isvr Institute of Sound and Vibration Research

Proceedings of The Queen's Anniversary Prize Workshop on Aircraft Jet and Broadband Noise

R.H. Self and P.F. Joseph

ISVR Technical Memorandum 969

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University of Southampton

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UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

FLUID DYNAMICS AND ACOUSTICS GROUP

Proceedings of The Queen's Anniversary Prize Workshop on Aircraft Jet and Broadband Noise

Edited by

R.H. Self and P.F. Joseph

ISVR Technical Memorandum No: 969

January 2007

Authorised for issue by
Professor R.J. Astley
Group Chairman

Proceedings of the Queen's Anniversary Prize
Workshop on
Aircraft Jet and Broadband Noise

held at
Chilworth Manor, Southampton University, 20th September 2006

&

The Queen's Anniversary Prize Lecture

isvr Institute of Sound and Vibration Research

The Queen's Anniversary Prizes 2005

FORWARD

In 2006 the Institute for Sound and Vibration Research was awarded the Queen's Anniversary Prize for Higher and Further Education . The award was made for the ISVR's "Sustained excellence and outstanding achievements in research in the field of sound and vibration". To commemorate the prize a series of lectures was instigated, each to be given by a speaker who is a world renowned authority in his field.

The First Queen's Anniversary Prize Lecture[1] was given by

Philip J. Morris
Boeing/ A.D. Welliver Professor of Aerospace Engineering
Penn State University

To coincide with the Professor Morris's lecture the workshop on Aircraft Jet and Broadband Noise was organised.

[1] Professor Morris's Lecture is given as an Appendix to these Proceedings

WORKSHOP ORGANISING COMMITTEE

Anurag Agarwal
Rod Self
Phil Joseph
Jeremy Astley

WORKSHOP PANELLISTS

Phil Morris
Paul Stange
Neil Sandham
Chris Morfey
Michel Roger
Stewart Glegg
Nigel Peake
Phil Joseph

ACKNOWLEDGEMENTS

The organising committee wish to thank all those people who helped to make the workshop a success, but especially the invited panel members. Thanks go to Susan Brindle for her invaluable secretarial support. The committee also acknowledge the financial support of the Engineering & Physical Sciences Research Council via grant number EP/E033709/1.

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AGENDA

A WORKSHOP ON

THE STATUS OF METHODS FOR THE PREDICTION OF BROADBAND NOISE

CHILWORTH MANOR, CHILWORTH, SOUTHAMPTON
SEPTEMBER 20, 2006

SCHEDULE

9.30. WELCOME – TEA AND COFFEE

10.00. WELCOME Jeremy Astley

10.10. **JET NOISE**

Introduction from Panel Chairman, Phil Morris

10.20. Industrial perspective from Paul Strange
10.30. Discussion

10.50. Phil Morris
11.00. Discussion

11.20. Neil Sandham
11.30. Discussion

11.50. Chris Morfey
12.00. Discussion

12.30. LUNCH

14.00. **FAN BROADBAND NOISE**

Introduction from Panel Chairman, Stewart Glegg

14.10. Industrial perspective from John Coupland
14.20. Discussion

14.40. Michel Roger
14.50. Discussion

15.10. Stewart Glegg
15.20. Discussion

15.40. TEA

16.00. Nigel Peake
16.10. Discussion

16.30. Phil Joseph.
16.40. Discussion

16.50. CONCLUDING REMARKS – Jeremy Astley
17.00. ADJOURN

OPENING REMARKS

The workshop was opened by Professor Jeremy Astley who began by noting that jet noise and fan broadband noise were among the hardest problems in aeroacoustics. He set out some broad objectives for the day ahead:

- Is there a consensus on the current state of the art with regard to the prediction of jet noise and fan broadband noise?
- Is it possible to make reasonable predictions on the future possibilities for tackling these sources?

The workshop would be divided into two sessions. The morning being devoted to jet noise and the afternoon would be devoted to fan broadband noise.

Professor Astley thanked those responsible for the organisation of the workshop and the invited panel members for their contributions and without further ado handed over to Professor Morris who would chair the jet noise session.

SESSION 1: JET NOISE

Introduction

Professor Philip Morris
Pennsylvania State University

This session is devoted to four invited presentations by panel members each to be followed by a brief discussion.

One may define the state of the art in jet noise prediction by saying that schemes based on Acoustic Analogy methods give very good results for angles greater than about 60 degrees to the downstream axis of the jet. Unfortunately, of course, this does not include the direction of peak noise.

At present, numerical simulations based on RANS and LES show some good results and offer the promise of becoming applicable to more realistic nozzle geometries and engine operating conditions.

To illustrate these observations Professor Morris showed a comparison for an Acoustic Analogy based method prediction with measurement of an isothermal Mach 0.9 jet at several angles to the jet axis. He also showed results from an LES calculation by Shur *et. al.* for a hot Mach 1.56 jet whom Professor Morris considered one of the more successful teams at this form of simulation.[2]

Professor Morris then laid out some questions that he hoped the workshop would address:

- Does the traditional view of convective amplification explain the peak noise radiation in jet noise?
- How do you calculate broadband shock-associated noise for general jet geometry or operating condition?
- Is there hope for a theory to explain how the large scale structures in the jet radiate noise at subsonic speeds without resorting to a direct calculation?
- What is the future of RANS and LES techniques for jet noise prediction?
- What is the impact of Reynolds number on noise generation?

The invited panellists for the session are:

- Dr Paul Strange of Rolls-Royce who would give an industrial perspective on the problem of jet noise

[2] The slides used by Professor Morris in his introductory remarks form the first few slides in his invited presentation that can be found below.

- Professor Philip Morris would address the question of convective amplification
- Professor Neil Sandham of Southampton University would speak about progress in numerical modelling --- in particular a nonlinear interaction model for subsonic jet noise and the status of LES
- Professor Chris Morfey of the ISVR would discuss our understanding of the physics of jet noise and the usefulness of RANS based methods.

Invited Presentation:
The Status of Methods for the Prediction of Broadband Noise
An Industrial Perspective on Jet Noise

Paul Strange
Team Leader – Exhaust Noise Component Technology
Rolls-Royce

Dr Strange began by illustrating the continuing importance of the jet noise component of overall aircraft noise. While the problem had been mitigated in the past by the introduction of high bypass ratio (BPR) engines, further improvements were needed if the ACARE targets were to be met. In any case, increasing the BPR was not always an option for some aircraft that would require lower BPR engines. It was also important to balance noise reduction against other concerns such as environmental regulations, operating costs, payload and range, and the needs of customers. These latter considerations would often act as constraints on the viability of proposed noise reduction technologies.

Dr Strange summarized the aero-engine needs as the supply of engines to the customer which satisfy all the relevant noise rules and regulations (and, ultimately, meet the ACARE targets). To do this required they be able:

- to <u>design</u> noise reduction features into the nozzle system which enable a given engine/aircraft to meet the target levels without compromising other engine attributes, e.g. weight, cost, specific fuel consumption (SFC)
- to <u>predict</u> the spectral levels and fieldshapes of the installed engine/aircraft geometry with sufficient accuracy to enable guarantees to be made with confidence

More often than not the industry had in the past relied on an experimental approach to guide them towards quieter engines. However, with the increasingly complex geometries being looked at the sheer number of parameters involved implies that any experimental programme on its own would be unmanageably large. Hence there is a growing need for theoreticians to guide experimentalists.

Currently industry relies on database methods (normally from model rig data extrapolated to full scale) and by evolution of the past experience to new engine designs. Thus the approach could be summarised as an empirical one that relied heavily on simple scaling laws. As the symmetries underlying scaling laws are removed (e.g. by introduction of azimuthal variations of the flow by the use of chevrons) there was an increasing need for more sophisticated prediction methods.

RANS cfd has proved a valuable resource in flow prediction and had been used to guide nozzle selection by considering predictions of turbulent kinetic energy and making subjective judgements on the likely resulting noise. However, the more formal predictions of Acoustic Analogy RANS based models had been of only limited use and the question as to the future usefulness of such methods was one of importance. LES methods presently showed promise but were of limited use without reduction in CPU times and extension to higher frequencies than available at the moment.

From an industrial perspective Dr Strange saw the current jet noise challenges as being:

- estimating jet noise levels at the preliminary design stage (particularly for novel designs)
- effect of flow profile changes on jet noise level - radial & circumferential
- establishing the 3D noise field of asymmetric nozzle geometries (source vs. propagation)
- active flow control - predicting the effect of applying time-varying perturbations at or upstream of the nozzle exit plane
- effect of nozzle devices in close-coupled engine installation situations
- predicting coaxial jet shock noise at high Mach number
- predicting jet-wing/jet-flap interaction effects

Open Discussion

Professor Philip Morris asked Paul Strange what he thought the maximum likely benefit of chevrons would be on a commercial engine. In reply Paul stated that the effect depends on BPR. Chevrons lose efficiency as the BPR increases and as velocity ratio (VR) increases. For instance, a Trent 800 with chevrons has a 1dB EPNL benefit but an equivalent Trent 900 or GE90 shows less than 0.5dB of EPNL benefit. He also noted that performance penalties increase as BPR increases.

Dr Ulf Michel (DLR) said that the Stage 4 requirements often mean that manufacturers must accept a performance lose to meet noise restrictions. However, he noted that the new Boeing 787 had chevron nozzles that may imply a performance loss despite them not being needed for noise suppression. He also noted that chevrons could reduce shock noise in cruise and invited Paul Strange to comment.

Paul Strange said that it was difficult to do this as it was not a Rolls-Royce decision but one that had been taken by Boeing who obviously had their own criteria that were commercially sensitive.

Professor Geoff Lilley (University of Southampton) asked Paul to comment on the use of core and bypass chevrons. Paul Strange said that the use of core chevrons was useful for engines with BPR 6 and below but at higher BPR's and VR's bypass chevrons were needed to produce a worthwhile noise benefit. He added that, because of the significant aerodynamic penalty they introduced, it was difficult to imagine combinations of core and bypass chevrons being used on high BPR engines for community noise reduction unless they were deployable.

Professor Jeremy Astley (ISVR) said his question was born of ignorance. If RANS gave a good prediction of TKE changes at 90 degrees would this imply a good prediction of the noise at other angles? Paul Strange replied that he could see no reason why not.

Philip Morris said he would change the line of questioning by asking the following: If Rolls-Royce were offered the chance to reduce noise by 3dB by employing a 1.6:1 aspect elliptic nozzle, would they use it? In other words, how much inertia is there in the industry to radical changes in nozzle design?

Paul Strange said this was a very interesting question and reminded Philip of Paul’s statement that noise reduction technologies needed to be considered in conjunction with other design and commercial considerations. Clearly such a radical change would have severe aerodynamic consequences and there would therefore undoubtedly be reluctance from this quarter. For example, how would the fan be accommodated? If cruise performance considerations indicated a need for a deployable solution then this in turn would raise worries about the fail safe. However, he noted that asymmetry introduced by the pylon gave no thrust penalty.

Geoff Lilley asked whether there was any thrust loss associated with the asymmetric nozzle investigated by Marcus Harper-Bourne (the results from which had been given in Paul’s presentation). Marcus Harper-Bourne (QinetiQ*)* said that he had not measured thrust in the experiments. He also said that it was possible to get noise reduction at certain azimuthal angles from both elliptic and offset nozzles. He felt that this was due to the increased shear layer width giving increased refractive reduction. At polar angles of 90 degrees the noise remained constant.

Dr Anurag Agarwal (ISVR) commented that Dimitri Papamoschou's group from UC Irvine had performed some experimental studies that suggest that jet noise can be reduced by a few dBs by deflecting the bypass stream downwards. Is Rolls-Royce considering such measures?

Paul Strange said that when Rolls-Royce first observed asymmetry effects because of the pylon they sought asymmetric bifurcation geometries that would give a noise benefit (1986 study). The result of this study was that the present arrangement was not far from the optimum. Tests have also recently been carried out at NASA Langley in which vanes have been deployed in the bypass duct of a model-scale BPR8 engine nozzle – see the paper by Henderson, Norum and Bridges.

Dr Jae-Wook Kim (School of Engineering Sciences, Southampton University) asked what determined the shape and number of chevrons. Paul Strange said that while the shape had been refined from simple v’s or castellates, the important factor was found to be the insertion angle --- but that the optimum had not yet be found. In response Dr Kim asked if the problem was universal or whether it depended on Re number, speed etc. Paul said that model scale and full scale measurements compared quite well.

In reference to the last point, Ulf Michel said that when rig measurements were compared with real jet measurements the latter showed an apparent increase in jet noise. Paul Strange disagreed and thought that it was not jet noise that was responsible for the increase. Philip Morris referred to measurements by Viswanathan who had taken very careful steps to exclude core noise and subsequently found very good agreement between model and full scale data.

Dr Brian Tester (ISVR) quoted Dr Mike Fisher's assertion that the fully mixed portion of the jet was always independent of nozzle details and would be the same for all jets of the same thrust. He asked if chevrons were altering this part of the flow. If so, would this represent some sort of breakthrough? Paul Strange answered by saying that chevrons altered the peak frequencies (associated with the end of the potential core (PC)) and that there should be no drop in low frequencies associated with the fully mixed jet. Indeed, if there was a low frequency benefit then this was always at the expense of a thrust loss. He thought that chevrons induce streamwise vorticity and a smaller azimuthal scale leading to enhanced turbulent growth with respect to mean velocity. Professor Morris noted that PIV measurements and LES calculations all show that there is reduction in noise generated from the region at the end of the PC with beneficial chevrons. Geoff Lilley asked for confirmation that the length of the PC was in fact shortened when chevrons were employed. Paul Strange and Philip Morris both agreed that this was the case.

The Status of Methods for the Prediction of Broadband Noise

An Industrial Perspective on Jet Noise

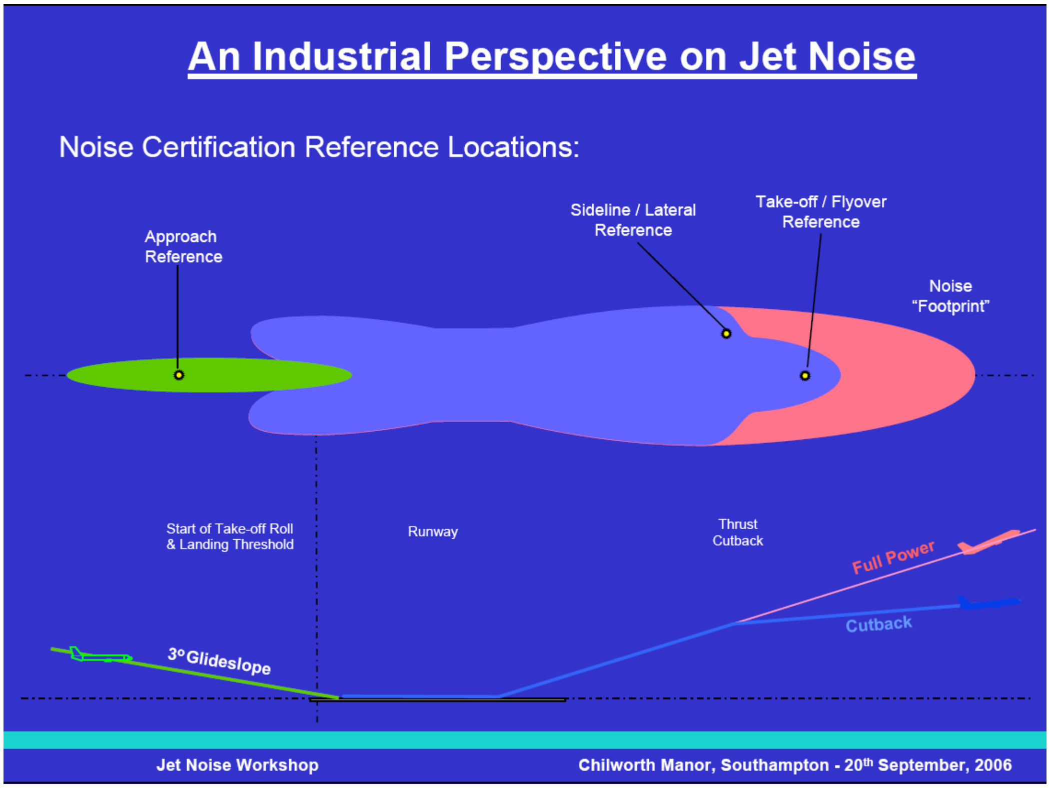
Paul Strange
Team Leader – Exhaust Noise Component Technology
Rolls-Royce

Jet Noise Workshop   Chilworth Manor, Southampton - 20th September, 2006

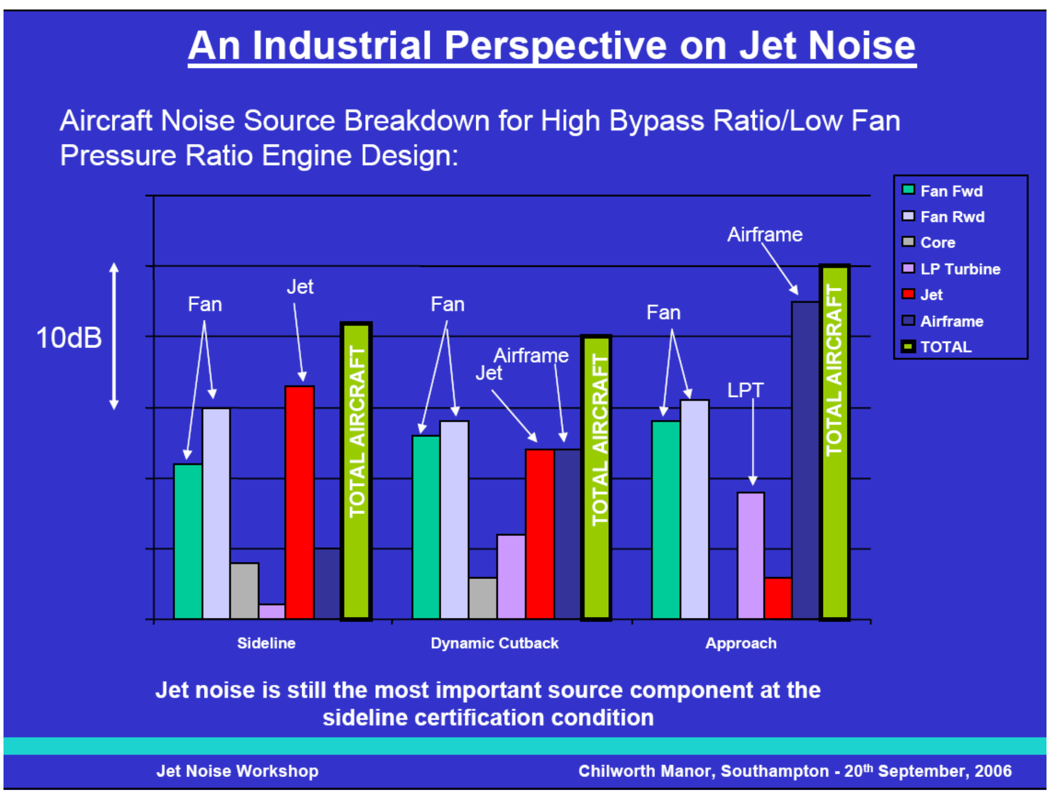
An Industrial Perspective on Jet Noise

Sources of Aircraft Noise

Jet Noise Workshop   Chilworth Manor, Southampton - 20th September, 2006

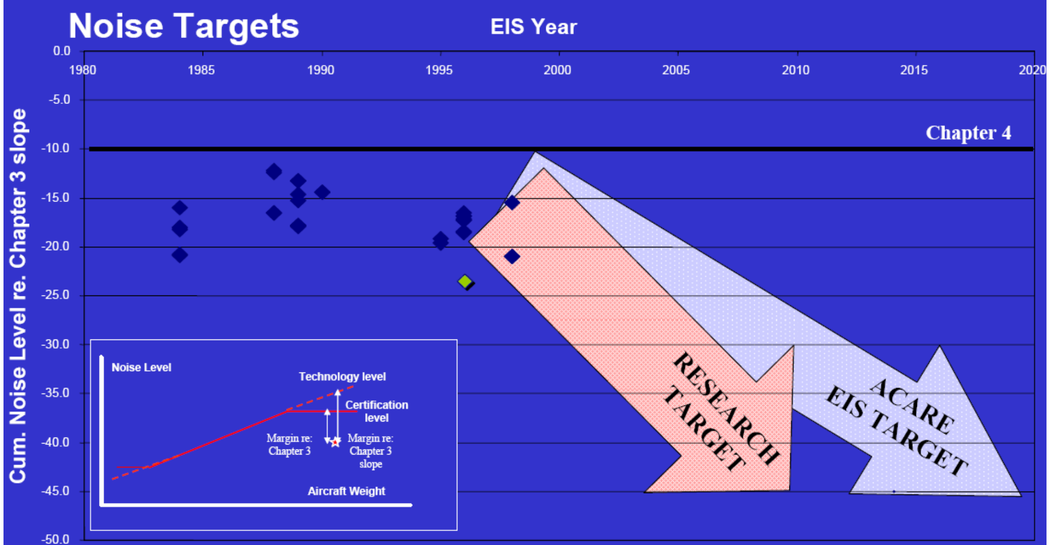


An Industrial Perspective on Jet Noise
Noise Certification Reference Locations:
Approach Reference
Sideline / Lateral Reference
Take-off / Flyover Reference
Noise "Footprint"
Start of Take-off Roll & Landing Threshold
Runway
Thrust Cutback
Full Power
Cutback
3° Glideslope
Jet Noise Workshop
Chilworth Manor, Southampton - 20th September, 2006



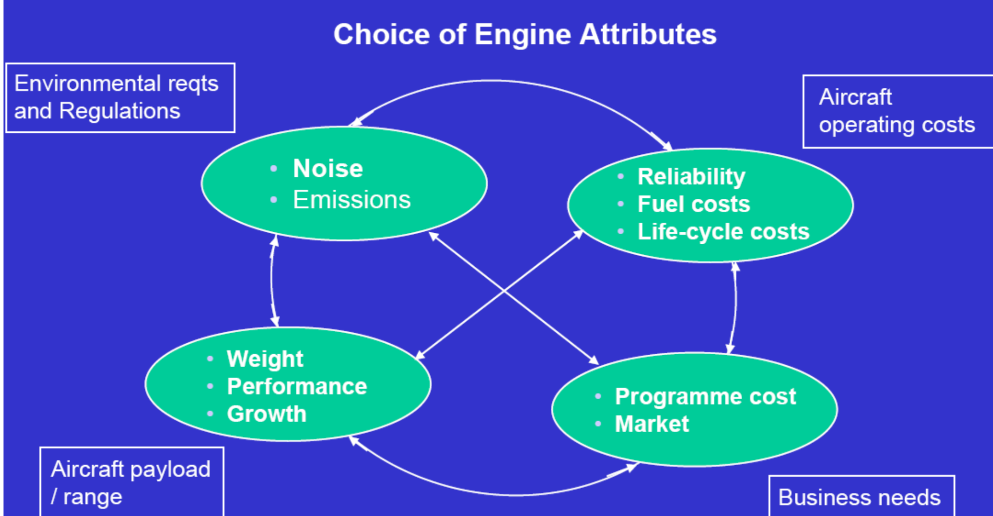
An Industrial Perspective on Jet Noise
Aircraft Noise Source Breakdown for High Bypass Ratio/Low Fan Pressure Ratio Engine Design:
Fan Fwd
Fan Rwd
Core
LP Turbine
Jet
Airframe
TOTAL
10dB
Fan
Jet
TOTAL AIRCRAFT
Fan
Airframe
Jet
TOTAL AIRCRAFT
Fan
LPT
Airframe
TOTAL AIRCRAFT
Sideline
Dynamic Cutback
Approach
Jet noise is still the most important source component at the sideline certification condition
Jet Noise Workshop
Chilworth Manor, Southampton - 20th September, 2006

An Industrial Perspective on Jet Noise



- Reduce perceived noise by half
- Eliminate noise nuisance outside airport boundaries

An Industrial Perspective on Jet Noise



An Industrial Perspective on Jet Noise

The aero-engine industry needs:-

- to supply engines to the customer which satisfy all the relevant noise rules and regulations (and, ultimately, meet the ACARE targets)

  i.e.

  to be able to design noise reduction features into the nozzle system which enable a given engine/aircraft to meet the target levels without compromising other engine attributes, e.g. weight, cost, sfc
  and

  to be able to predict the spectral levels and fieldshapes of the installed engine/aircraft geometry with sufficient accuracy to enable guarantees to be made with confidence

An Industrial Perspective on Jet Noise

Observations

- New ideas for jet noise reduction, though perhaps inspired by the theoretical framework, have more often been developed rather through experimental studies

- It is now becoming more difficult to make progress from experiment alone

  - it is impractical - the large number of parameters involved in the optimisation of noise reduction devices such as passive mixing devices (e.g. serrations), or active flow control, make for a very large programme

  - the empirical correlations rely on evolutionary nozzle geometry designs, with novel designs this approach covers only small ranges of parameters

  but also

  - detailed experiments need to be carried out to validate the computational methods

- The experimentalist and the theoretician need to get to know each other better!

