge) could give guidance



Tip-vortex simulation for contra-rotating fans – courtesy DLR

Noise sources

- Tip vortex formulation due to Fukumoto (Phys. Fluids **17** pp, 1-17)

$$\Psi_m = \frac{\Gamma}{4\pi}\begin{cases} r^2/l^2 - \log\left(a^2\right) \\ a^2/l^2 - \log\left(r^2\right) \end{cases} - \frac{\Gamma a r}{\pi l^2}\operatorname{Re}\begin{cases} H_0\left(r/l, a/l, \chi\right) \\ H_0\left(a/l, r/l, \chi\right) \end{cases}$$

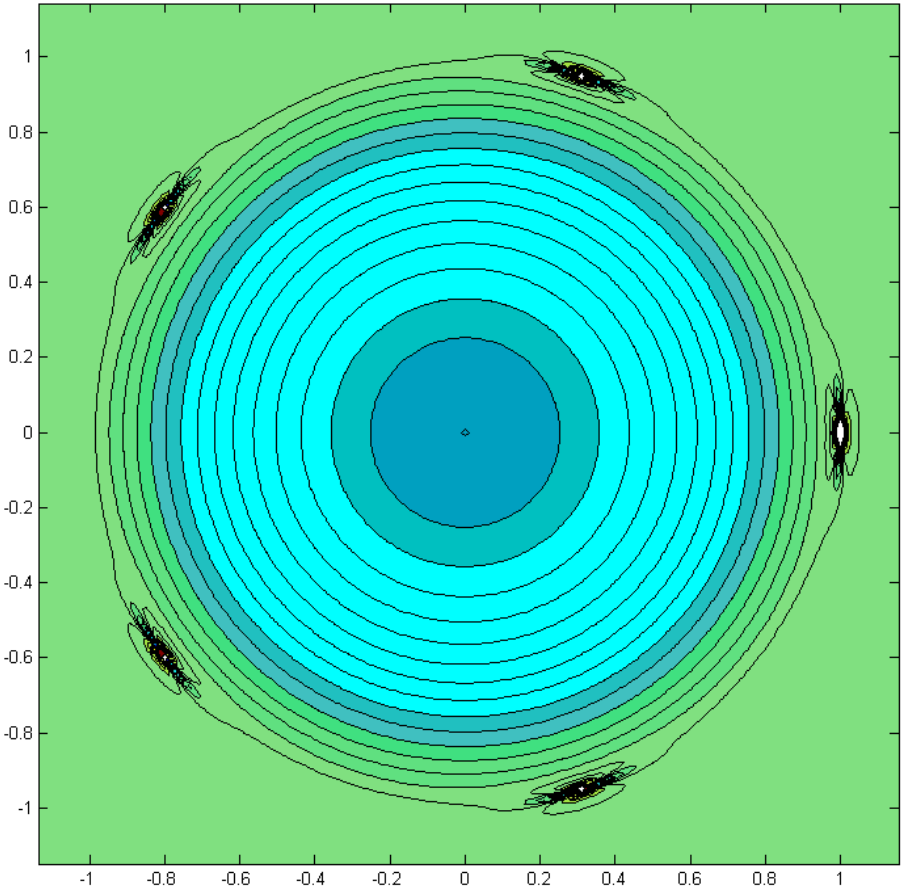
$$H_0(x, y, \chi) = \sum_{m=1}^{\infty} m I_m^{\prime}(mx) K_m^{\prime}(my) \exp(im\chi)$$

- Using these expressions the upwash onto a counter-rotating propeller blade can be expressed in the form

$$v_k \exp\{i\omega t - kx\}$$

Noise sources

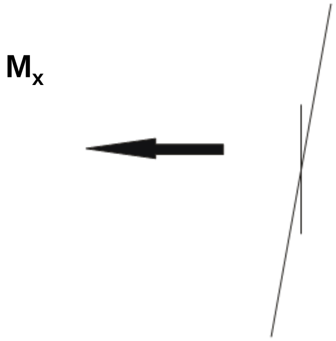
- Stream function (due to tip-vortex) downstream of a five-bladed propeller