An Industrial Perspective on Jet Noise

Noise Prediction

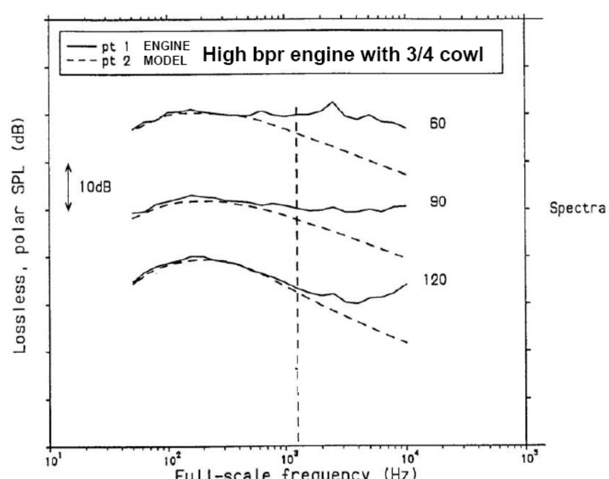
Current Practice - Database

- rig tests of model-scale replicas of the full-scale nozzle geometries
  - the measurements have limited frequency range and/or have been taken in the geometric near field of the source
  - angular range is limited
    - statically, in the forward arc due to size of chamber
    - in flight, in the rear arc due to inaccuracy in refraction corrections
  - azimuthal variation
  - representative inlet conditions? (e.g. boundary layers, flow profiles)
- so, the data is extrapolated at high frequency and extremes of the angular range
- correlations are constructed using simple scaling rules
- measurements obtained with nozzle geometries specific to engine projects are checked against static engine data

An Industrial Perspective on Jet Noise

Noise Prediction

Current Practice



Static Comparison

(1/18 scale model)

An Industrial Perspective on Jet Noise

Yes, really 1/18 scale model!

An Industrial Perspective on Jet Noise

Noise Prediction – Computational Schemes

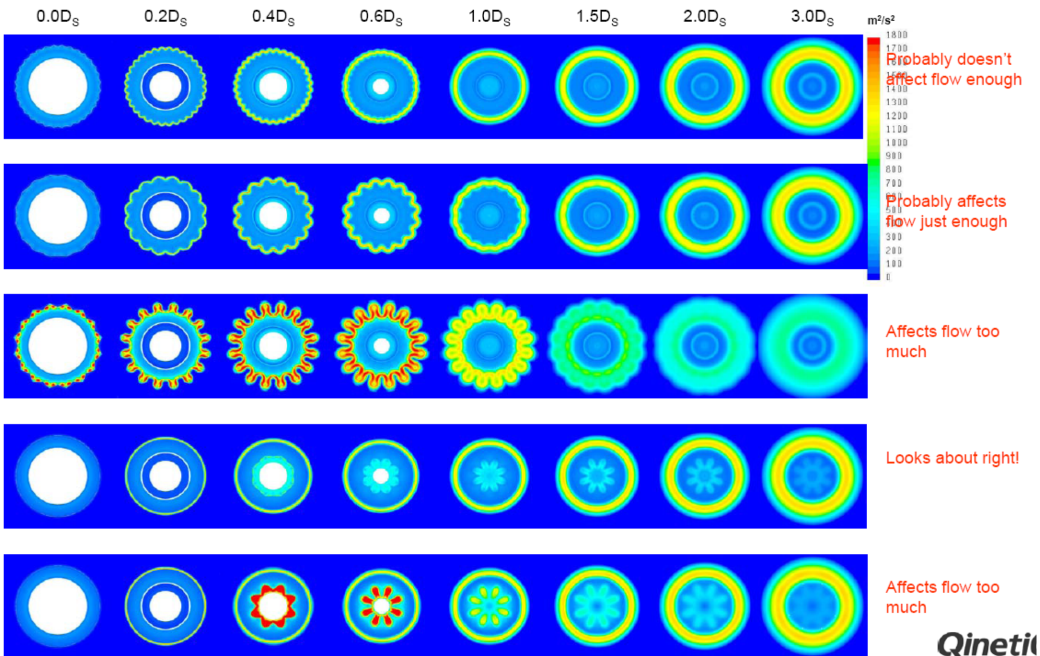
RANS + acoustic model

- flow predictions (kε) have proved to be a useful means of down-selecting nozzle geometries in situations where a number of parameter values need to be chosen simply by examining relative levels of tke (see example on following charts)

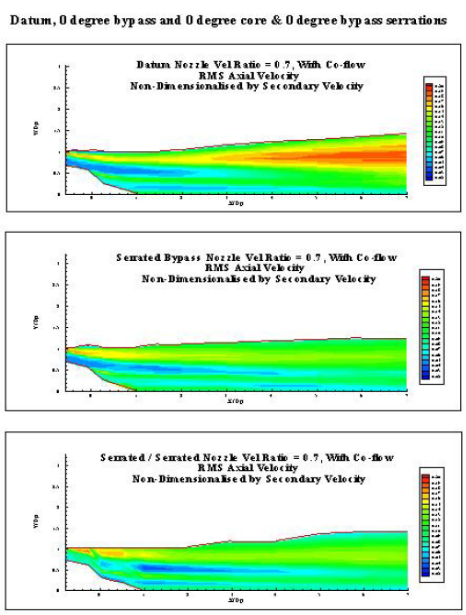
- noise predictions depend on quality of modelling (turbulence & acoustic) and any specific models are not necessarily good in a given situation e.g. vorticity term in Birch et al modelling of chevron hf noise (AIAA 2006-2600)

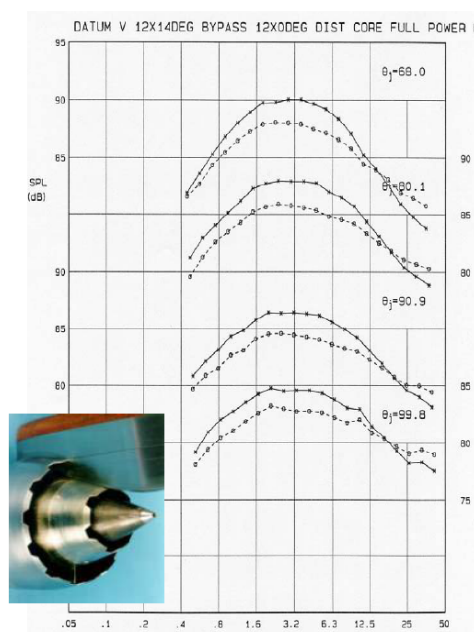
- limited use in active flow control situation?

An Industrial Perspective on Jet Noise



Noise Behaviour Forecast by CFD – Serrated Nozzles Example





An Industrial Perspective on Jet Noise

Noise Prediction – Computational Schemes

LES-based Methods

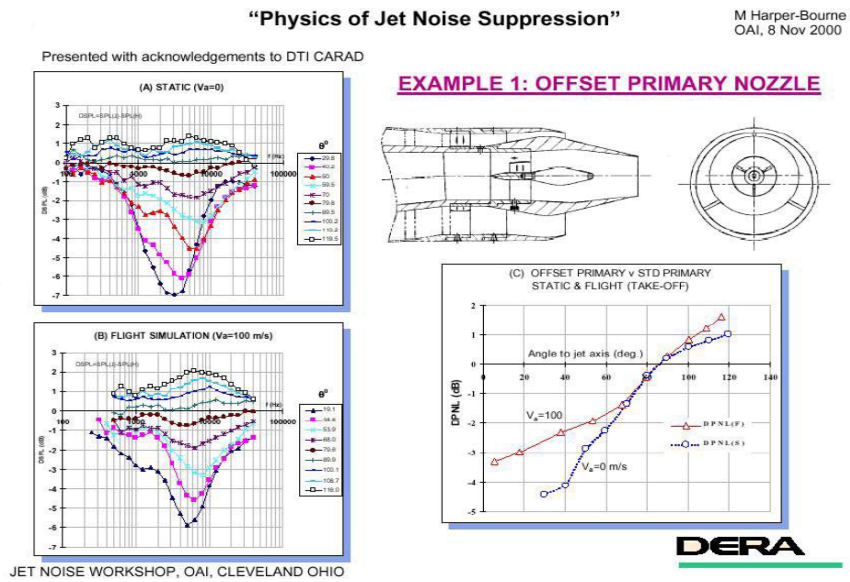
- offer the potential of a more complete approach, but are currently still computationally expensive
  - realistically still limited to quite low frequencies
  - prediction of usefully high frequencies requires dense grids and very small time steps $\Rightarrow$ lot of CPU time for long enough sample
- it would appear that fundamental work still needed in terms of computational schemes & SGS models
- capable of quite good relative predictions, but accuracy of absolute levels needs further work
- in conjunction with advanced analysis techniques being applied to detailed experimental data, they provide an opportunity to study noise generation mechanisms

An Industrial Perspective on Jet Noise

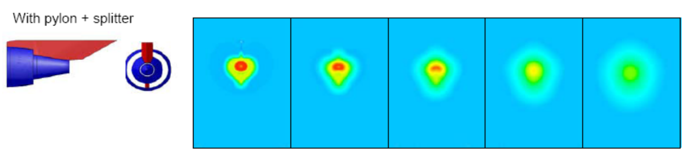
What are the Current Jet Noise Challenges?

- estimating jet noise levels at the preliminary design stage (particularly for novel designs)
- effect of flow profile changes on jet noise level - radial & circumferential
- establishing the 3D noise field of asymmetric nozzle geometries (source vs. propagation)
- active flow control - predicting the effect of applying time-varying perturbations at or upstream of the nozzle exit plane
- effect of nozzle devices in close-coupled engine installation situations
- predicting coaxial jet shock noise at high Mach number
- predicting jet-wing/jet-flap interaction effects

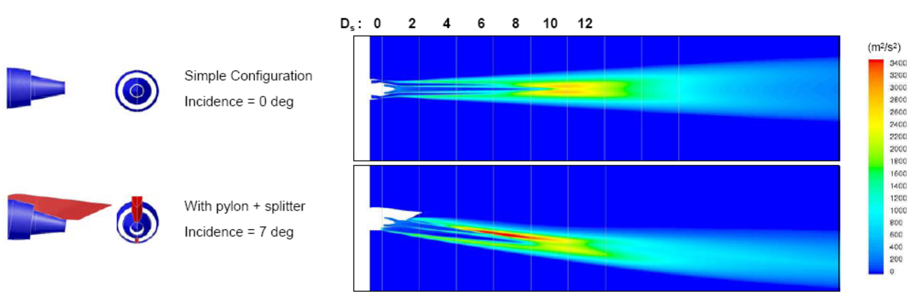
Source & Propagation Effects - Asymmetric Nozzles



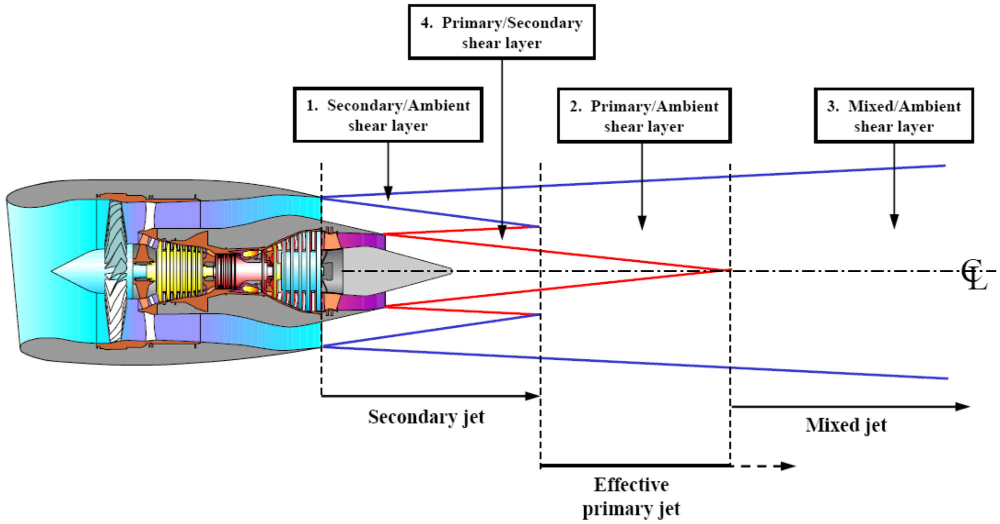
Source & Propagation Effects – Pylons/Bifurcations



Source & Propagation Effects – Incidence Effects



Coaxial Jet Noise Prediction Model - 4 Source Model



Invited Presentation:
Professor Philip Morris
Pennsylvania State University

Professor Morris began his presentation by reminding the audience of the questions he had posed in his introductory talk. The first of these was on the subject of convective amplification and this would form the main part of his talk. However, he wished to start by making a few comments on the other questions.

How do you calculate broadband shock-associated noise for general jet geometry or operating condition? Professor Morris felt that there was hope that this issue could be solved within a RANS based Acoustic Analogy methodology. He looked to an upcoming NASA programme to give some answers.

Is there hope for a theory to explain how the large scale structures in the jet radiate noise at subsonic speeds without resorting to a direct calculation? The answer here was very probably and Professor Morris hoped that some results would be forthcoming at the next AIAA conference.

With regard to the question on the future of RANS and LES techniques for jet noise prediction, Professor Morris thought the situation very healthy, but configurations computed need to be more realistic. Lastly, he thought that the impact of Reynolds number on noise generation was probably not great once the Reynolds number exceeds 300,000. Simulations at lower Reynolds numbers can help in the understanding of basic physics of sound generation – but, like experimental data, one needs to know how to analyze the vast amount of data. However, he noted that for chevron nozzles there was some ambiguity regarding the correct lengthscale in deciding the Re number.

Returning to the main subject of his presentation, Professor Morris stated that the answer to the question of whether the traditional view of convective amplification explains the peak noise radiation in jet noise was a simple no![3]

He began by outlining the classical view of noise directivity and referred to the question of fixed v. moving frame analyses that had occupied early researchers. Using a Gaussian model for the cross-correlation he showed that if the mathematics was done properly the result of 5 powers of Doppler amplification was found in both the fixed and moving frames. However, he also noted that Lighthill's theory used a far field approximation and therefore the frame transformations need only to be applied to radiating wavenumbers to obtain equal results.

This is not simply a matter of convenience since one should model the statistics in the same frame as the measurements were performed, i.e. the fixed frame. Referring to the work of Marcus Harper-Bourne this was a more realistic reflection of the physics given in the fixed frame and resulted in 3 powers of Doppler factor amplification at high frequency with little or no amplification at low frequencies.

[3] Professor Morris added that this categoric statement was made to stimulate subsequent discussion. It is not a closed question by any means.

Professor Morris then went on to question the use of a Green's function associated with a moving source. If a fixed frame analysis is performed then the source convection is already accounted for in the cross-correlation model so isn't use a moving source Green's function a type of double counting? He referred to measurements by K. Viswanathan of Boeing and showed results at various angles (measured w.r.t. upstream axis) plotting the effective amplification factor against St number for different jet Mach numbers. He noted that the results showed no amplification at low frequencies and that the peak frequency did not shift at higher Mach numbers (classical theory would indicate a Doppler shift). These results indicated that while OASPL may well vary as U^8, the SPL does not follow this rule at angles other than 90 degrees. This was confirmed by the plot of Viswanathan for spectra at 125 degrees that collapsed when a $U^{7.98}$ dependency was assumed. If convective amplification was real then the data would not do this.

Open Discussion

Professor Geoff Lilley (Southampton University) asked if Professor Morris was saying that refraction explains the results. Philip Morris responded by saying that mean flow acoustic interaction effects are very real and are reasonably well explained by solutions to Lilley's equation. Refraction does generate a zone of relative silence. However, it is possible that if the noise in the peak noise direction is generated by alternative noise source mechanism (see Professor Sandham's presentation), it might be unaffected by refraction effects.

Commenting on the use of a moving source Green's function, Professor Chris Morfey (ISVR) said that there was no obvious reason apart from say flight effects. For a geometric acoustics (GA) model it may be of some benefit but it was not normally justified. Professor Morris agreed that for looking at some mean flow effects it made sense to employ the moving formulation. They also agreed that these cases could be effectively covered if one said that the correct frame was one fixed to the jet nozzle.

Dr Ulf Michel (DLR) thought that the only correct way of describing jet noise was with a fixed frame analysis because this was the frame of the observer. The double integral occurring in a Lighthill type calculation was only valid in a fixed frame because the volumes are functions of time. He referred to the work of Michalke and went on to say that he thought directivity arose as a result of interference within the usource region --- coherence changes with directivity because the coherence lengthscale changes.

Professor Morris responded to Ulf's comments by agreeing that the work of Michalke had been generally overlooked.

Dr Brian Tester (ISVR*)* reminded the participants of the work of Mani in the early 1970's who had used a moving source Green function model within a fixed jet. This approach had, he thought, confused a lot of the early research in mean flow-acoustic interaction.

Professor Peter Davies (ISVR) said that it was common to employ reciprocity when using Green's functions but that this didn't work when flow was present. He noted that a moving source Green's function would violate conservation and questioned its use on this basis. Philip Morris said that some of the difficulties were overcome using an adjoint methodology but noted that the fixed frame was the correct one to employ this technique.

Marcus Harper-Bourne (QinetiQ) commented that he had performed the measurements referred to by Professor Morris at only one point in the jet. There was therefore doubt concerning how the results would scale at other positions. Philip Morris said that he dearly wished that Marcus had in fact made measurements at other points! He reminded Marcus that he had deduced 3 (as opposed to the classical 5) powers of Doppler amplification with the assumption that the U^8 law was valid at all angles, the suggestion he was making was that this latter assumption might not be correct. Marcus responded that he did not agree with this --- it was true that 5 powers appeared to be incorrect, but convective amplification was *St* number dependent --- at *St* about 1 it happened to be well fitted by 3 powers of Doppler.

Professor Geoff Lilley commented that in both his early and his later work on this subject he had always found a need for both convective amplification and a Doppler shift and that he felt the U^8 worked well if they were both included.

Dr Brian Tester said that the U^8 law certainly held at 90 degrees for isothermal jets. However, he noted that the entropy source present for hot jets scaled differently.

Professor Morris concluded the discussion by saying that although no consensus had been reached he hoped that what had clearly come out of it was that we should not automatically assume that what was done 50 years ago (and may well have been reasonable given the then state of knowledge) was telling us the whole truth. There was clearly much work to be done before this issue would be settled.

Broadband Noise Prediction

Introduction

Philip J. Morris
Penn State University

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State of the Art

- Prediction schemes based on an acoustic analogy now provide excellent predictions for a wide range of operating conditions – but only at angles greater than 60-70 degrees to the jet downstream axis
- Numerical simulations using hybrid RANS/LES methods have shown great promise with good predictions for a wide range of operating conditions and jet geometries

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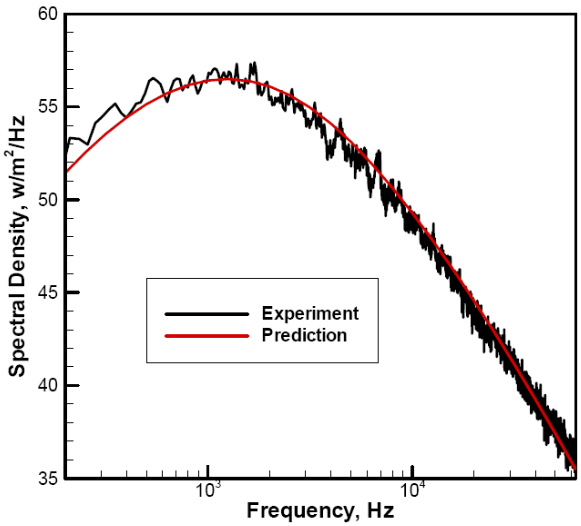
Predicted Spectral Density at 90º

$$M_j = 0.9, T_t / T_o = 1.0$$



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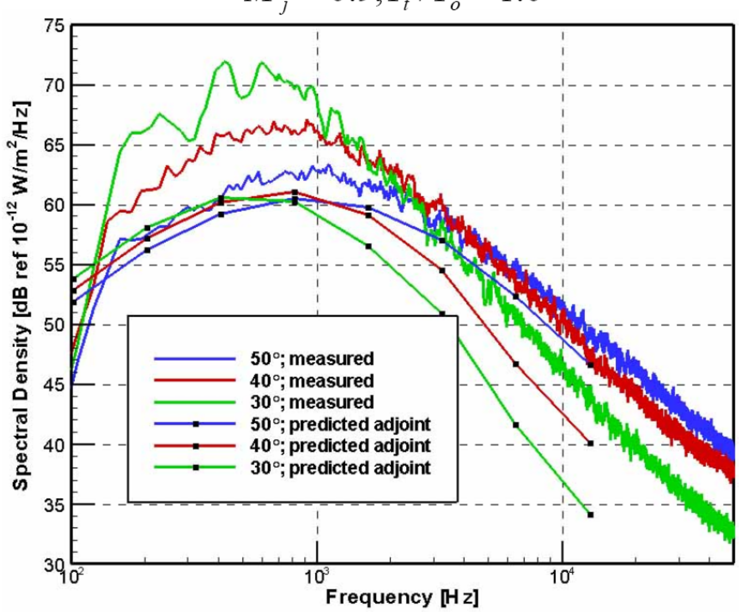
Predicted Spectral Density in Peak Noise Directions

$$M_j = 0.9, T_t / T_o = 1.0$$



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Jet Flow and Noise Simulations

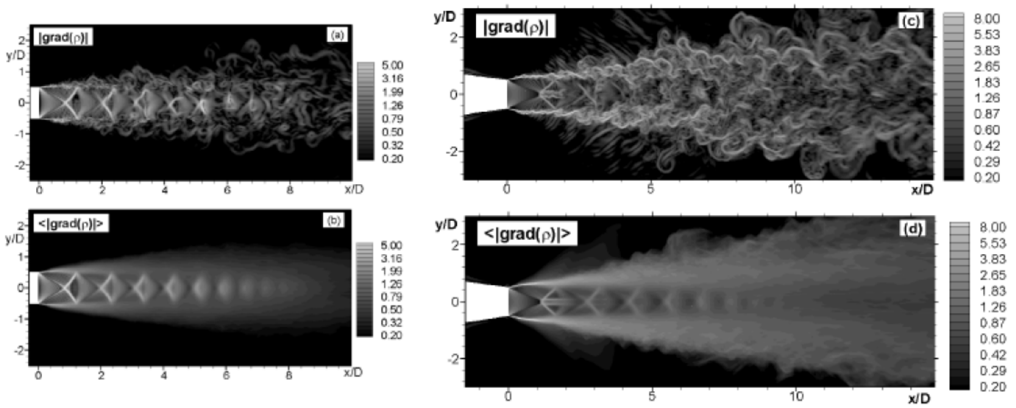

Figure 3. Snapshots (a, c) and time-average (b, d) of magnitude of density gradient ("numerical Schlierens") for the cold (a, b) and hot (c, d) sonic under-expanded jets.

Jet Flow and Noise Simulations

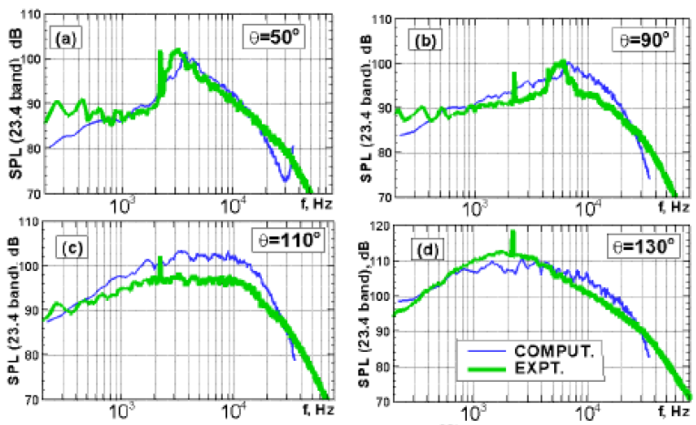

Figure 6. Computed and measured[21] narrow-band SPL spectra for the hot sonic under-expanded jet at M_{FE}=1.56. Distance 98 diameters.

Questions

- Does the traditional view of convective amplification explain the peak noise radiation in jet noise?
- How do you calculate broadband shock-associated noise for general jet geometry or operating condition?
- Is there hope for a theory to explain how the large scale structures in the jet radiate noise at subsonic speeds without resorting to a direct calculation ?
- What is the future of RANS and LES techniques for jet noise prediction?
- What is the impact of Reynolds number on noise generation ?

Panelists

- Paul Strange – an industrial perspective
- Phil Morris
- Neil Sandham
- Chris Morfey

- Each panelist will have 10 minutes for presentation followed by 20 minutes of discussion

Questions

- Does the traditional view of convective amplification explain the peak noise radiation in jet noise?
- How do you calculate broadband shock-associated noise for general jet geometry or operating condition?
- Is there hope for a theory to explain how the large scale structures in the jet radiate noise at subsonic speeds without resorting to a direct calculation ?
- What is the future of RANS and LES techniques for jet noise prediction?
- What is the impact of Reynolds number on noise generation ?

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Questions

- Does the traditional view of convective amplification explain the peak noise radiation in jet noise?
- How do you calculate broadband shock-associated noise for general jet geometry or operating condition? Upcoming NASA program.
- Is there hope for a theory to explain how the large scale structures in the jet radiate noise at subsonic speeds without resorting to a direct calculation? Very probably
- What is the future of RANS and LES techniques for jet noise prediction? Very healthy, but configurations need to be more realistic.
- What is the impact of Reynolds number on noise generation? Probably not a great impact once the Reynolds number exceeds 300,000. Simulations at lower Reynolds numbers can help in the understanding of basic physics of sound generation – but, like experimental data, one needs to know how to analyze the vast amount of data

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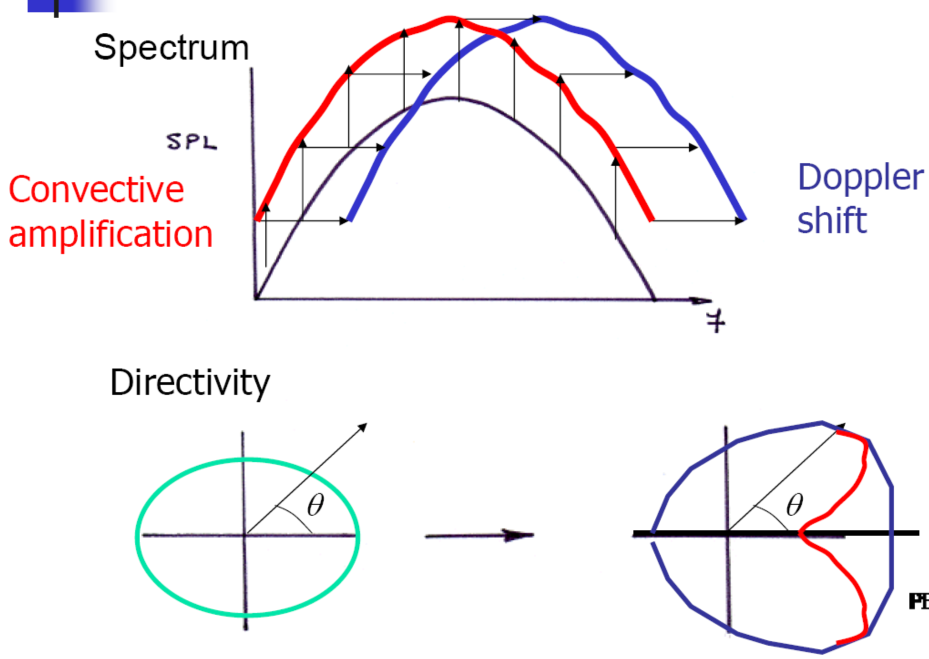
Answers

- Does the traditional view of convective amplification explain the peak noise radiation in jet noise? No.
- How do you calculate broadband shock-associated noise for general jet geometry or operating condition?
- Is there hope for a theory to explain how the large scale structures in the jet radiate noise at subsonic speeds without resorting to a direct calculation ?
- What is the future of RANS and LES techniques for jet noise prediction?
- What is the impact of Reynolds number on noise generation ?

Classical View of Noise Directivity



Outline

- Fixed versus moving frame analysis
- Effect of choice of statistical model
- Green's function for a moving source?
- Experimental evidence
  - Doppler shift
  - Data collapse

Fixed Versus Moving Frame

- Use Lighthill's analogy for convenience
- Fixed frame analysis -Far field spectral density

$$S(\mathbf{x},\gamma)=\frac{1}{16\pi^2 a_o^{\ 4}}\int_{V(\mathbf{y})}\gamma^4 H_x^{\ f}\left(\mathbf{y},\frac{\gamma\mathbf{x}}{a_o x},\gamma\right)d\mathbf{y}$$

- Moving frame analysis

$$S(\mathbf{x},\gamma)=\frac{1}{16\pi^2 a_o^{\ 4}}\int_{V(\mathbf{y})}\gamma^4 H_x^{\ m}\left(\mathbf{y},\frac{\gamma\mathbf{x}}{a_o x},\gamma\left(1-M_c\cos\theta\right)\right)d\mathbf{y}$$

Coordinate Transformation

- It would appear that, for equal far field spectral density,

$$H_x^{\,f}\left(\mathbf{y},\frac{\gamma\mathbf{x}}{a_o x},\gamma\right)=H_x^{\,m}\left(\mathbf{y},\frac{\gamma\mathbf{x}}{a_o x},\gamma\left(1-M_c\cos\theta\right)\right)$$

- But, this needs only to be satisfied for the radiating wavenumbers

Particular Example -Gaussian

- Let the cross-correlation in the moving frame be modeled by,

$$R_x^{\,m}\left(\mathbf{y},\delta,\tau\right)=\rho_s^{\,2}u_s^{\,4}\exp\left[-\left(\frac{\delta_1^{\,2}}{\ell_x^{\,2}}+\frac{\delta_2^{\,2}}{\ell_\perp^{\,2}}+\frac{\delta_3^{\,2}}{\ell_\perp^{\,2}}+\omega_s^{\,2}\tau^2\right)\right]$$

- Then,

$$S\left(\mathbf{x},\gamma\right)=\frac{1}{16\pi^2 a_o^{\,4}}\int\limits_{V(\mathbf{y})}\left(\frac{\gamma}{\omega_s}\right)^4\ell_x\ell_\perp^{\,2}\omega_s^{\,3}\rho_s^{\,2}u_s^{\,4}\exp\left[-\frac{\gamma^2C_\theta^{\,2}}{4\omega_s^{\,2}}\right]d\mathbf{y}$$

$$C_\theta=\left[\left(1-M_c\cos\theta\right)^2+\frac{\omega_s^{\,2}}{a_o^{\,2}}\left(\ell_x^{\,2}\cos^2\theta+\ell_\perp^{\,2}\sin^2\theta\right)\right]^{1/2}$$

Gaussian Statistics

- Integrate over frequency –

$$\overline{p^2}(\mathbf{x}) = \frac{3}{4\sqrt{\pi}x^2 a_o^{\ 4}} \int_{V(\mathbf{y})} \frac{\rho_s^{\ 2} \ell_x \ell_\perp^{\ 2} \omega_s^{\ 3} u_s^{\ 4}}{C_\theta^{\ 5}} d\mathbf{y}$$

- The same result can be obtained (exactly) if the moving frame cross correlation is transformed to a fixed frame using the simple transformation,

$$\boldsymbol{\delta} = \boldsymbol{\Delta} - \mathbf{i} a_o M_c \tau$$

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Alternative Models

- Other models provide a better overall fit to the measured cross correlation functions
- Harper-Bourne proposed that the cross spectral density be modeled as

$$C_x(\mathbf{y},\boldsymbol{\Delta},\gamma) = S_x(\mathbf{y},\mathbf{0},\gamma) R_\eta(\mathbf{y},\boldsymbol{\Delta},\gamma)\exp(i\gamma\Delta_1/U_c)$$

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Alternative Models

- If the autocorrelation is modeled by an exponential and the spatial correlation is modeled by

$$R_\eta(y,\Delta,\gamma)=\exp\left[-\sqrt{\frac{\Delta_1^{\,2}}{\ell_x^{\,2}}+\frac{\left(\Delta_2^{\,2}+\Delta_3^{\,2}\right)^2}{\ell_\perp^{\,4}}}\right]$$

$$S(\mathbf{x},\gamma)=\frac{1}{8\pi^2x^2a_o^{\,4}}\int_{V(\mathbf{y})}\left(\frac{\gamma}{\omega_s}\right)^4\frac{\rho_s^{\,2}u_s^{\,4}\ell_x\ell_\perp^{\,2}}{\left(1+\gamma^2/\omega_s^{\,2}\right)\left(1+s_d^{\,2}\right)^{3/2}}d\mathbf{y}$$

$$s_d=\frac{\gamma\ell_x}{U_c}\left(1-M_c\cos\theta\right)$$

Convective Amplification

- All the directivity is contained in the factor

$$\left(1+s_d^{\,2}\right)^{-3/2}=\left[1+\frac{\gamma^2\ell_x^{\,2}}{U_c^{\,2}}\left(1-M_c\cos\theta\right)^2\right]^{-3/2}$$

- At low frequencies (St<<1)

$$\gamma\ell_x/U_c\approx 1.3\mathbf{St}<<1$$

- At high frequencies (St>>1)

$$\gamma\ell_x/U_c\approx 1.5$$

Choice of Green's Function

- Why use a Green's function associated with moving point source?
- The source convection is described in the cross correlation function
- Is this double counting? Probably

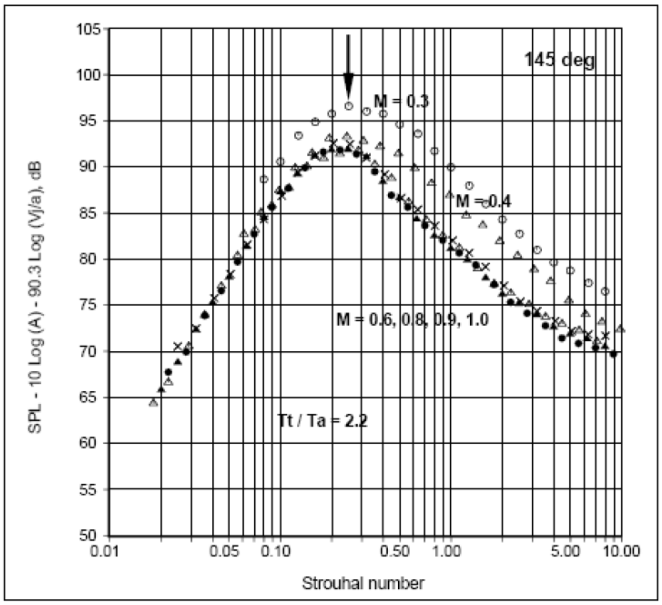
Experimental Evidence

M	Mc	[(1-Mc cos(55)]	[(1-Mc cos(50)]	[(1-Mc cos(35)]
0.3	0.301	0.827	0.807	0.753
0.4	0.413	0.763	0.735	0.662
0.5	0.511	0.707	0.672	0.581
0.6	0.609	0.651	0.609	0.501
0.7	0.700	0.598	0.550	0.427
0.8	0.784	0.550	0.496	0.358
0.9	0.875	0.498	0.438	0.283
1.0	0.952	0.454	0.388	0.220

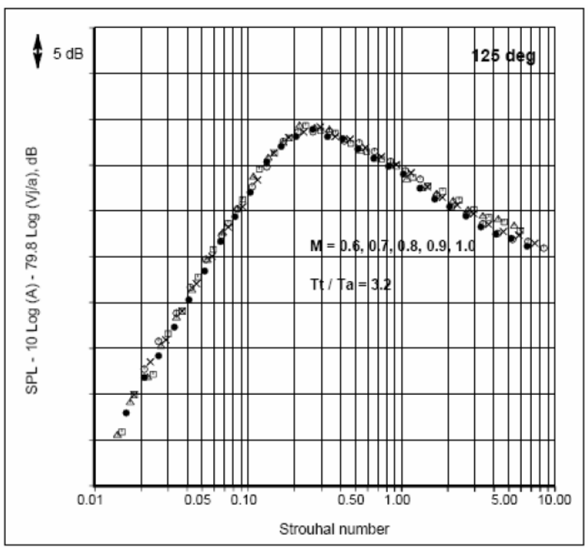
Table 2. Tabulation of jet Mach number, Mc and Doppler factor. Tr/Ta=2.2.

Data from K. Viswanathan – Boeing, Seattle

Doppler Shift?

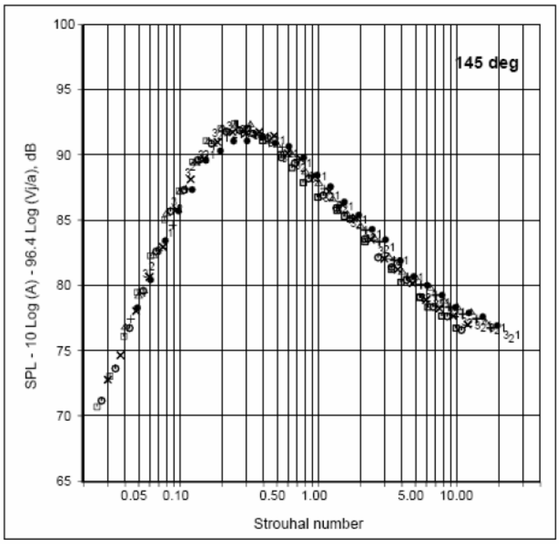


Spectral Collapse



Based only on velocity exponent!!

Spectral Collapse



If a Doppler shift and convection amplification were present, the data could not be collapsed on velocity alone

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Invited Presentation:

Jet Noise Topics
Nonlinear Interaction Model of Subsonic Jet Noise
Large Eddy Simulation

Professor Neil Sandham
University of Southampton

Professor Sandham said that he would split his talk in two, first describing the nonlinear interaction model and then taking questions before moving on to discuss LES.

PART 1
Nonlinear Interaction Model of Subsonic Jet Noise

Professor Sandham described the work undertaken on a plane 2-D Mach 0.9 jet. An IVP had been posed by introducing a localised disturbance at time t=0 and the development of the shear layer response studied. The full Navier-Stokes solution for a vortex packet showed that noise was produced before the vortices began interacting with each other and he asked how one should solve for this noise? He went on to explain how this had been done using a "coupled linear model".

Starting with a given reference flow the homogeneous linear IVP is solved simultaneously with the inhomogeneous LEE using an equivalent body force in the style of Goldstein gives nonlinear interaction between the modes obtained from the homogeneous problem. It is found that while the linear model gives no sound radiation the non-linear interaction model mimics the Navier-Stokes solution and results in significant sound generation.

PART 1
Open Discussion

Professor Philip Morris asked how the supersonic modes are generated in the weakly nonlinear model. He was thinking about large scale structures and noted that there were two possible mechanisms by which such structures could radiate: weakly non-linear interactions or by rapid breakdown. Neil Sandham replied that this model could give an estimation of what portion of the energy is produced by weakly nonlinear processes. . A Parabilized Stability Equations (PSE) approach may be an efficient way of obtaining the details of different modes. Philip Morris remarked that during a rapid decay process the rapid escalation in the number of modes made it difficult to maintain numerical stability.

PART 2
Large Eddy Simulation

Professor Sandham reviewed the application of LES to jet noise. He said that the trick is to compute only a portion of the spectrum to keep the calculation computationally cheap, but also sufficient of the spectrum that the useful physics is captured.

Traditional LES used a sub-grid model but some researchers (e.g. the group at ECL) preferred filtering. This involves dropping the sub-grid and instead filtering the entire flow field on every n^{th} time step. LES techniques are not mature and most active groups have their own implementations.

An important consideration is that of boundary conditions, which need to be non-reflecting. The most widely used methods employ a fringe zone in which the equations are changed to dissipate the noise before the boundary is reached. These however require tunable coefficients so there is a danger that they are case sensitive.

Acoustic field coupling is by way of FWH, Kirchhoff or coupled LEE/wave equation.

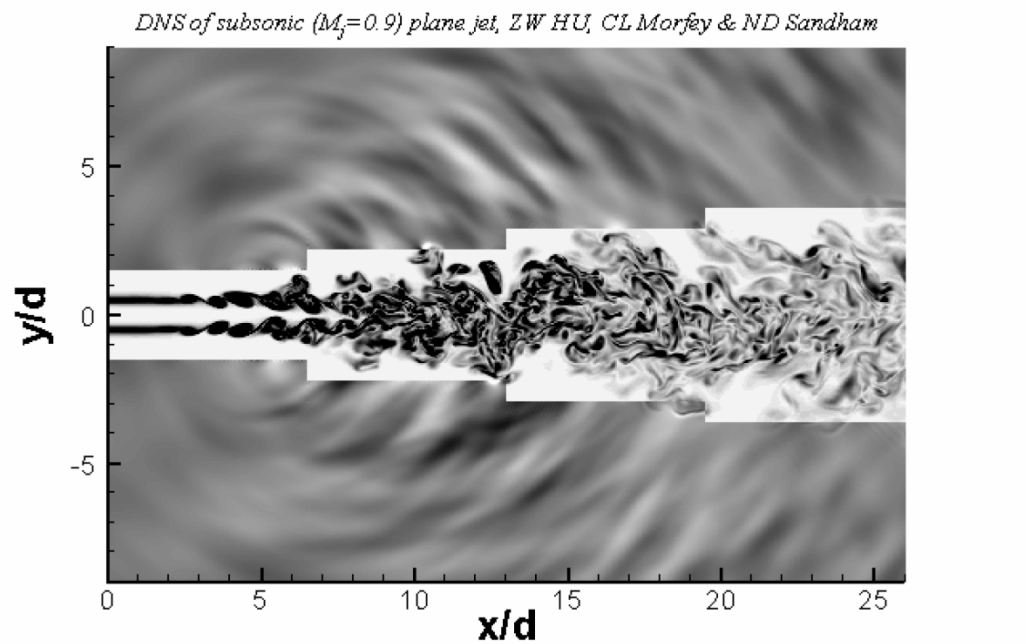
For some applications, such as flow control applied at the nozzle, LES may be prohibitively expensive due to the resolution requirements of turbulent boundary layers.