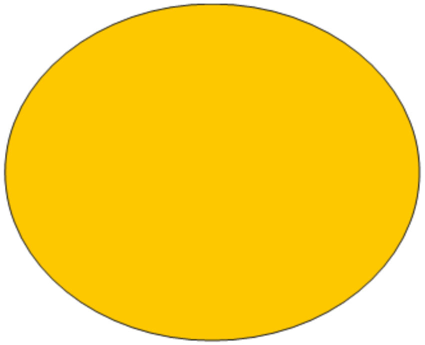
Incidence tones

- Unsteady loading on the blade produced by the propeller propagating at an angle of incidence
  - This results in the blade undergoing a change in angle of attack as it rotates, which produces an unsteady load on each blade
  - The unsteady upwash onto each propeller blade can be expressed as

$$v = M_x c_0 \cos\alpha \sin\alpha_p \cos\left\{\Omega t + \frac{\sin\alpha}{r}(X + s)\right\}$$



Side view

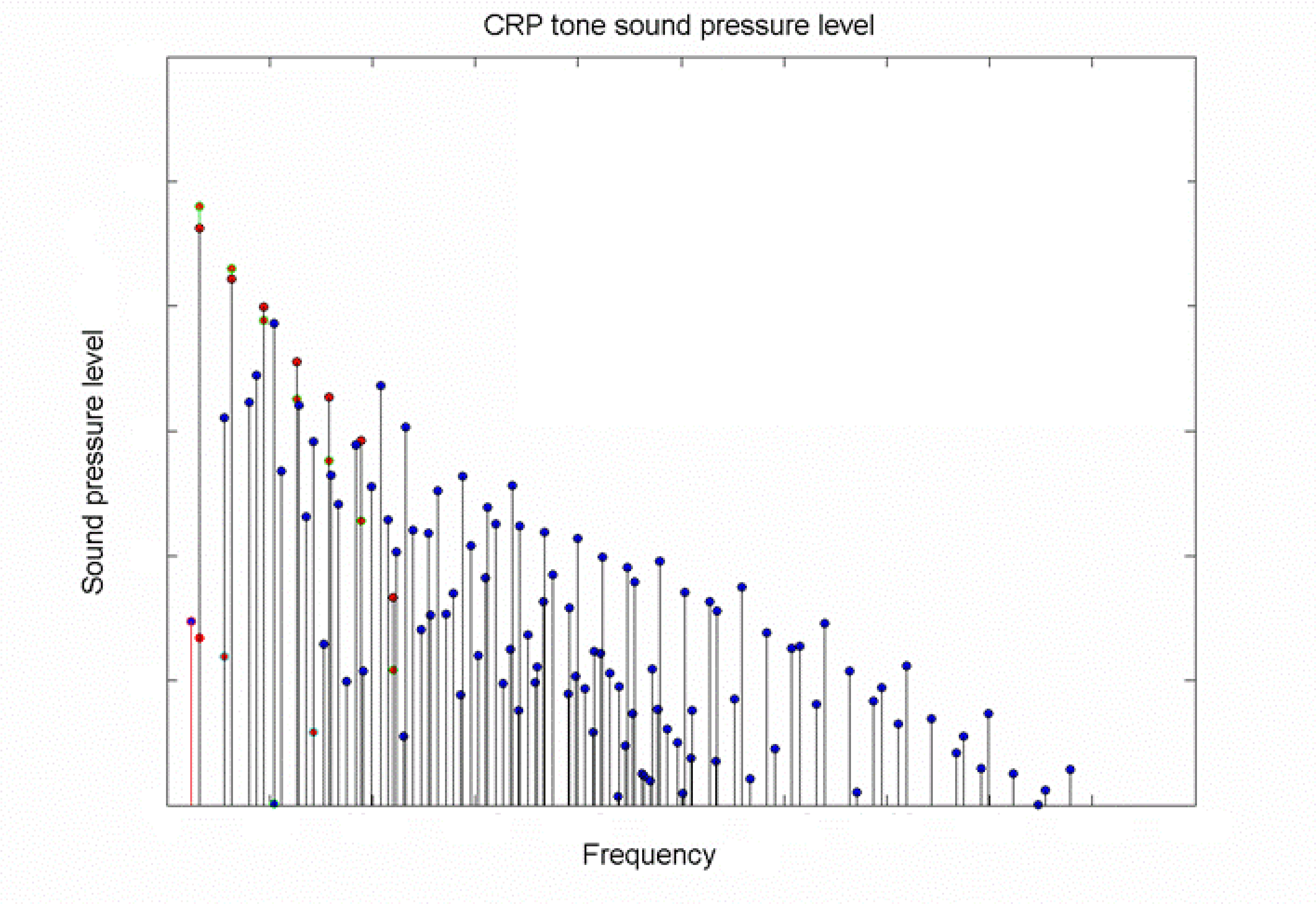


Front view

Noise sources

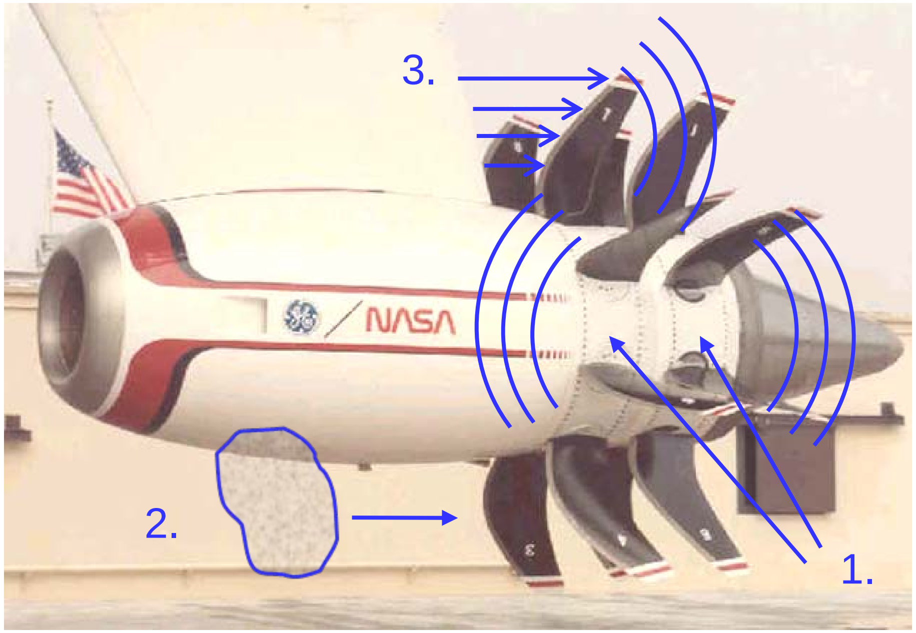
- Steady distortion noise
    - When a spatially varying but steady (in time) flow-field impinges upon the rotor ‘disc’, as the propeller rotates, the upwash onto the blade varies with rotor position. This varying upwash produces a periodic loading on the blade and therefore tonal noise
    - Sources of steady distortion include,
        - Flow over wing
        - Flow over fuselage