PART 2
Open Discussion

Professor Geoff Lilley asked what Professor Sandham's views were on work being undertaken in Russia on volume based methods. Professor Lilley said that he thought such schemes gave good results at low frequency compared to FD methods but not so good at high frequencies. Professor Sandham replied that these groups (e.g. Shur et al 2005) used hybrid methods. He noted that using up-winding schemes increased dissipation, enabling stable calculations on a coarser grid, but that than the grid required very careful design.

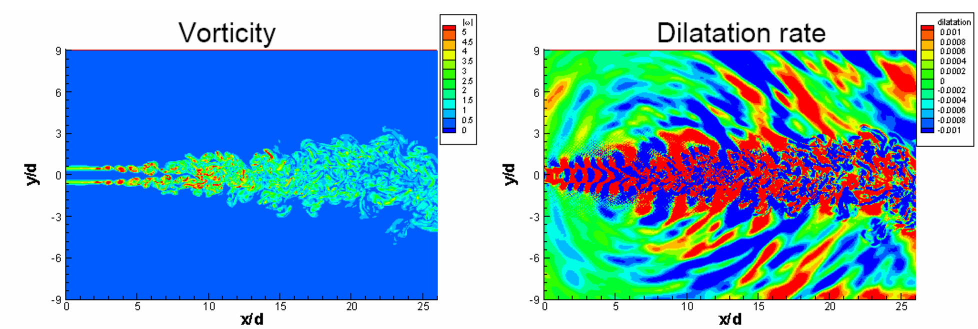
Professor Chris Morfey noted that LES schemes required that one stay close to the jet during the calculation because it was too dissipative to get very far away.

Philip Morris asked about grid requirements and trailing edge conditions, he wondered how Neil Sandham got the jet flow started. Neil replied that ideally one would always start jet calculations on the upstream nozzle so that the nozzle trailing edge is included in the calculation.



Jet Noise Topics

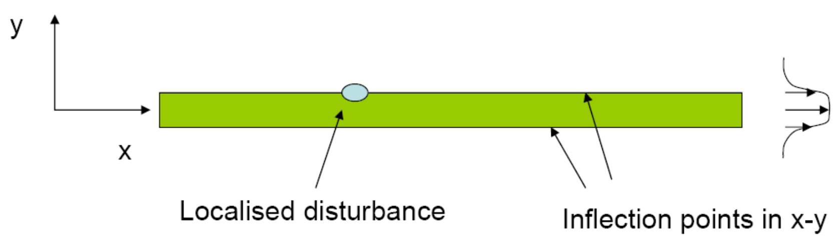
(a) nonlinear interaction model of subsonic jet noise
(b) large eddy simulation



Neil Sandham, Chris Morfey and Zhiwei Hu
University of Southampton

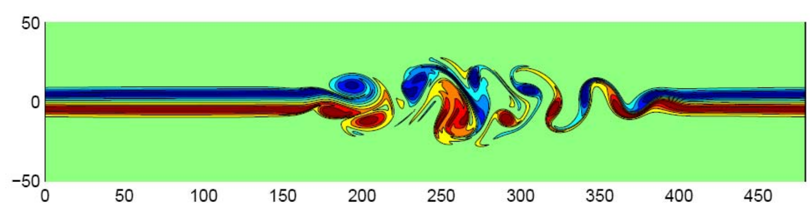
(a) Nonlinear interaction modeling

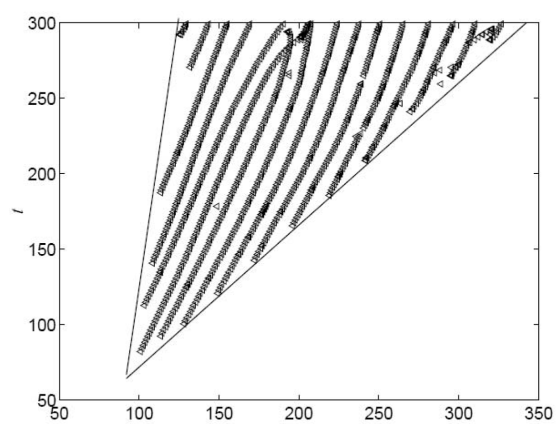
- Parallel, plane, two-dimensional jet at M=0.9
- Initial value problem
  - localised disturbance at t=0
  - impulse response
- Nonlinear stages: vortex packet



Advantages: no inflow/outflow boundaries, ability to localise source in space/time

Navier-Stokes solution: vortex packet





Coupled 'linear' model

Separation of linear and weakly nonlinear response

For a given reference flow, solve

$$\boxed{L\left(\rho^L, u^L, v^L, p^L\right) = 0}$$

Homogeneous equation
Linear initial value problem

Simultaneously solve

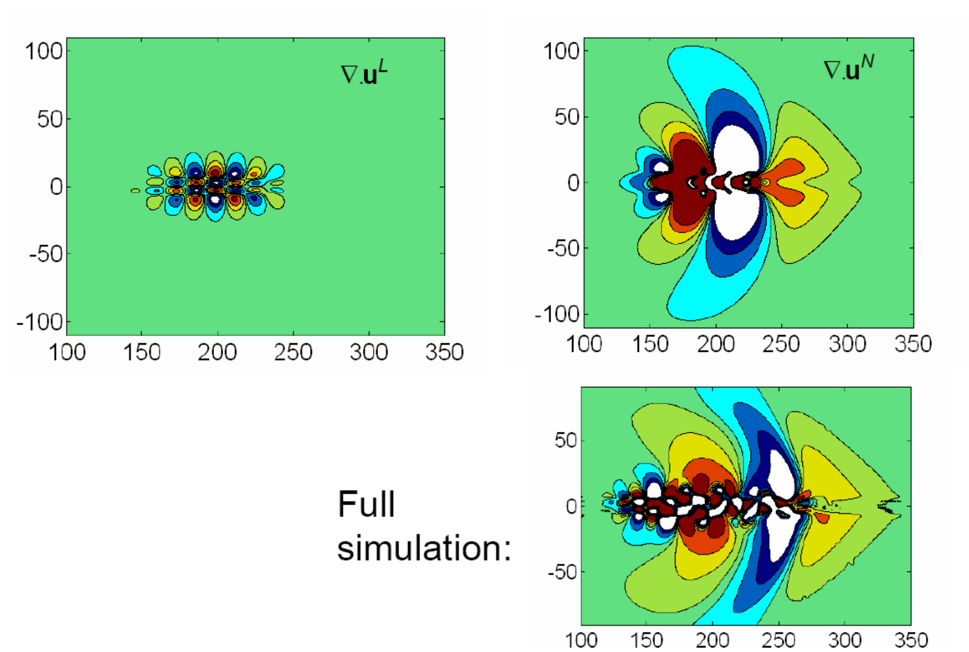
$$\boxed{L\left(\rho^N, u^N, v^N, p^N\right) = R\left(f_x, f_y\right)}$$

Inhomogeneous equation
Zero initial condition

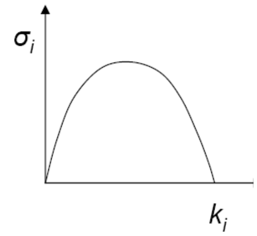
$$f_i = -\frac{\partial u_i^L u_j^L}{\partial x_j}$$

Equivalent body force
(Goldstein, 2001)

Linear and nonlinear response



Nonlinear eigenmode interactions
(temporal formulation)



- Normal modes

$$u_i^L = \hat{u}_i \exp(\mathrm{i}k_i x)\exp\left(\int (\sigma_i - \mathrm{i}\omega_i)dt\right) + c.c.$$

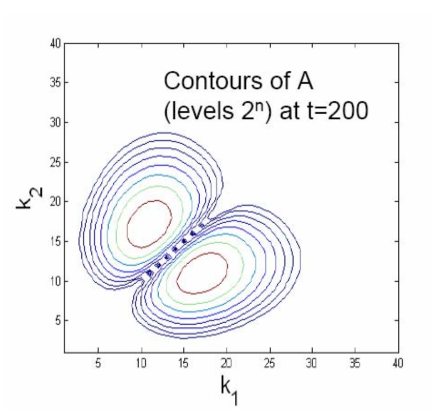
- Example source term mode interactions

$$\frac{\partial^2 (u_i^L u_j^L)}{\partial x^2} = A_{ij}^{+}\hat{u}_i\hat{u}_j \exp(\mathrm{i}(k_i + k_j)x) + A_{ij}^{-}\hat{u}_i\hat{u}_j^{\dagger} \exp(\mathrm{i}(k_i - k_j)x) + c.c.$$

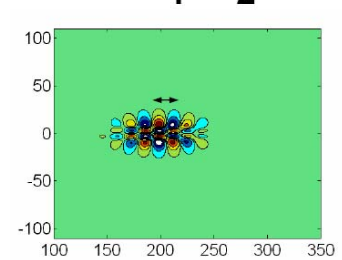
$$A_{ij}^{+} = -(k_i + k_j)^2 \exp\left(\int (\sigma_i + \sigma_j - \mathrm{i}(\omega_i + \omega_j))dt\right)$$

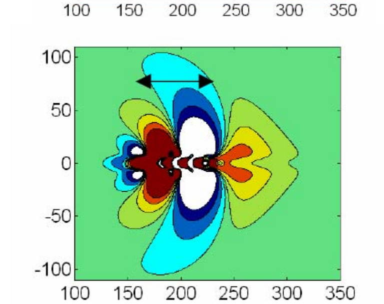
$$A_{ij}^{-} = -(k_i - k_j)^2 \exp\left(\int (\sigma_i + \sigma_j - \mathrm{i}(\omega_i - \omega_j))dt\right)$$

Contribution to acoustic forcing of difference modes k_1-k_2



$$A = (k_1 - k_2)^2 \exp(n_1 + n_2)$$



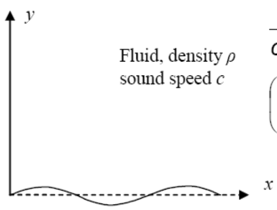


$n_{1,2}$ is the usual n-factor

k_1+k_2 combinations lead to high frequency modes that are cut-off

Δk=5 corresponds to λ = 70 for sound; k=14 for LST modes corresponds to λ = 25

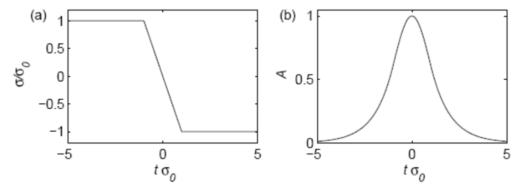
Wavy-wall problem revisited



$$\frac{1}{c^2}\frac{\partial^2 \phi}{\partial t^2} + \left(k_x^2 + k_z^2\right)\phi = \frac{\partial^2 \phi}{\partial y^2}$$

$$\left(\frac{\partial \phi}{\partial y}\right)_0 = \exp((\sigma - i\omega)t + i\psi)$$

$$\begin{aligned} \sigma &= \sigma_0 \quad \text{for} \quad t \le -\Delta \\ &= -\frac{\sigma_0 t}{\Delta} \quad \text{for} \quad -\Delta \le t \le \Delta \\ &= -\sigma_0 \quad \text{for} \quad t \ge \Delta \end{aligned}$$

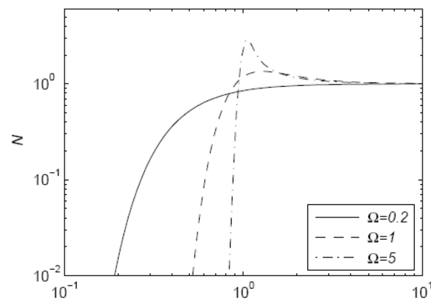


Problem Parameters

$$M = \frac{\omega}{k_x c} \quad \Omega = \frac{\omega}{\sigma_0} \quad G = \sigma_0 \Delta$$

Normalised acoustic energy output

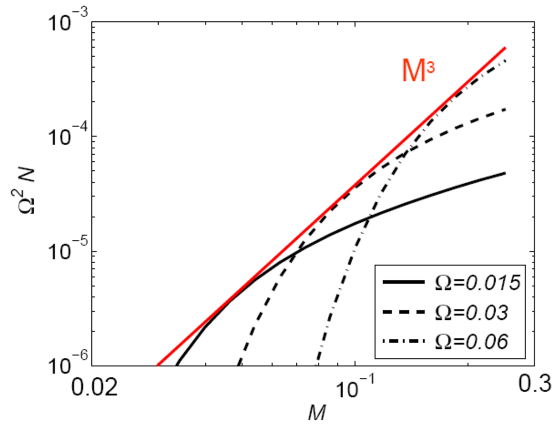
$$N = \frac{-\int_{-\Delta}^{\Delta} \left(\frac{\partial \phi}{\partial y}\right)_0 \left(\frac{\partial \phi}{\partial t}\right)_0 dt}{c\int_{-\Delta}^{\Delta} \left(\frac{\partial \phi}{\partial y}\right)_0^2 dt}$$



G=10

Combine with source model

Progressive change in *Ω* with Mach number M_c



$$\Omega^2 N$$

Frequency factor (source term)

Radiation energy factor (wavy wall model)

Omits the effect of Mach number on:
(a) Mode saturation
(b) Hydrodynamic field

Refs:
JSV 294, 2006
JFM 565, 2006

(b) Large Eddy Simulation

- Numerical issues
  - Subgrid model vs filtering
  - Fringe zone boundary conditions
  - Acoustic field coupling
    - FWH vs Kirchhoff vs coupled LEE/wave equation
- Application
  - Control via trailing edge devices
  - Numerical resolution of wall boundary layers is much more demanding

Invited Presentation:

Jet Noise

Professor Chris Morfey
ISVR
University of Southampton

Professor Chris Morfey said that he wished to tackle the following questions:

- Do we understand jet noise well enough for practical purposes? That is for the application by industry. He assumed that the answer to this was "no".
- What aspects of the physics are not well understood? And why?
- Do RANS–based prediction schemes still have a useful role? He asked this in the light of advances in LES and DNS.

Numerical simulations with LES are beginning to produce usable results (spectra) up to St = 2 and large domains and low-dissipation codes allow direct computation of the sound field. Is this all that is required? Is it simply a matter of computation time? There were already methods for speeding the computations for industrial application so what else was there?

At present there were still unanswered questions in our understanding of jet noise. For example what was our understanding on the status of the U^8 law discussed during Professor Morris's presentation? And what was the role of large scale structures? He thought that these structures played an important role via non-linear interaction of modes.

Another important aspect that was not well understood was the effect of upstream conditions on jet noise. There was a serious lack of controlled experimental data on this point.

Given the rather poor understanding that we had at present, Professor Morfey was unsure of our future ability to actively control jet noise.

Chris Morfey questioned whether there was any mileage left in RANS based modelling or if we should now look to more sophisticated CFD such as Reynolds Stress models. Again he emphasised the lack of good experimental data to help guide such decisions and said that the work of Marcus Harper-Bourne remained the "gold standard" in this regard. He also repeated Professor Morris's comment that Marcus had only measured data at one position in the jet, which was a great pity. The paper by John Freund was also worthy of mention as an early attempt to gather data on fluctuating Reynolds stresses in a turbulent jet via DNS: the jet Reynolds number was low (3600) but data were not limited to a single location in the jet.

Professor Morfey concluded by commenting on the fact that after 30 years work we had yet to fully account for the flow acoustic interaction within the cone of silence. He also wondered if instability waves were important and whether there was a need to develop models that could account for them.

Open Discussion

Philip Morris commented on DNS and LES data. He said that the John Freund data was useful but noted that one of the problems of such calculations was that relevant data needed to be extracted at the time of the simulations; one couldn't for example go back later and compute two point correlations. With LES the source two-point correlations tended to be over estimated, with large and multiple zero-crossings, because of the lack of the randomising nature of the small scales, that are modelled, not simulated.

Professor Chris Morfey made an open question concerning Reynolds number effects for Re < 300,000, did the measurements of Viswanathan mean that model scale data should now be treated as suspect?

Professor Geoff Lilley said that for hot jets with Re < 300,000 the model scale data does not compare well with full scale. He endorsed Professor Morfey's statement on the need for good experimental data.

Professor Neil Sandham said that a series of DNS calculations at differing Reynolds numbers should show any dependence. However, calculations covering a factor of 10 variation may be 5 to 10 years away for a jet.

Professor Morris said he would make a follow-up point about experimentation. Rather than the present preoccupation with PIV, LDV etc., it would be nice to see someone do a Ph.D. using hot wires because the evidence is that the cross-correlations are not affected strongly by increase in jet velocity. Thus a comprehensive survey of the entire jet would be possible, without the need for expensive optical techniques, using hot-wires. This would address the question as to whether the correlation properties vary in different regions of the jet.

Dr. Paul Strange said he agreed with the points made concerning the need for further experimentation. With regard to active control he said that the question in his mind was always "what do you need to do to the flow to reduce the noise?" He added that the work done by Jon Freund on control needed to be further extended and supported by experiment.

Dr Tom Hynes (University of Cambridge) asked what sort of calculation was needed for a practical situation. There were problems with LES close to the nozzle because of grid considerations and he wondered if RANS close to the nozzle with LES further downstream was the answer. Equally, do we need to start DNS close to the nozzle? Neil Sandham said that you are always worried about missing upstream effects if the calculation was started close to the nozzle and that it was better to go upstream and incorporate the boundary layer. He said that what Tom had described (i.e. the RANS/LES combination) was essentially DES. Tom Hynes responded by asking if the upstream conditions were something that could be obtained experimentally. Neil

Sandham replied that yes, this was possible and that an alternative would be to calculate the turbulent boundary layer separately and use this as a starting point.

Professor Philip Morris expressed surprise that people had not picked up on the adjoint LEE method of Tam and Auriult to get the mean flow acoustic interaction effect. This was not confined to axisymmetric situations and could be used for non-circular jets. Given that the technique was effectively LEE why wasn’t it used? Or was he missing something? Chris Morfey asked about the source term in this formulation and Philip replied that the source was placed at the far-field observer position so that that a very nearly plane wave hit the whole jet. The solution to the adjoint problem tells you in a reciprocal sense what the flow-acoustic interaction is. Chris Morfey then asked about instabilities but these could be suppressed in frequency space. Dr Agarwal said that he understood the method used monopole sources but Professor Morris pointed out that once the reciprocal Green’s function was found multipole solutions were easily obtained by differentiation.

Commenting on our understanding of the physics and Professor Morfey’s question regarding upstream conditions, Professor Peter Davies said that the work that he had done several years ago comparing measurements with those of Peter Bradshaw had showed there was a strong dependence of the flow on upstream conditions. He pointed out that there was a strong acoustic field in the flow and thought that there was also some evidence that upstream flow conditions were affected by the downstream acoustics. In particular he thought that an acoustic feedback mechanism may have some part to play in the action of corrugated nozzles.

Discussion topics

- Do we understand jet noise well enough for practical purposes?
- What aspects of the physics are not well understood?
- Do RANS–based prediction schemes still have a useful role?

Do we understand jet noise well enough for practical purposes?

- Numerical simulations with LES are beginning to produce usable results (spectra) up to St = 2
- For research purposes, large domains and low-dissipation codes allow direct computation of the sound field
  [Bogey, Bailly (2006) TCFD : $0 < x/D < 15$, $r/D < 7.5$]
- For industrial purposes, smaller domains allow adequate capture of the jet for wave extrapolation purposes, and allow faster computation
  [Shur, Spalart, Strelets (2005) IJA]

What aspects of the physics are not understood?

- Influence of (i) upstream flow conditions
  (nozzle boundary layer, free-stream turbulence)
  (ii) upstream acoustic conditions
  on far-field noise from subsonic jets

- Are there two distinct mechanisms of jet noise?

- Role of instability waves on the jet column:
  linear versus *nonlinear* radiation mechanisms
  [Cooper, Crighton (2000) EurJMech B; Sandham, Morfey, Hu (2006) JFM, in press]

- Possibilities for active control of radiated sound

Do RANS–based prediction schemes still have a useful role?

- Need for improved source models (Reynolds-stress components and temperature-dipole source components) with appropriate cross-power spectral density behaviour

- Practical calculation of flow–acoustic interaction effects, including the cone of relative silence

- Do instability waves need to be considered?

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SESSION 2: FAN BROADBAND NOISE

Introduction
Professor Stewart Glegg,
Florida Atlantic University

This session is devoted to four invited presentations by panel members each to be followed by a brief discussion. The panel members were:

Professor Stewart Glegg,
Professor Nigel Peake
Professor Michel Roger
Dr. Phil Joseph

Introduction by Professor Stewart Glegg
Professor Glegg gave a brief introduction to the problems facing the aeroacoustics community in trying to model the broadband noise due to ducted rotors and stators. He mentioned that the problems in predicting fan broadband noise were similar to those in jet noise prediction but also different. He posed two sets of questions:

•What is the dominant broadband noise source on a modern high bypass aeroengine, and what evidence is there to support this?

•What is the possibility that RANs,LES, and DNS methods will be able to compute the broadband noise from a complete fan stage?

•How accurately can analytical/empirical techniques capture the physics of noise generation in real aero engines?

Additional questions were, "what should we be determining in experimental tests?" Some possibilities are:

Experimental Testing
–Scaling
–Frequency shifts
–Low frequency rig noise
–Isolated airfoil measurements in wind tunnels

Furthermore, how useful are the following in broadband noise prediction?:

FEM methods

Integration of Analytical and Numerical Methods

Invited Presentation:
Fan Broadband Noise Prediction
An Industrial Perspective

John Coupland
Noise Engineering/Aerothermal Methods
Rolls-Royce

John Coupland began by putting the fan broadband noise radiated from a modern turbofan engine into context by comparing it to the other dominant sources, such as the jet noise at takeoff and airframe noise on approach. He showed that, on approach and takeoff, fan broadband noise is at least the second most important noise source. He also indicated that fan broadband noise increases as the by pass ratio increases. Clearly, this is a problem due to the current tendency towards increasingly higher ratio by pass engines. He then surveyed the various broadband noise sources and indicated that it was likely that the broadband noise due to interaction between the turbulent wake onto the stator was the dominant source followed by rotor self noise in which the turbulent boundary layer on the fan blades interacts with the sharp trailing edge.

John Coupland then showed typical sound power spectra obtained from a fan rig. Results were shown at 60% and 80% fan speed. In these examples, the broadband spectra were characterised by a slow rate of decay with frequency. In the 80% fan sped case the spectrum was effectively flat over nearly 80 engine orders. This result was attributed to some kind of blockage effect. John then showed another figure demonstrating the variation of power level versus relative Mach number onto the rotor blades for a high working line and low working line case. The high working line example was shown to be almost 3dB greater than the low working case suggesting that fan broadband noise increases as blade loading increases.

Another interesting result was in the form of the sound power level plotted against Engine Order and spinning mode order. This demonstrated clearly that the nearly all of the modes spin in the direction of the rotor. John suggested that was evidence for the dominance of rotor – stator interaction noise.

John Coupland showed the well-known measurement results made by Ganz et al Boeing in which the individual broadband noise sources were measured by systematically removing the remaining sources. This graph shows clearly the dominance of rotor – stator interaction broadband noise over the other sources by up to 5dB. John then addressed the hierarchies of model that could be used to model fan broadband noise, such as LES, the use of correlations from fan rig testing, semi-analytic mehods and the use of RANS turbulence models. One pertinent question is whether RANS solutions can be used to provide inputs to fan/OGV noise prediction models, especially for the difficult situation of ‘off-design’. He then discussed some other issues that need to be addressed to make fan broadband noise predictions, such as noise transmission through the blade rows.

John speculated on the prospect of noise control for fan broadband noise in the near future. He suggested that broadband noise was resistant to control and that a more radical approach was required, such as flow control.

Open discussion

Professor Chris Morfey raised the prospect of measuring the acoustic pressure in the rotating frame in order to characterise the noise radiated from the rotor.

Dr Brian Tester questioned the effect of high by pass ratio on fan broadband noise since OGV noise was thought to be dominant in the front and back of the engine.

Professor Stewart Glegg asked John Coupland on his confidence in being able to predict the broadband noise due to changing engine design. John replied that confidence was very low.

A general debate then followed about the generality and relevance of the Boeing test to full-scale engine tests. Dr Tester thought that fan speeds and pressure ratios were not reprentative of real engine conditions.

Rolls-Royce

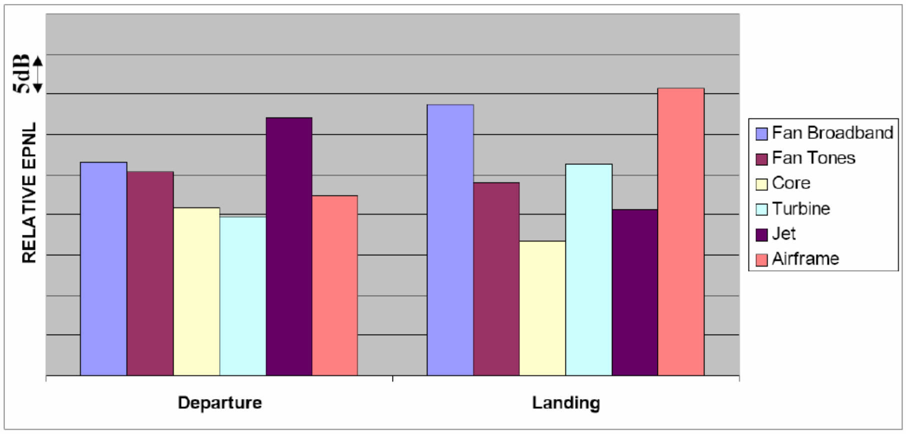
Fan Broadband Noise Prediction

An Industrial Perspective

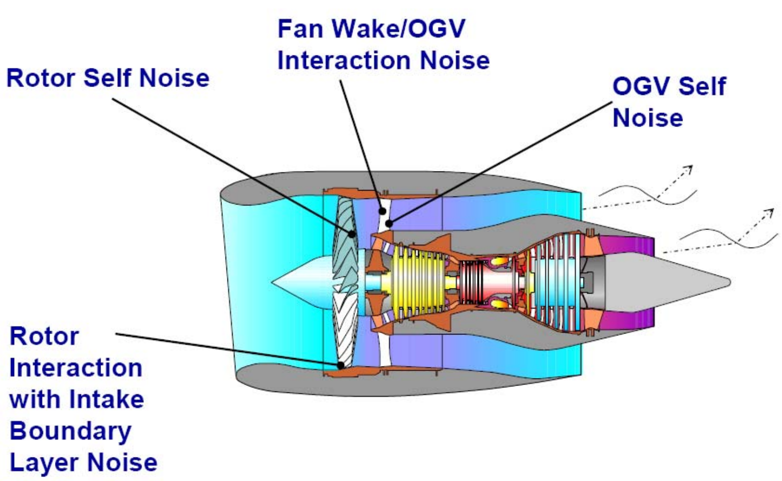
John Coupland
Noise Engineering / Aerothermal Methods
Rolls-Royce plc
Derby

Fan Broadband Noise – The Context

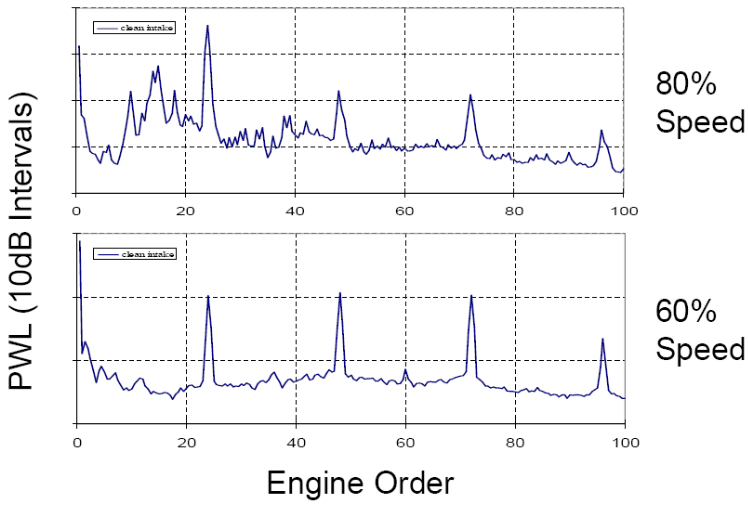
Fan Broadband Noise - Importance



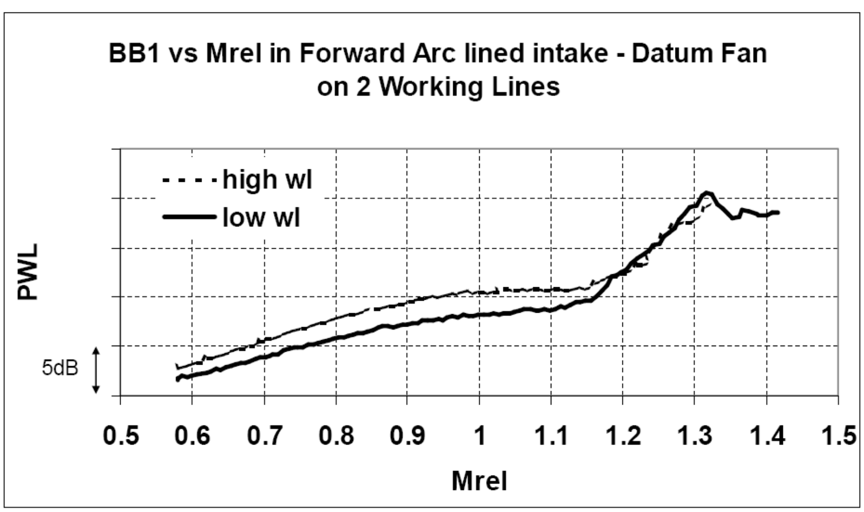
Fan Broadband Noise – Noise Sources



Fan Broadband Noise – Rig Spectra



Fan Broadband Noise - Some Trends



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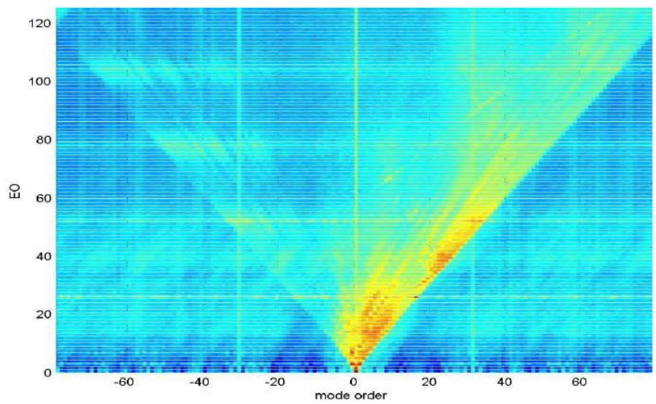
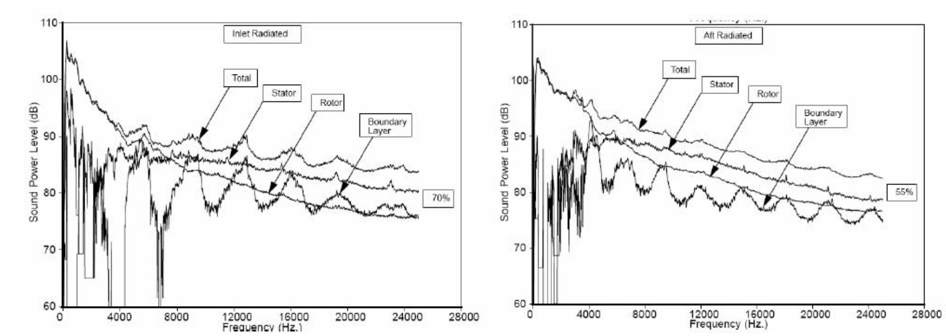
Fan Broadband Noise – Mode Detection

Broadband Noise at 50% - Remote View

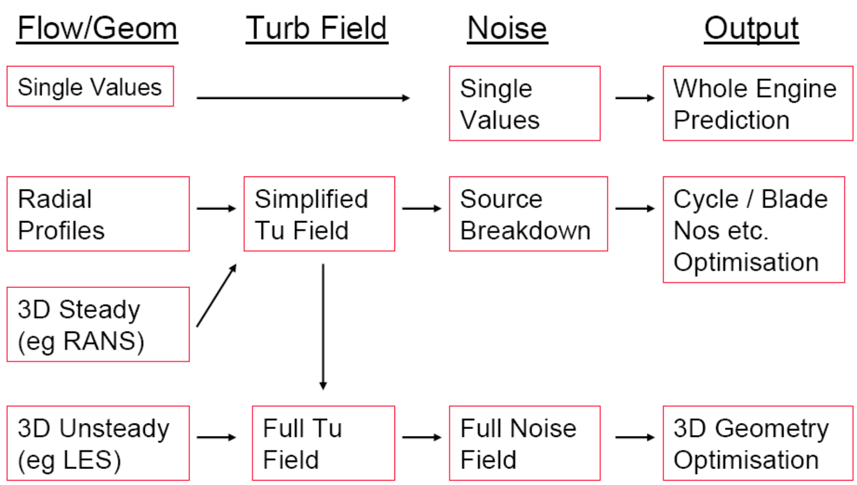


Fan Broadband Noise - Noise Sources

Results from Boeing 18-Inch Fan Rig Broadband Noise Test, Ganz et al, NASA/CR-1998-208704



Fan Broadband Noise – Model Hierarchy



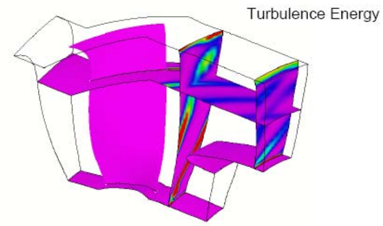
Fan Broadband Noise – Design Methods

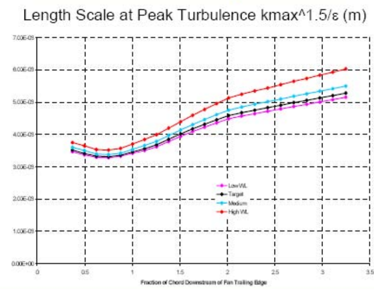
- **Correlations**
  - **Built up from engine and rig testing**
  - **Noise correlated with M_{rel}, Loading (working line), Geometry, ….**
  - **Corrections for flight, field shape, ……**
- **Semi-analytic models**
  - **Models for each source – rotor self, wake-OGV interaction, …**
  - **Turbulence spectrum**
    - **From correlation (based on loading, loss, etc)**
    - **Or intensity and scale could be from RANS CFD via turbulence model**
  - **Gust response from 2D theory, or 2D LINSUB or 2D/3D CFD**
  - **Model for acoustic radiation to intake or bypass duct**
- **Some issues**
  - **Noise transmission**
  - **Effect of 3D flow and turbulence structure**
  - **Best turbulence model closure for length scale ? – no real prediction of two-point information**

Fan Broadband Noise – RANS

Can we use RANS to provide input to Fan-OGV Broadband Noise Models ?

- 3D RANS is used as standard in Fan and OGV/ESS design.
- So can RANS turbulence model provide data for acoustic models
  - Rotor self noise
    - Boundary layer turbulence and scales
  - Wake-OGV interaction noise
    - Wake turbulence and length scales
    - Wake momentum thickness
- RANS can provide better data at Noise operating points
  - Off-design aerodynamics
  - Working line variation

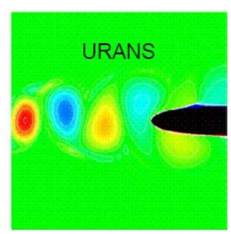




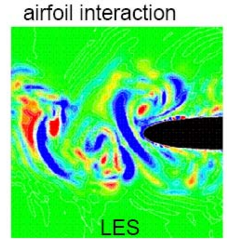
Fan Broadband Noise - LES

Can we use Large-Eddy Simulation for Fan-OGV Broadband Noise prediction ?

- **Reynolds Number issue**
  - **Fan blade Reynolds number ~ $5*10^6$**
  - **Do we need to resolve all the near wall turbulent structures (streaks, hairpin vortices, …) ?**
  - **LES is currently restricted to flows not dominated by near wall effects (see e.g. EU LESFOIL project), so can do jets, combustors, …., but can we do blades and wakes ?**
- **Annular Blade Cascade issue**
  - **Blade passage non-periodicity in turbulent flow – does it matter ?**
  - **Upstream rotor rotation relative to OGV – big problem for LES, but does it matter for noise ?**
- **Real Flows are 3D issue**
  - **Important to resolve 3D rotor flow and turbulence structure ?**
    - **End wall boundary layers**
    - **Tip clearance flow interaction**
    - **Hub endwall corner separation**
- **LES is inevitably going to be expensive !**
  - **Estimate ~20M cells for Fan or OGV at high Re**
  - **Estimate ~50K time steps per rotor passing period at high Re**
  - **How many rotor passing periods to get BB1 noise ?**



Cylinder wake – airfoil interaction



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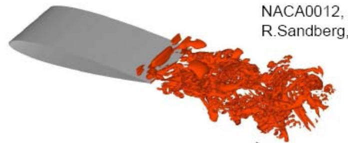
Fan Broadband Noise – LES Targets

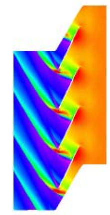
NACA0012, Re~10000, M=0.6
R.Sandberg, N.Sandham, Southampton

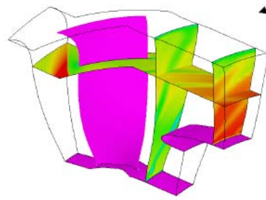


2D Airfoil, low Re

increasing Re,
increasing
complexity

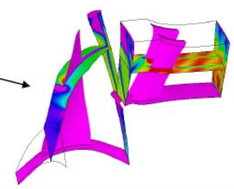
2D Blade (spanwise uniform, multipassage, boundary layers, wakes)





3D Airfoil

(endwall flows)



3D Airfoil, unsteady multirow, high Re

(unsteady wake passing on OGV)

Fan Broadband Noise – Reduction

- **Industry ultimately needs methods, and experiments, to provide low fan stage broadband noise designs**
- **3D blade (Fan and OGV/ESS) optimisation (already in place for tones)**
- **Engine cycle optimisation**
- **Detailed design for noise reduction**
  - **Rotor boundary layer flow control**
    - **Boundary layer suction/blowing ?**
    - **Turbulence manipulation ?**
    - **Trailing edge blowing ?**
    - **….. ?**
  - **Rotor wake turbulence control**
    - **Rotor trailing edge treatment ?**
    - **…. ?**
  - **OGV treatment for reduced response**
    - **Lined OGVs ?**
    - **…. ?**

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Fan Broadband Noise - Requirements

- **Industrial Requirements**
  - Provide engines to customers that satisfy noise regulations
  - Generate design strategies to reduce fan broadband noise
  - Achieve fan broadband noise reduction whilst achieving other engine design requirements (performance, aeromechanical, cost, ……)
  - Need prediction methods for broadband noise to quickly analyse new engines and designs
  - Need prediction methods to investigate fan broadband noise generation mechanisms to provide physical understanding that leads to design ideas for noise reduction
  - Need experimental data (noise and turbulence) to provide understanding on mechanisms and for validation of prediction methods
    - Idealised geometries for detailed validation
    - Realistic geometries at realistic conditions

Invited Presentation:
Status of Methods for the Predition of Broadband Noise

Michel Roger
Ecole Central de Lyon

Michel Roger began with a general survey of theoretical and experimental approaches for understanding the broadband noise generation from both single aerofoils and real fan configurations. He said that there was value in addressing generic problems, such as single aerofoils, to try and understanding the main features of the generating mechanisms.

Michel then began to discuss alternative analytic technique for the prediction of broadband aerofoil radiation. These, he said, were generally based on zero-thickness and flat plate assumptions and locally uniform flow. The techniques he discussed were based on the acoustic analogy, either the Lighthill theory or the Ffowcs Williams and Hawkings formulation.

The classical approach to aerofoil broadband noise prediction based on flat plate theory was briefly discussed. The approach is essentially statistical in which the radiated pressure spectrum is related to the pressure of the hydrodynamic boundary layer spectrum on the airfoil surface and a radiation transfer function. This imnplies that the input to the prediction scheme much originate from either computations or experiment.

Michel presentade a number of examples of the use of this kind of approach. The first is an example of self-noise radiation. In this example, incompressible LES is applied to copute the surface sources with a Kirchoff surface techniaue to compute the radiated field. The Spanwise coherence is deduced from experiment due to the limited Spanwise extent. Very good agreement for zero angle of attack was presented with other configurations still in progress. A significant limitation of the approach, therefore, is the requirement for experimental data. A similar approach was used to Michel to compute the noise radiation due to vortex shedding. Agreement with experimental data was shown to within 5dB.

Michel concluded his talk with a number of examples of the measured broadband noise from a realistic aerofoil. In one example, the effect of camber was shown to be negligible. Measurements were shown to be in close agreement with predictions obtained from flat plate calculations. In another example, godd agreement with the flat plate solution was obtained but only at high frequencies. Another mechanism is suspected at lower frequencies.

Michel finished his talk with the following list of pertinent questions concerning airfoil broadband noise radiation:

Q1. Flat plate assumption/thickness ans camber effects?
Q2. What about refraction effects
Q3. Are the input data suited/available?
Q4. Can they be deduced from standard steady CFD

Q5. Limitations of the existing unsteady CFD?

Q6. Extension from stationary airfoil to rotating baldes?

Q7. How does the single airfoil response compare with respect to a cascade response (S. Glegg)

Open Session

Professor Phil Morris raised the point that there was ambiguity about where to locate the Kirchoff surface. He said that its position would vary depending on whether the incompressible or compressible LES solution is used.

September 20, 2006

The status of methods for the prediction of broadband noise

Single-airfoil analytical models

Michel Roger, Ecole Centrale de Lyon

	CAA or/and hybrid methods	Analytical methods (acoustic analogy)	Experiments
Real, 3D configurations (fan)	Not available (short-term to mid-term)	Achievable, questionable	Expensive and/or harder to analyse
Generic configurations (isolated airfoil)	Accurate, heavy, high expertise	Well suited when validated	Tractable, quite clear

Validations

Easy extentions

- Address generic problems to try and identify the main features of generating mechanisms
- Propose fast-running models for the assessment of fan noise at preliminary design

About alternative analytical techniques

Generally based on a zero-thickness flat-plate assumption and a locally uniform flow. Dedicated to a separate noise-generating mechanism.

Based on the acoustic analogy, either **Lighthill** or **Ffowcs Williams & Hawkings**.

Ignored (and maybe important) features:

- Scattering details due to real airfoil geometry **Q1**
- Refraction by flow gradients **Q2**

Unsteady velocity as source term (Lighthill's stress tensor)

+

Approximate tailored Green's function

Wall-pressure (compressible) as source term (induced unsteady lift)

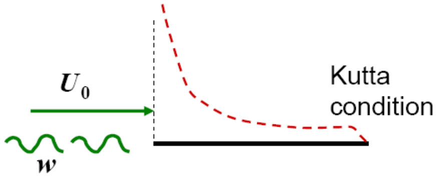
+

Free-space Green's function

→ **Post-processing tools of flow data**

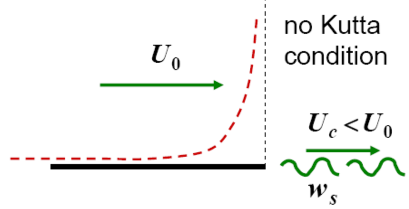
'Unified' problem statement – Schwarzschild's technique

Turbulence-interaction noise: *classical Sears' problem*



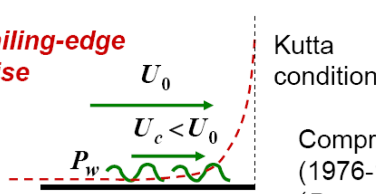
Compressible solution, by Amiet (1975).

Vortex-shedding noise: *reversed Sears' problem*



Compressible HF solution, extension of Amiet's analysis (*Roger et al AIAA paper 2006-2607*).