Predicted noise spectrum



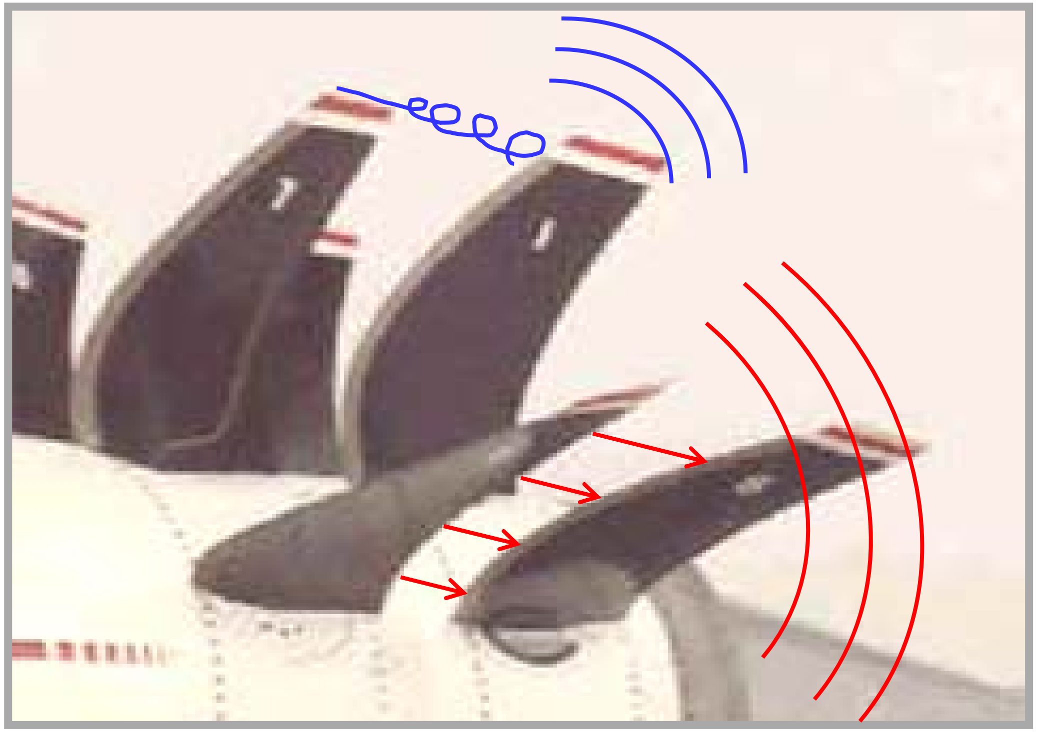
Broadband noise sources

- Rotor self-noise
  - Produced by the turbulent boundary layer on the surface of the aerofoil being 'diffracted' by the propeller trailing edge
- Ingested atmospheric turbulence noise
  - Produced by the ingestion and subsequent interaction of atmospheric turbulence by the propeller blades



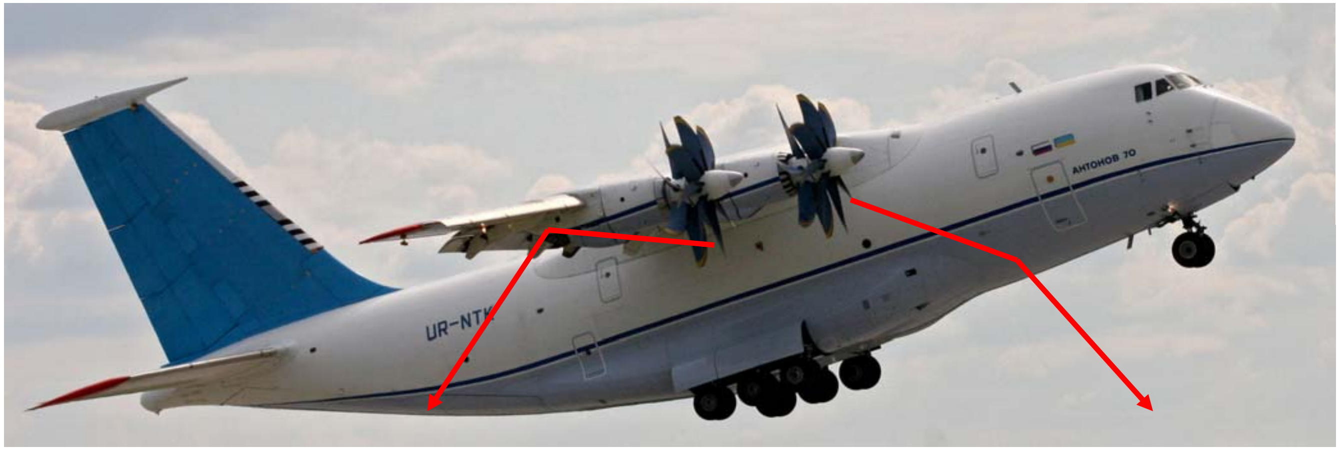
Broadband noise sources

- Rotor turbulent wake interaction noise
  - This is produced when the turbulent wake from the upstream rotor impinges on the downstream rotor producing broadband noise.