Trailing-edge noise



Compressible solution, Amiet (1976-1978) and extensions (*Roger & Moreau (2005), Sandberg et al AIAA paper 2006-2514…*).

Statistical approach

The far-field sound PSD is related to some statistics in the flow and to the corresponding spanwise correlation length

$$S_{pp}(\vec{x},\omega) \propto ctst \;\underset{?}{S(\omega)}\;\underset{?}{\ell_y(\omega)}\;\left|TF\right|^2$$

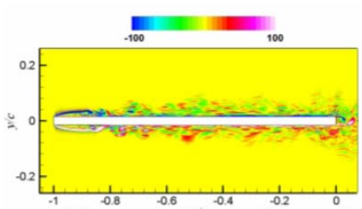
*Upstream velocity spectrum (turbulence-interaction noise), '**hydrodynamic**' wall-pressure spectrum (trailing-edge noise), near-wake velocity spectrum (vortex-shedding noise)*

Input data must be available from either computations or experiments

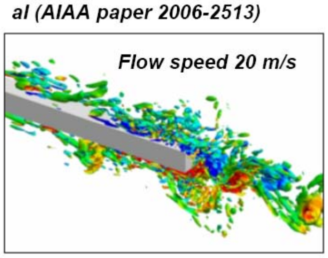
Q3

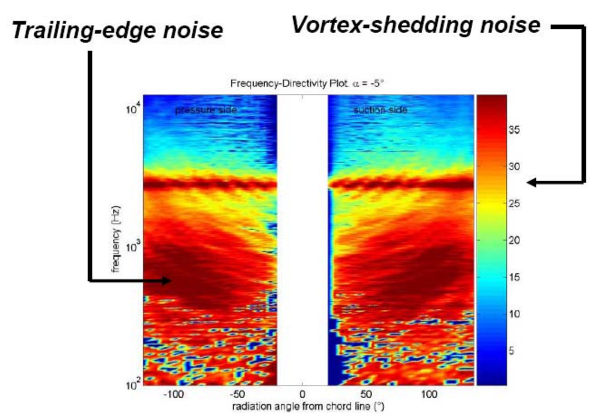
Example 1 : flat-plate self-noise

Trailing-edge noise (from turbulent boundary layers) and vortex-shedding noise are different mechanisms. Far-field measurements in the mid-span plane.



LES computations by Chang et al (AIAA paper 2006-2513)





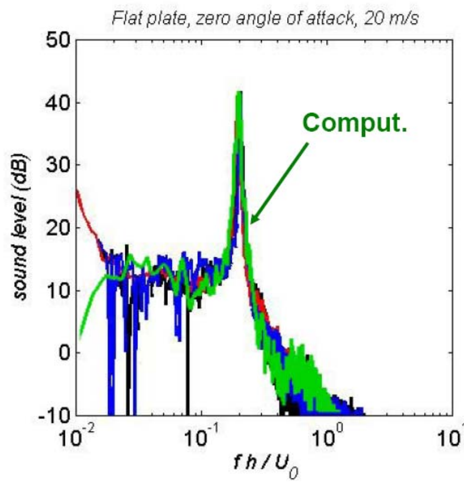
Experiment, 40 m/s, angle of attack 5°

Typical computational technique & results

Incompressible LES in a limited domain around the sources (plate), 2D reduction of the linearized compressible perturbed equations, 2D Kirchhoff-surface technique and 3D correction (far-field noise in the mid-span plane).

Spanwise coherence deduced from experiment due to limited computational domain extent.

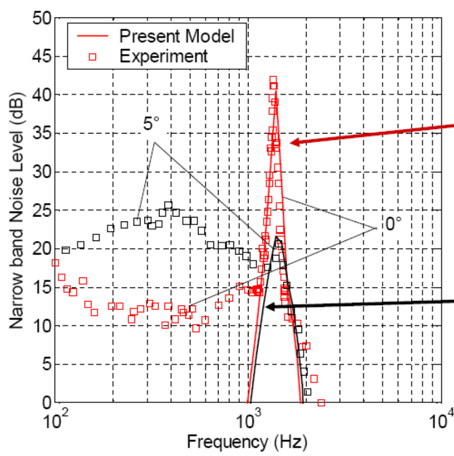
Very good agreement for zero angle of attack, other conditions still in progress.



Chang et al (AIAA paper 2006-2513)

→ Limitations: here the computations needs measured data **Q5**

Typical analytical predictions
Flat-plate vortex-shedding noise



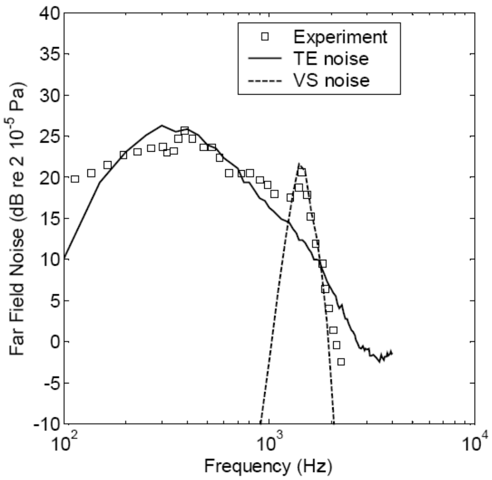
Good prediction of the peak at zero angle of attack, but clear separation between mechanisms.

Preliminary result at 5°, lower limit, possible errors up to + 5 dB

Present results and following to be presented at InterNoise 06

*Input data: LES-**computed** velocity spectrum and **measured** spanwise coherence*

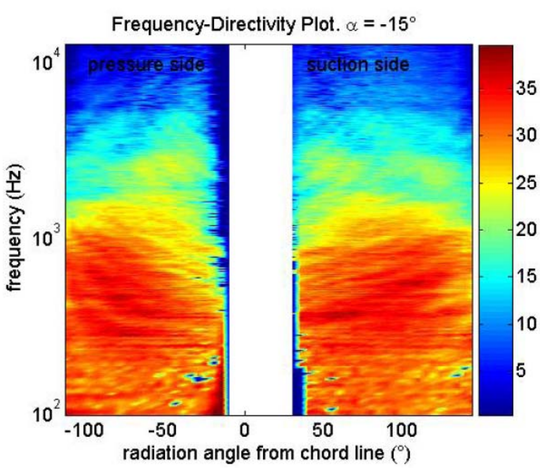
Complete flat plate self-noise



Separate predictions for trailing-edge noise and vortex-shedding noise, with different input data

Input data may not be available: are they easily related to mean-flow parameters, such as provided by RANS computations ? **Q4**

Example 2 : CD airfoil

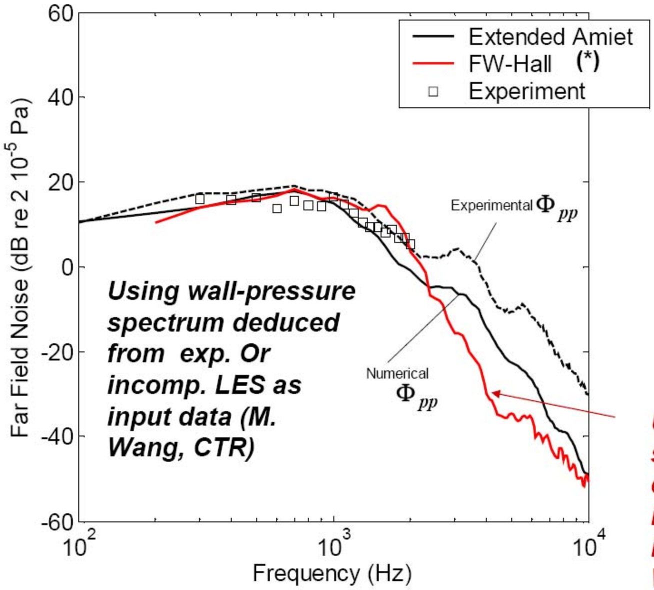


Camber effect seems negligible…

Q1

Moderately cambered, 4% relative thickness, Controlled-Diffusion airfoil (VALEO)

CD airfoil – trailing-edge noise predictions



Different high-frequency trends

High-frequency filtering by LES

Q5

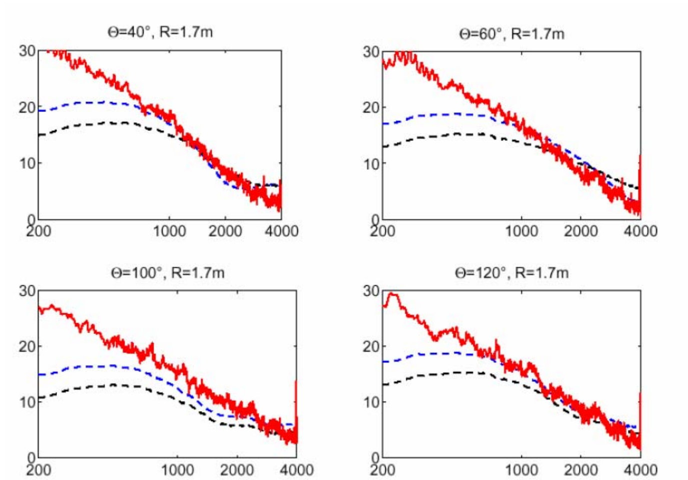
Using Lighthill's stress tensor deduced from incomp. LES as input data (M. Wang, CTR)

(*) *Howe's finite-chord tailored Green's function (2001)*

Application to a low-speed fan (CETIAT-ECL) case 1

Yannick Rozenberg

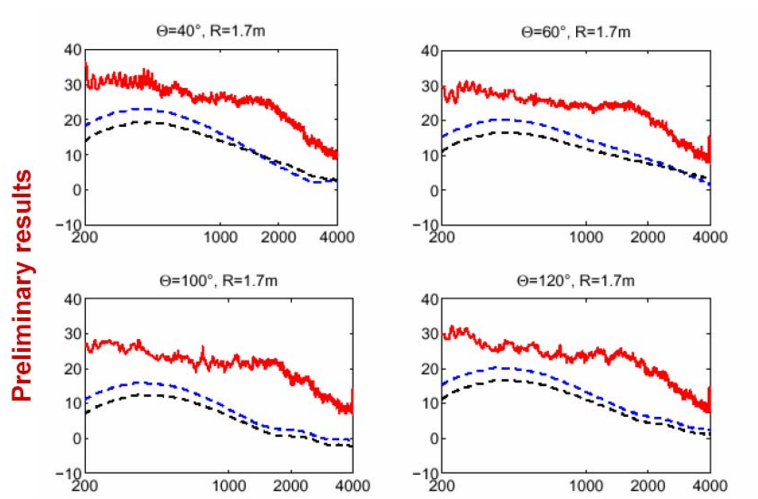
Preliminary results



Q6

Trailing-edge noise model (extended Amiet) only. Input data from measured blade wall pressures. Another mechanism is suspected at low frequencies (turbulence-interaction noise ?).

Application to a low-speed fan (CETIAT-ECL)   case 2



Trailing-edge noise model only. Vortex-shedding noise is suspected at high frequencies. Calculations still in progress.

Questions

Q1 Flat-plate assumption / thickness and camber effects ?

Q2 What about the refraction effects ?

Q3 Are the input data suited/available ?

Q4 Can they be deduced from standard steady CFD ?

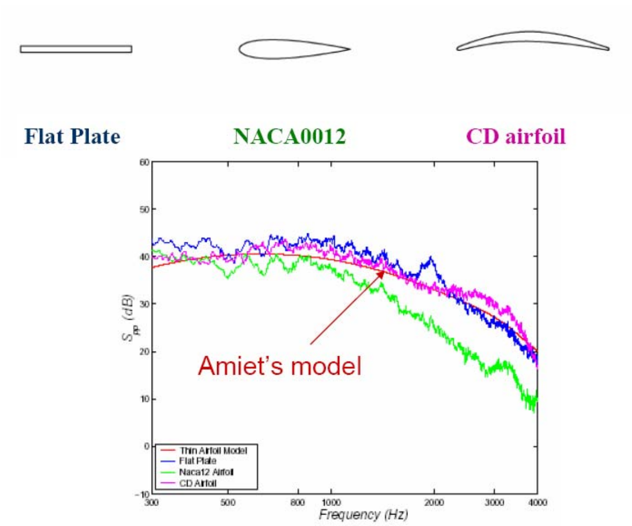
Q5 Limitations of the existing unsteady CFD ?

Q6 Extension from stationary airfoil to rotating blades ?

Q7 How does the single-airfoil response compare with respect to a cascade response (S. Glegg) ?

Pieces of answers for questions

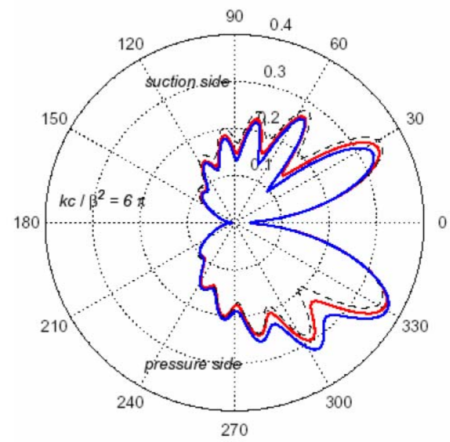
Q1 Thickness is important for turbulence-interaction noise



From Moreau et al AIAA paper 2005-2973

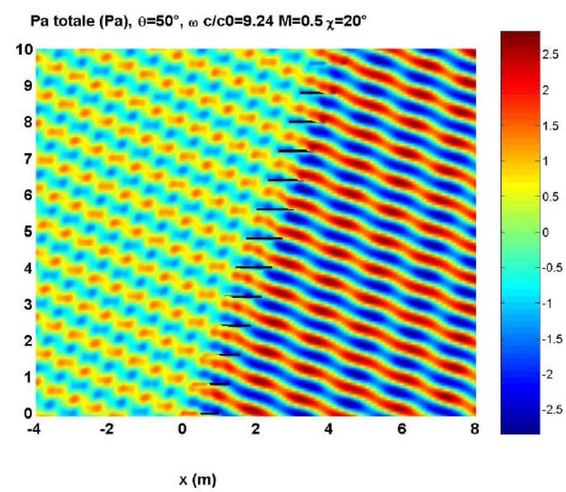
Camber correction for turbulence-interaction noise.

The induced unsteady lift from Amiet's theory is distributed over a curved mean camber line for radiated noise calculations



From Moreau et al AIAA paper 2005-2973

Cascade effect (see Stewart Glegg)



Oblique wave transmission through a blade row showing evidence of a cascade effect (*Hélène Posson using Glegg's model, work on progress*)

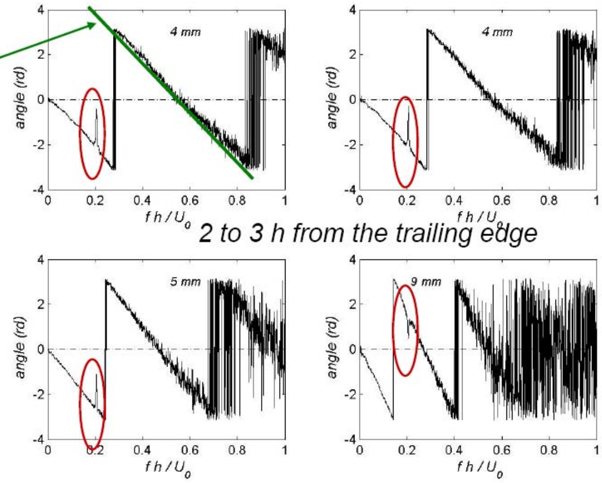
Similar effects expected on sound generation from impinging turbulence.

Phase diagrams from streamwise sensors (5° angle of attack)

Generally used to provide the convection speed of boundary layer disturbances (main slope over an extended frequency range)

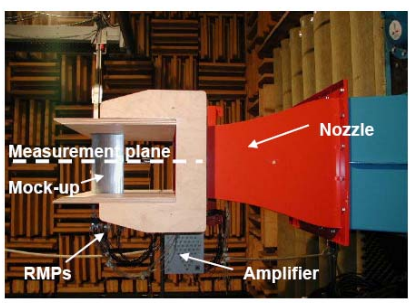
$$\frac{U_c}{U_0} = 2\pi \frac{\eta}{h} \frac{\Delta S_t}{\Delta \phi}$$

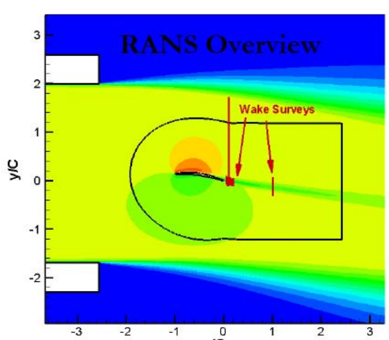
$$\boxed{\frac{U_c}{U_0} \approx 0.7}$$



Accidents at Strouhal 0.2 confirm a different mechanism and a non-convective effect on the wall-pressure.

CD-airfoil test case (VALEO)





← RANS set-up simulation

← Measured boundary conditions for LES computations

Invited Presentation:
Fan Broadband Noise :
What do we Need to Know ?

Stewart Glegg
Florida Atlantic University

Professor Glegg began by posing the following fundamental questions:

•What is the dominant broadband noise source on a modern high bypass aeroengine, and what evidence is there to support this?
•What is the possibility that RANs,LES, and DNS methods will be able to compute the broadband noise from a complete fan stage?
•How accurately can analytical/empirical techniques capture the physics of noise generation in real aero engines?

Following earlier discussion in the day he raised some additional questions:

Experimental Testing
–Scaling
–Frequency shifts
–Low frequency rig noise
–Isolated airfoil measurements in wind tunnels
FEM methods
Integration of Analytical and Numerical Methods

Professor Glegg started by summarising the basic sources of fan broadband noise. He highlighted the dominance of rotor – stator interaction noise over rotor self-noise by showing a result from the Boeing tests. It showed that the rotor – stator interaction exceeded the self-noise source by between 2 and 5dB depending on the number of stator vanes. In general, the figure showed the broadband noise increases in rough proportion to the number of vanes.

Stewart then proceeded to illustrate the complexity of the unsteady velocity field by showing a contour map of the rms turbulence velocity plotted over a duct cross section. The increased turbulence in the wake is clearly visible. He then showed another result from the Boeing test which demonstrates the effect of rotor tip gap on turbulence levels. Increasing the tip gap was shown to be substantially increase the turbulence in the boundary layer. Stewart the turned his attaention to the effect of balde loading on fan broadband noise. Whilst loading was shown in the Boeing test to have only a marginal effect of the noise, the reason for this was found to be surprisingly subtle. Increasing the loading was shown to reduce the flow velocity onto the stator vanes but at the same time increase the turbulence intensity. The combined effect is a negligible change in total radiated sound power.

Stewart concluded by discussing the data required to fully characterise a turbulent wake. He showed the turbulent energy distribution in the wake of a single aerofoil as measured by Devenport. Stewart then described how the traditional Fourier representation of turbulence was very inefficient. A more efficient representation was thought to be a modal representation of the turbulent field that closely matches the modes of the duct.

Open discussion

Professor Roger raised the issue of using strip theory to account for the spanwise variation in aerodynamic parameters and how this can be used to match to the radial modes in the duct. A general discussion occurred between Nigel Peake and Stewart Glegg concerning the correctness of the cutoff conditions in the use of the high frequency approximation. Nigel assured the audience that these were correctly treated. Phil Joseph questioned whether it necessary to include the duct in the computation of sound power from the cascade. Following wider audience discussion on this subject no clear consensus emerged about the answer.

Fan Broadband Noise

Introduction

Questions

- What is the dominant broadband noise source on a modern high bypass aeroengine, and what evidence is there to support this?
- What is the possibility that RANs,LES, and DNS methods will be able to compute the broadband noise from a complete fan stage?
- How accurately can analytical/empirical techniques capture the physics of noise generation in real aero engines?

Additional Questions

Experimental Testing
- Scaling
- Frequency shifts
- Low frequency rig noise
- Isolated airfoil measurements in wind tunnels

FEM methods

Integration of Analytical and Numerical Methods

Fan Broadband Noise: *What do we need to know?*

Presented at the Fan Broadband Noise Workshop

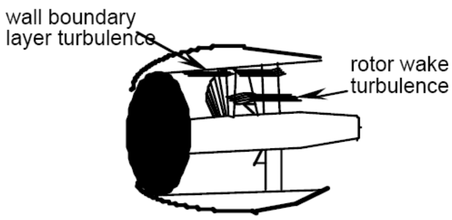
ISVR, Southampton University

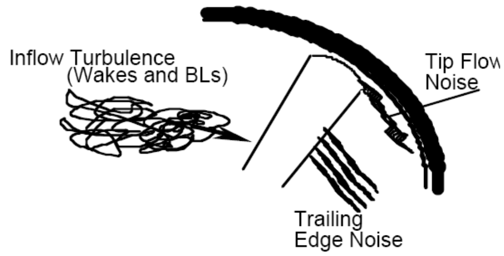
September 2006

Stewart Glegg

Florida Atlantic University

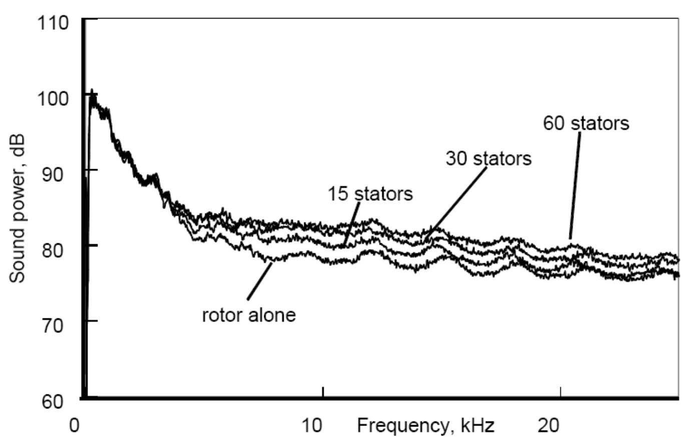
Broadband Fan Noise





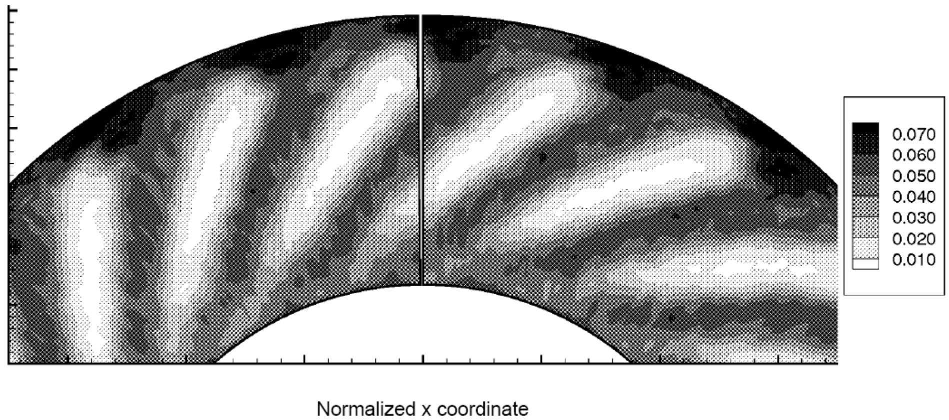
- Inflow Turbulence: Wall BL and Rotor wakes
- Rotor Self Noise: Trailing Edge Noise and Tip Flow Noise

Importance of Rotor Stator Interaction



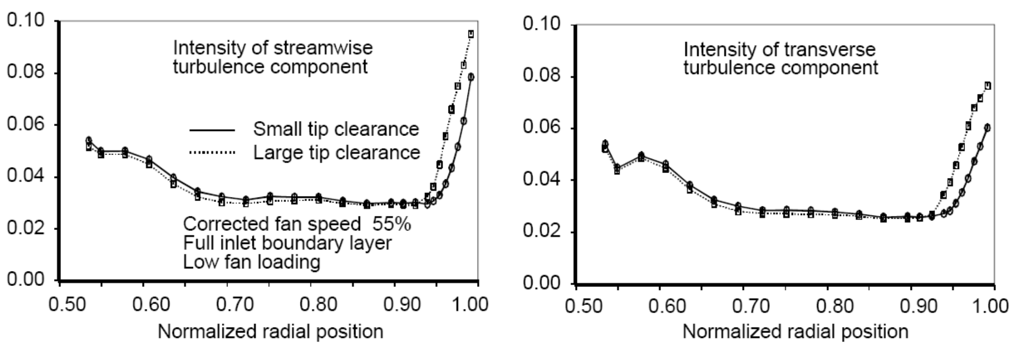
Results from Boeing Fan Rig Test

Unsteady Flow in the Fan Duct



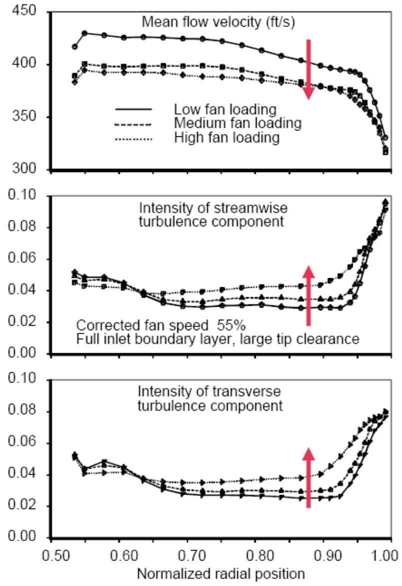
Results from Boeing fan Rig Test

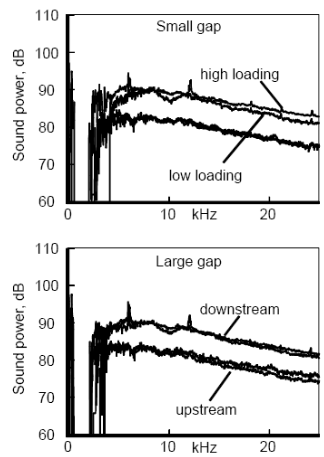
Effect of Tip Gap Size on the Unsteady Flow in the Fan Duct



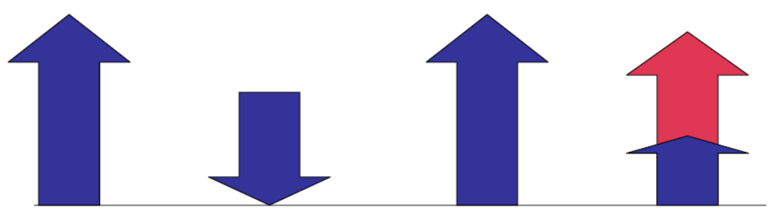
Results from Boeing fan Rig Test

Effect of Loading on Mean Flow, Turbulence and Noise from the Stators





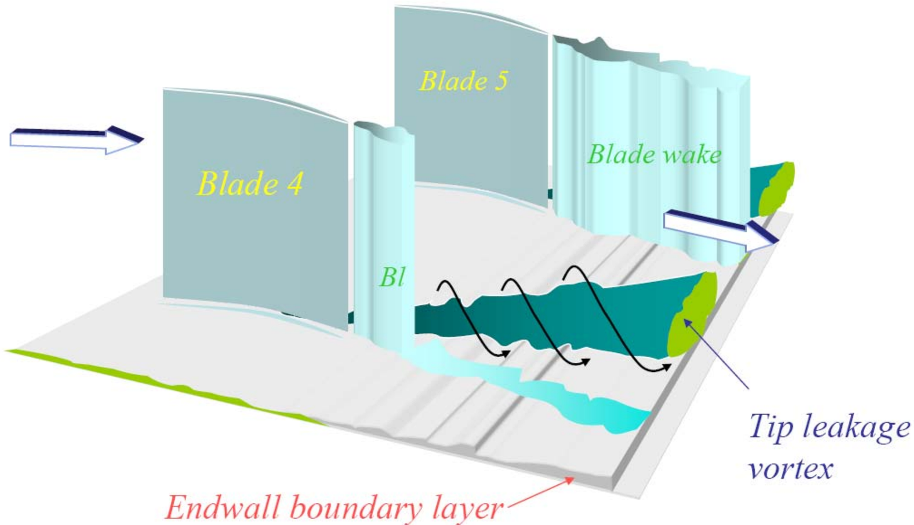
Effect of Loading on Stator Noise



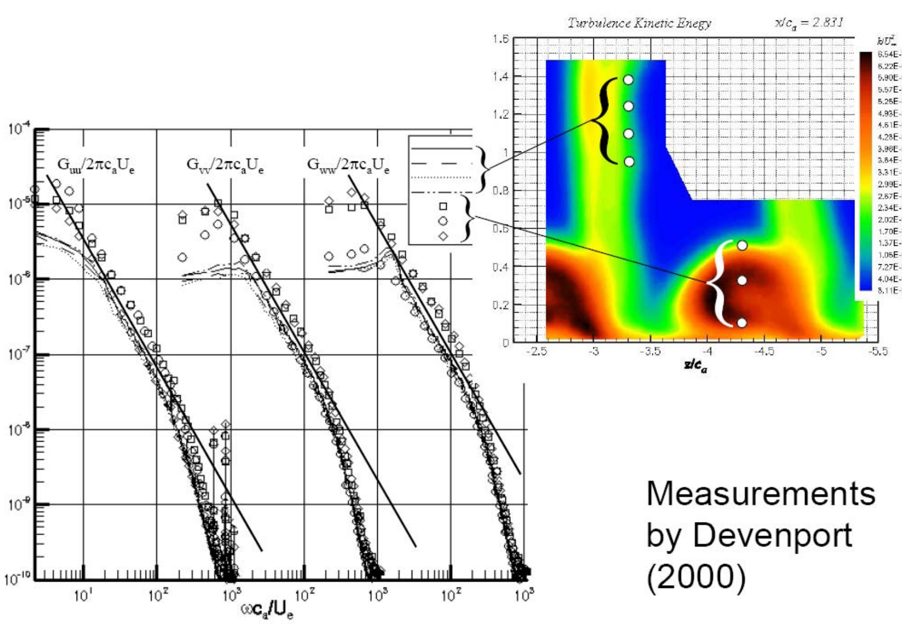
Loading Mean Flow Turbulence Noise

The noise increase due to loading depends on the engine design

The Blade Wakes



Velocity Spectra in the Wake



Measurements by Devenport (2000)

What We Need to Predict Stator Noise

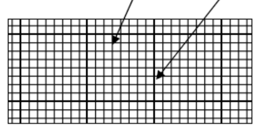
• The Mean Flow Velocity Distribution in the Fan Duct (RANS)
• The Turbulence Intensity Distribution (RANS)
• The 3D blade response function and how it couples with duct modes (Only rectilinear models available)
• A fully coupled model for propagation through the blade rows (Hanson)
• 6 components of the wavenumber spectrum for the turbulence in the fan duct (not known)

$$\Phi_{ij}(\mathbf{k},\omega) \quad \text{or} \quad u_i(\mathbf{x},\omega)=\sum_{m,n=1}^{\infty} a_{m,n}(\omega)\phi_i^{(m,n)}(\kappa_{mn}r)e^{im\theta+ik_{mn}x}$$

$$\text{and} \quad \mathrm{Ex}[a_{m,n}(\omega)a_{m',n'}(\omega)^*]$$

Statistical Description of the Flow

$$Ex[u_i(\mathbf{x},t)u_j(\mathbf{x'},t')]=R_{ij}(\mathbf{x},\mathbf{x'},t,t')$$



Note: for homogeneous stationary flows the correlation function is only dependent on *t-t'* and **x-x'**

Invited Presentation:
Fan Broadband Noise

Nigel Peake
University of Cambridge

Nigel began with a review of past and present projects that he is involved with related to the understanding of fan broadband noise. Before proceeding to talk about broadband noise Nigel presented some results relevant to unsteady distortion noise in which tones are generated by the stretching of initially isotropic turbulence. He then presented some results on the broadband noise radiated though turbulence – cascade interaction. Whilst stator blade geometry was found to be important for tones, its effect on broadband noise was shown to be much less significant. A graph was presented showing the variation of noise power spectrum for various blade thicknesses. Differences of not more than 2dB were predicted between flat plate calculations and for a blade with 12% thickness.

Professor Peake presented a list of the assumptions made in his model of broadband rotor – stator interaction, which included the propagation and distortion of the wake though the swirling flow. Nigel showed plots of the unsteady wake velocity across various duct cross section to illustrate the disorting effect of the swirling flow. He then reminded the audience that aerofoil radiation is only efficient when the phase speeds of the incident gust along the blade leading edge is supersonic. Nigel then presented contours of phase speed against OGV sweep and lean which showed clearly the combinations of both parameters for which efficient radiation occurs.

Professor then addressed the issue of sound generation across vortical flows and showed that under circumstances the mean vorticity can couple the unsrteady vorticity to the to the fluctuating pressure. An interesting observation by Nigel is that sound propagation thought the swirling flow causes it to grow algebraically, suggesting that the presence of swirl is a fundamental feature that must be included in the prediction. Nigel then concluded with a review of work undertaken on exhaust noise involving sound propagation though flows of different velocities.

Open Discussion

Dr Joseph asked Professor Peake to speculate on whether wake skewing and stretching would have a significant effect on fan broadband noise as it does for tones. Nigel replied that the computations were ongoing but thought that it was unlikely that the effect would be significant.

Professor Peake agreed with Professor Glegg that his earlier views on the modelling of the cascade response function had been reasonable.

Fan Broadband Noise

Southampton, September 2006

Nigel Peake

N.Peake@damtp.cam.ac.uk

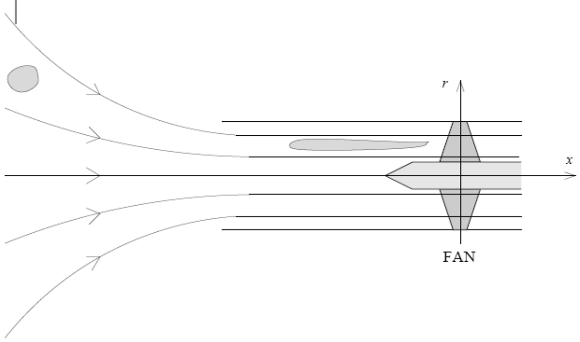
DAMTP & CUED

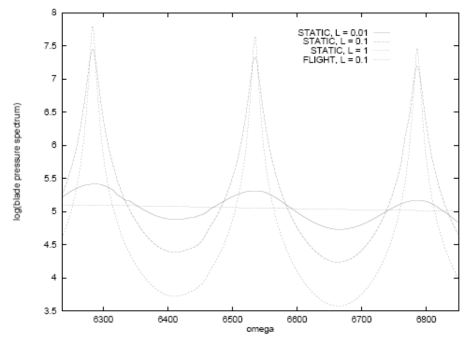
University of Cambridge

Some past and current projects

- Unsteady distortion noise (Sharan Majumdar, Rolls-Royce/EPSRC CASE award).
- Cascade-turbulence interaction (Ingmar Evers, EPSRC DTA).
- Rotor-stator tonal noise (Alison Cooper, EPSRC PDRA).
- Stability of vortical mean flow (Chris Heaton, EPSRC DTA).
- Rotor-stator broadband noise (Adrian Lloyd & Qinling Li, EPSRC).

Unsteady distortion noise





Generation of tones associated with stretching of initially isotropic turbulence.

Cascade-turbulence interaction

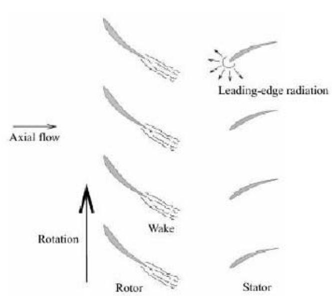


FIGURE 1. Rotor–stator interaction.

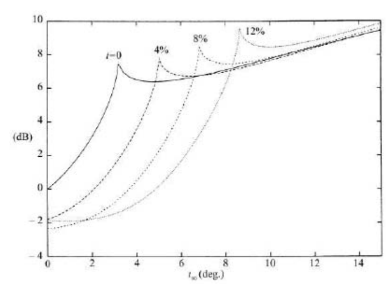


FIGURE 6. Normalized energy flux for a cascade of NACA 00XX blades for varying angle of attack.

Effects of stator blade geometry included - crucial for tones....

$$\Pi \sim \int \phi_{22}|A_N|^2 + \phi|A_T|^2 + 2\mathrm{Re}(\phi_{12}A_N A_T^*)$$

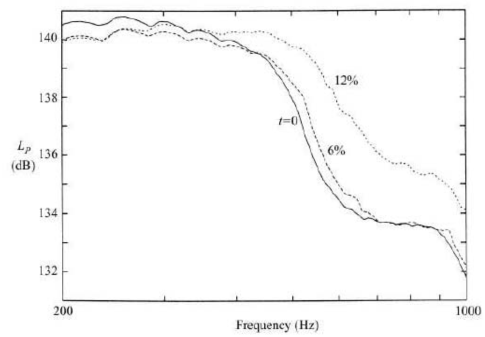
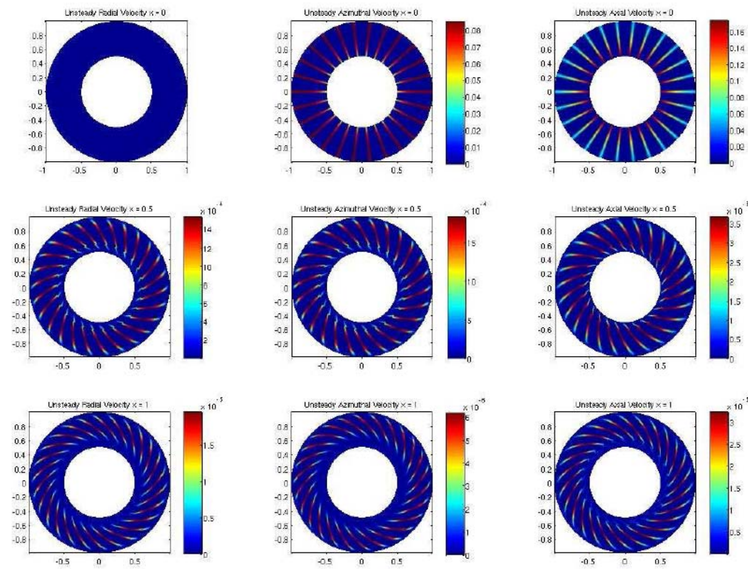


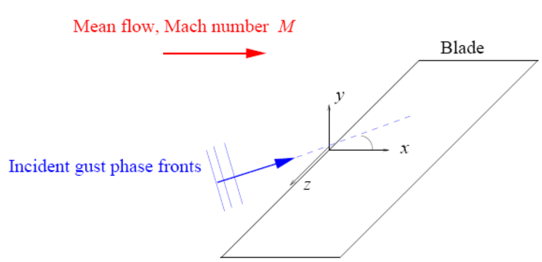
FIGURE 11. Noise spectrum for a cascade of uncambered airfoils at zero angle of attack, with thicknesses $t = 0$, 6, 12% of chord. Here $M_\infty = 0.5$.

Prediction of rotor-stator noise

- Modelling using high blade number asymptotics.
- Propagation and distortion of wake through swirl.
- Now included dissipation terms to model turbulent diffusion
- Interaction of distorted wake with stators.
- Generation and propagation of resulting noise.



For tonal noise...



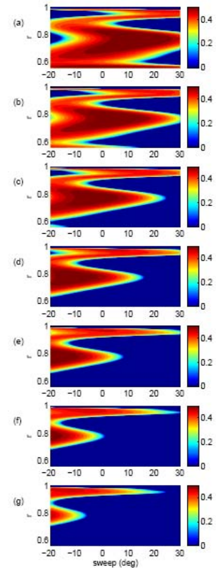
Gust component

$$\exp(\mathrm{i}kt - \mathrm{i}k[x + k_y y + k_z z])$$

Noise radiated if

$$w^2 \propto \frac{M^2}{(1 - M^2)} - k_z^2 > 0$$

i.e. AS LONG AS GUST IS NOT ‘TOO’ OBLIQUE.

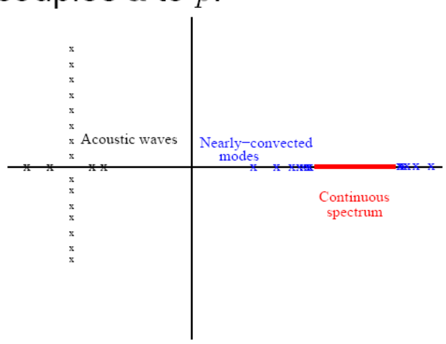


Contours of $w^2 > 0$, against OGV sweep, varying lean.

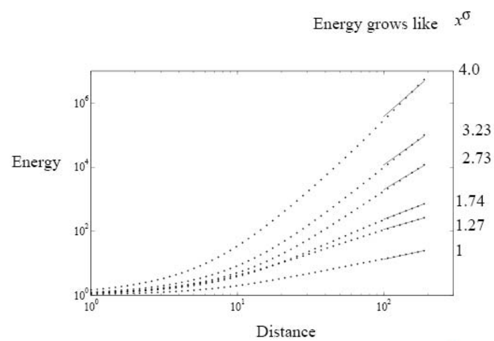
Vortical mean flow - basic issue

$$\mathbf{u}(\mathbf{x},t) = \mathbf{U}(\mathbf{x}) + \nabla\phi(\mathbf{x},t) + \mathbf{a}(\mathbf{x},t) \quad , \qquad p = -\rho_0 \frac{D\phi}{Dt}$$

Mean Vorticity couples $\mathbf{a}$ to p.



Algebraic growth



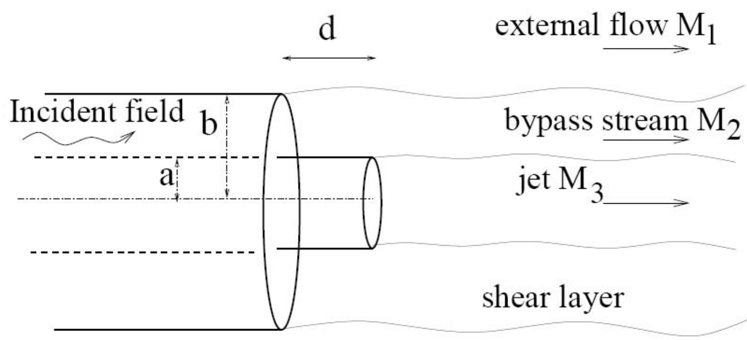
- Algebraic growth in rotor-stator gap? (Large swirl, short distance)
- Algebraic growth in bypass duct? (Small swirl, larger distance)

EPSRC project on broadband noise

- Computation and modelling of broadband noise due to wake-OGV interaction.
- NP, WND and Mark Savill (Cranfield). Start date 25.09.06.
- LES of rotor wakes, distortion of large eddies.
- Numerical and analytical approaches to radiation problem.

Exhaust noise

- NP, RJA & GG (ISVR) and David Abrahams (Manchester).
- Exact solution using matrix Wiener-Hopf method - buried case now done.



Invited Presentation:
What affects Fan Broadband Noise and what doesn't?
Possibilities for Noise Control

Phil Joseph
Institute of Sound and Vibration Research

Phil Joseph began by reminding the audience that theoretical predictions and experimental data suggests that fan broadband noise is insensitive to *most* changes that can realistically be made on an aero-engine. Does this truism suggest that fan broadband noise should be easy to predict with accuracy? Furthermore, what can be done to reduce fan broadband noise? Dr Joseph stated that the objective of his talk is a brief review of recent work performed at the ISVR aimed at assessing this sensitivity.

Dr Joseph began by reviewing his recent work on turbulence – cascade interaction noise. He discussed the evidence for a critical frequency, above which, the radiated sound power fro the cascade is proportional to the number of stator blades suggesting that cascade effects are comparatively weak. This concept has allowed an analytic expression to be derived for the radiated sound power from the cascade that is valid only above the critical frequency. Phil summarised the results of a parametric study of turbulence – cascade interaction noise and presented a list of parameters on which rotator – stator interaction noise is robust.

Phil Joseph then proceeded to discuss the effects of sweep and lean on fan broadband noise. This issue was addressed by reference to the experimental results made on an Allison fan tested in the NASA Glen wind tunnel. It showed that the combined effects of sweep and lean produced a reduction in fan broadband noise by no more than about 2 to 3dB.

Continuing with the theme of robustness to changes, Dr Joseph presented predictions of turbulence intensity and length-scale for a fan at six different working lines. Changes were shown to be exceeding small whose effect on broadband noise is likely to be limited to just a few decibels.