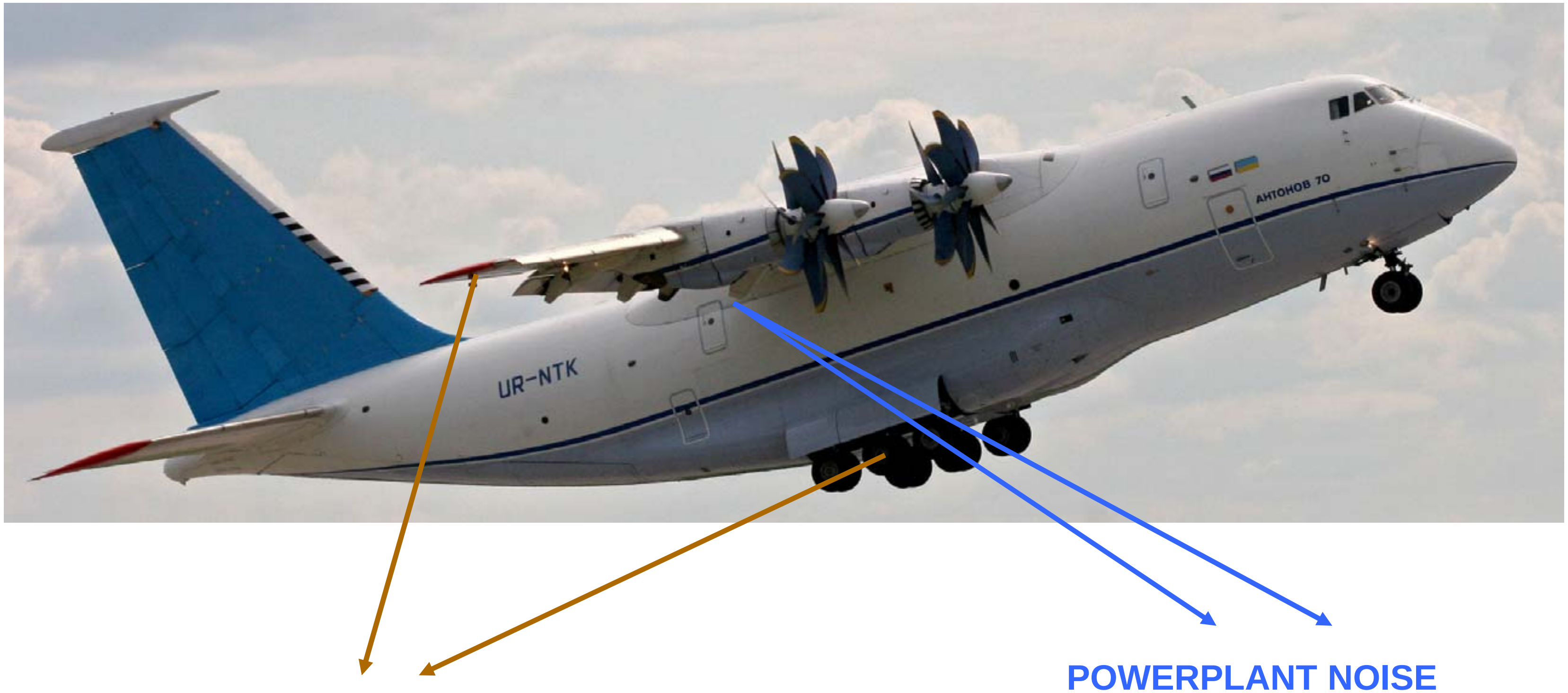
Installation effects

- Reflection off wing and fuselage



- Propagation effects
  - Refraction due to atmospheric conditions
  - Possible 'hay-stacking' which may affect the tonal nature of the spectrum

Other noise sources

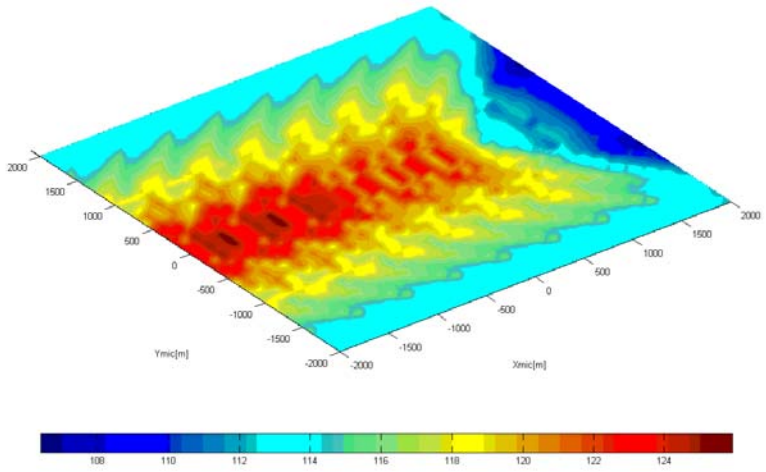


POWERPLANT NOISE

AIRFRAME NOISE

Whole aircraft noise prediction

- The AOR noise models described above can be implemented into a whole aircraft noise prediction scheme and can be used to calculate the noise from an entire airplane including sources such as airframe and core sources
- The whole aircraft noise prediction software SOPRANO can be used to do this.
- A sample ‘footprint’ for a propeller driven aircraft flying over-head is given below.



Summary

- This talk has concentrated on the use of analytic methods for predicting AOR noise
- Analytic methods can be used to produce quick noise predictions which makes them ideal for use as a design tool
- Each source must be considered separately
- The formulation is difficult, however the analytic models give insight into dominant noise sources and what parameters affect them
- Comparisons with experiments indicate a high level of accuracy

Any questions?