Phil Joseph then discussed his recent work on rotor self-noise. He began by summarising the assumptions made in his model, which is essentially a flat plate model with the use of correlation results to deduce the surface boundary layer spectrum from the steady flow speed, angle of attach and the chord. Results were shown to be roughly consistent with the well-known Brook's prediction scheme for aerofoil self-noise prediction. Aerofoil geometry was demonstrated to produce only minor changes to the radiation directivity except at high reduced frequency and Mach number.

Dr Joseph presented some preliminary DNS predictions made by Richard Sandberg of the noise radiated by a single harmonic vortical gust convecting over a half-plane. The aim of this study was to validate the classical flat plate in which viscous effects are absent. Comparison with the flat plate theory was generally good.

Phil Joseph concluded his talk on some predictions of rotor self-noise predictions. The results of a parameter study was shown indicating the power spectrum versus balde setting angle and Mach number. Noise was demonstrated to increase by about 1.4dB per increase in blade angle. He also presented a comparison of the noise between a four-bladed fan and a twelve bladed fan, with the latter having a chord 1/3 of the former so that their thrust areas remained constant. The twelve-bladed fan was shown to produce the lowest noise despite having far fewer blades (and therefore trailing edges). This was because the thinner boundary layer developed on the shorter chord and hence lower turbulence intensity.

Open Discussion

Much of the comments on Dr Joseph's talk centred on the DNS results and the interpretation of some spurious wakes in the DNS solution. Richard explained that these were due to pressure fluctuations in the wake which at some angles dominates the total radiated sound field.

Responding to Dr Joseph's assertion that the duct does not have a significant effect on the broadband sound power, Professor Peak suggested that rotor directivity must be modified since it does not radiate sound on-axis unlike ducted rotors. Dr Joseph conceded that might be the case but the total radiated sound power might still remain the same with and without the duct.

What affects fan broadband noise and what doesn't?

Possibilities for noise control

P. Joseph

How can fan broadband noise be affected?

Theoretical predictions and experimental data suggests that fan broadband noise is insensitive to *most* changes that can realistically be made in an aero-engine

Is this correct?

If so

Does this mean that fan broadband noise should be easy to predict accurately?

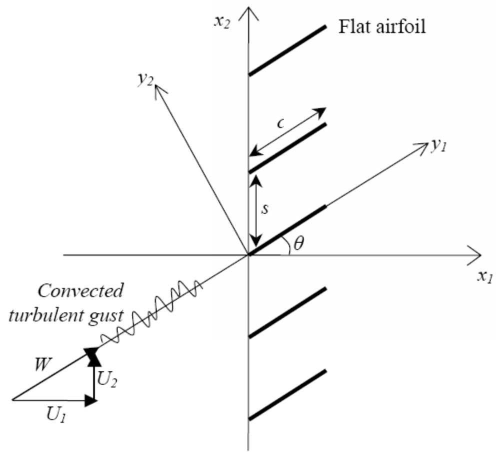
What can be done to reduce significantly fan broadband noise?

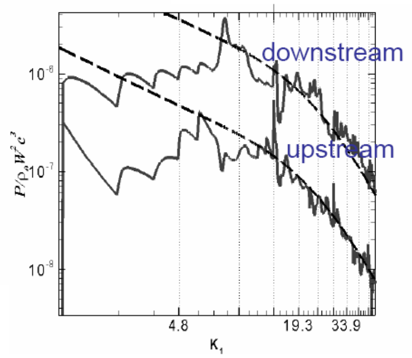
This talk is a brief review of recent work performed at the ISVR aimed at assessing this sensitivity

Rotor – Stator Interaction

Turbulence- cascade interaction

A theoretical study by Cheong and Joseph has recently been undertaken of the spectrum of sound power due to interaction between **isotropic**, **homogeneous** turbulence with a *cascade* of **2*D*** flat plate airfoils

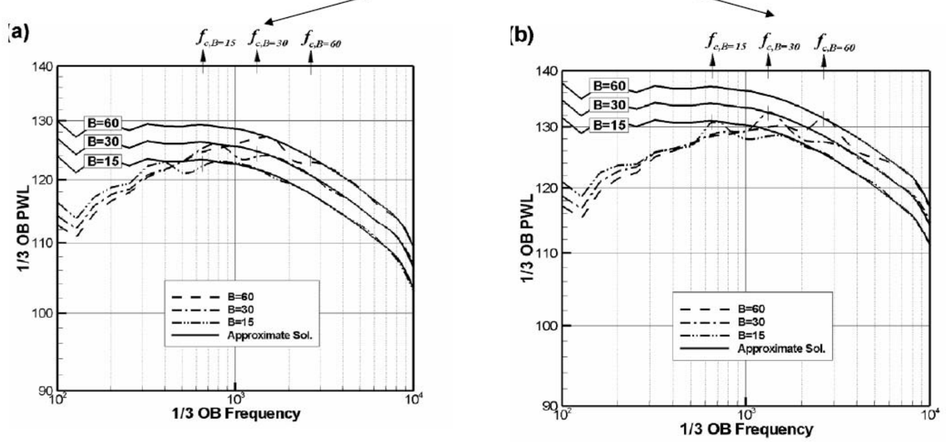




C. Cheong, P. Joseph, and S. Lee. High frequency formulation for the acoustic power spectrum due to cascsade-turebulence interaction. *J. Acoust. Soc. Am.* **119**, 108 (2006).

Sound power spectrum; Evidence for a critical frequency

$$\underbrace{f_c = B\Delta f_+ = \frac{1-M^2}{M_2 + \left(1-M_1^2\right)^{1/2}}\frac{a}{s}}$$



Upstream power

Downstream power

How significant are cascade effects?

A critical frequency f_c has been identified, corresponding to when λ = s

$$f_c = B\Delta f_+ = \frac{1-M^2}{M_2 + \left(1-M_1^2\right)^{1/2}} \frac{a}{s}$$

At $f = f_c$ all wavenumber components of turbulence excite propagating cascade modes, whereas below it, only some of the wavenumber components excite cuton modes.

$f < f_c$ — Noise *sensitive* to details of cascade

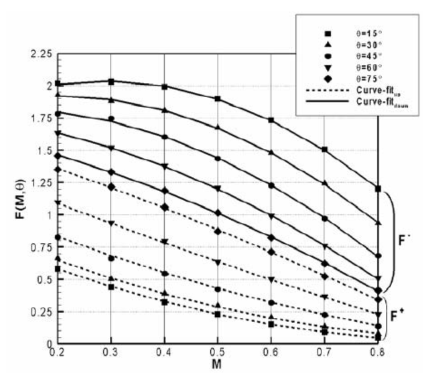
$f > f_c$ — Noise *robust* to details of cascade

High-frequency characteristics of cascade – turbulence interaction

Theoretical analysis of the high frequency spectrum of sound power per unit span for $\omega > \omega_c$.

$$P^{\pm}(\omega) \approx F^{\pm}(M,\theta) \frac{B\rho_0 a \Lambda \overline{w^2}}{\pi\omega\cos\theta} \frac{M^2\left(1-M^2\cos^2\theta\right)^{1/2}}{(1-M^2)} \frac{4+13\Lambda^2 K_1^2}{16\left(1+\Lambda^2 K_1^2\right)^{5/2}}$$

B	Number blades
a	Sound speed
$\overline{w^2}$	mean square turbulence velocity
Λ	turbulence length-scale
M	W/c
K_1	ω/W



Characteristics of cascade – turbulence interaction

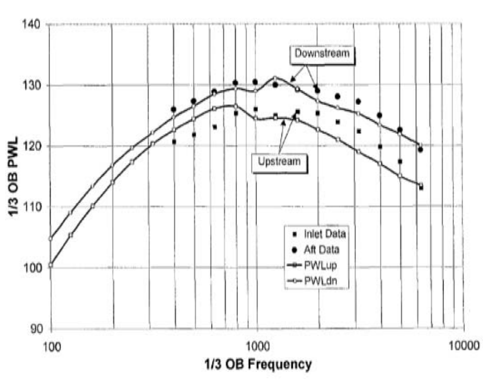
This result shows that, above the critical frequency, broadband noise power due to turbulence interacting with a cascade of flat plates is:

- Proportional to blade number
- Independent of chord and solidity
- proportional to $M^5 \rightarrow M^6$
- Weakly dependent on stagger angle
- Low noise for $\omega\Lambda/W$ << 1 and $\omega\Lambda/W$ >>1

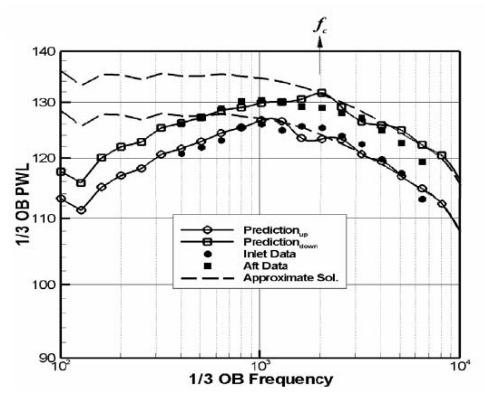
Rotor – stator interaction noise is therefore robust to these parameters

3D effects?

Similar agreement with experimental data obtained using 2*D* theory as that obtained by Hanson using 3*D* theory



Hanson 2001

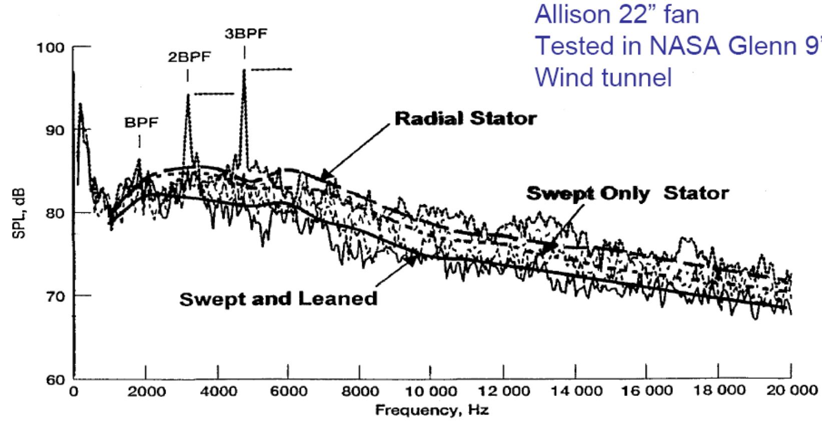


Cheong, Joseph, Lee 2005

Turbulence intensity = 2%
Length-scale/*R* = 3.5%

Sweep and Lean

Allison 22” fan
Tested in NASA Glenn 9’X5’
Wind tunnel

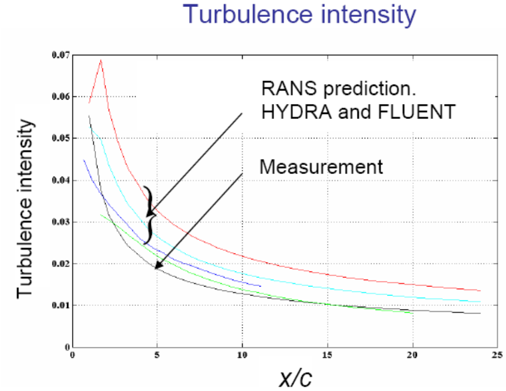


30º sweep: 1.1 dB reduction
30 º sweep and lean: 3.9dB reduction

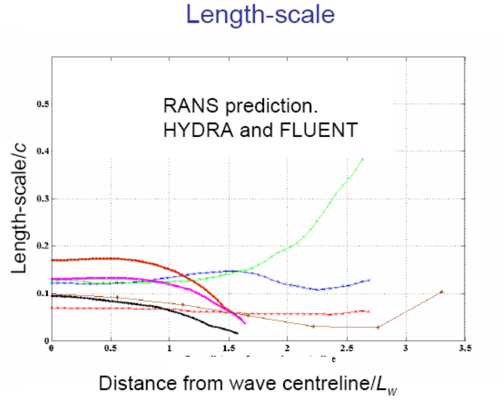
R. Woodward, D. Elliott, C. Hughes, J. Berton. 1999. Benefits of swept and leaned stators for noise reduction. AIAA 99 - 0479

RANS prediction of wake turbulence from a NACA0012 aerofoil

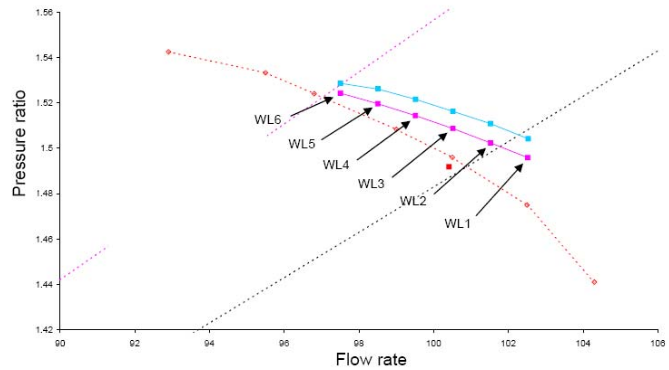
Turbulence intensity

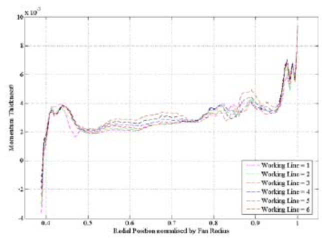


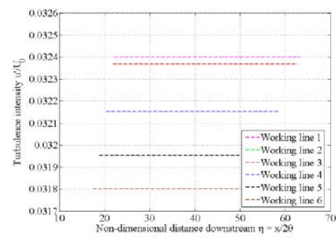
Length-scale

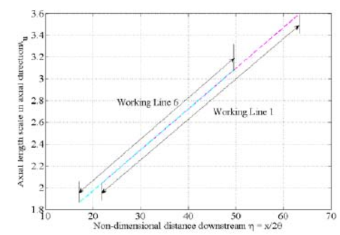


Effect of working line









Rotor Self Noise

Aerofoil and Rotor Trailing Edge Noise Prediction

A study has been undertaken of the trailing edge self-noise due to a single airfoil[1] and an open rotor[2]

Main elements of the broadband noise model are:

A numerical procedure to compute the sources over the blade surface

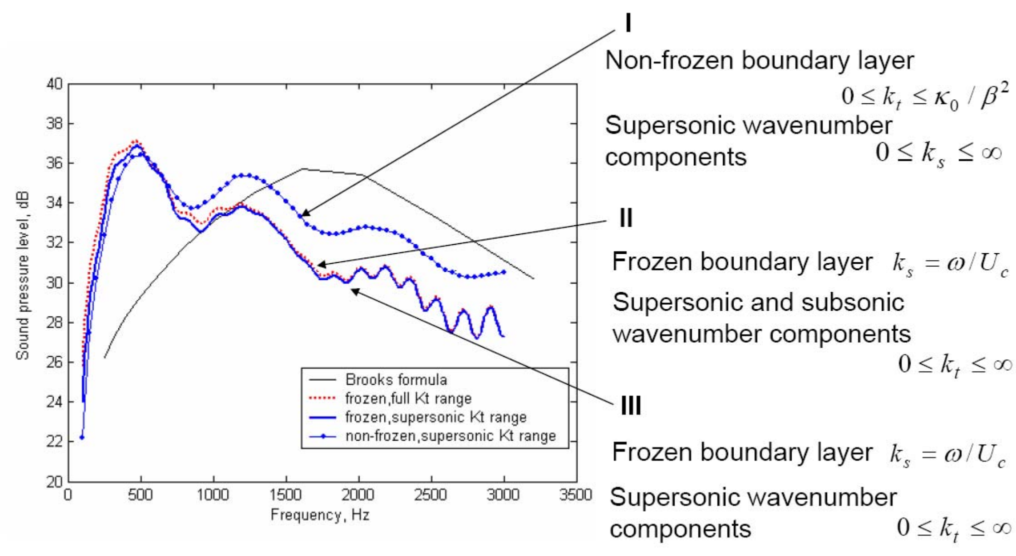
Empirical expressions to predict the boundary layer surface pressure spectrum as a function of incidence angle, flow speed and chord.

Use of unsteady aerofoil flat plate theory to compute the blade surface pressure

[1]Q.Zhou, P.Joseph. A frequency domain numerical method for airfoil broadband self-noise prediction. *Journal of Sound and Vibration* (In Press).

[2]Q. Zhou and P. F. Joseph. Frequency-Domain Method for Rotor Self-Noise Prediction, *AIAA Journal*, **44**, 1197

Self noise radiation from a NACA0012 aerofoil Comparison with the Brooks prediction scheme

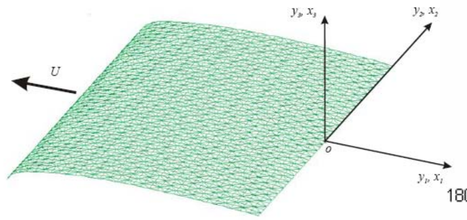


Self-Noise Directivity;
Effect of Airfoil Geometry

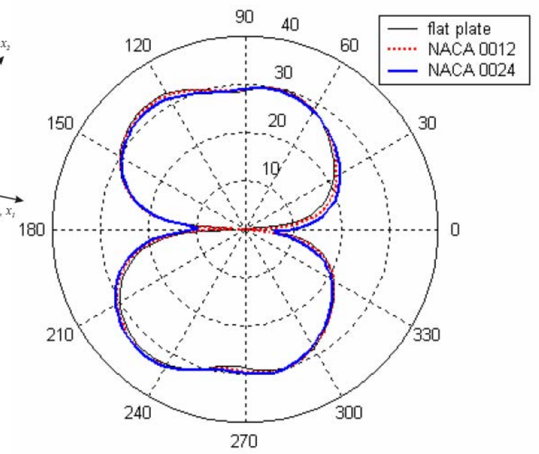
$\sigma_1 = 12.13$

$M = 0.3$

$\alpha = 4°$

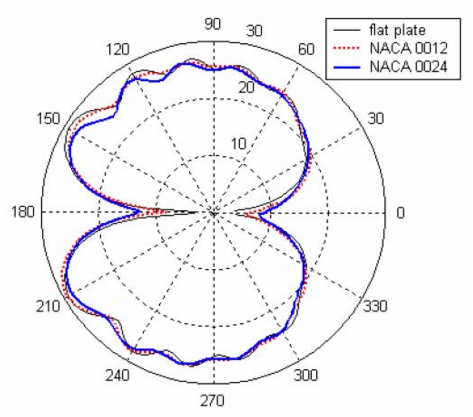


Polar Directivity

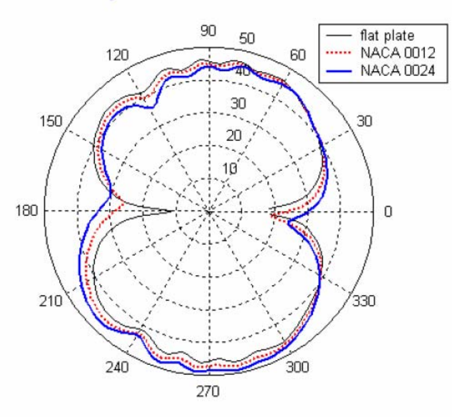


Effect on directivity of Mach number and frequency

Polar Directivity



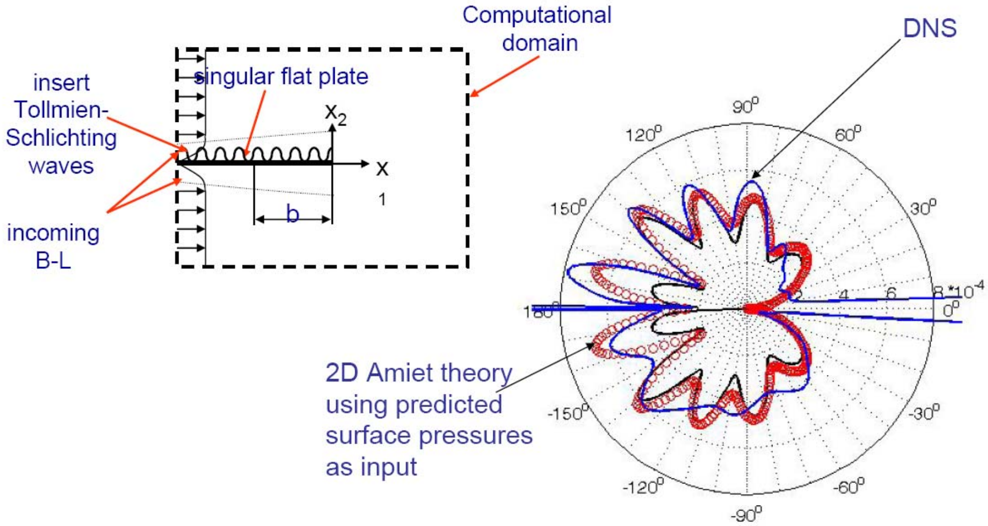
$\sigma_1 = 32.35$, $M = 0.3$



$\sigma_1 = 4.549$, $M = 0.8$

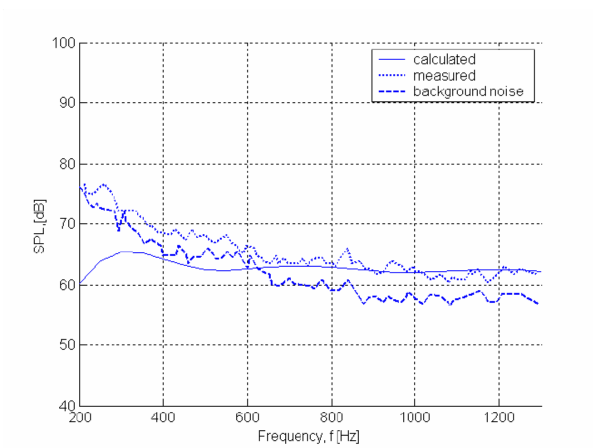
Blade thickness is important when hydrodynamic wavelength comparable to blade thickness

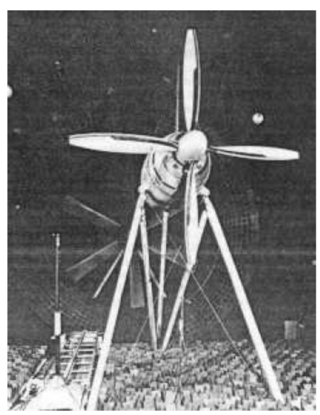
Relevance of the inviscid theory



R.D.Sandberg, N.D. Sandham, P. Joseph , DNS OF TRAILING-EDGE NOISE GENERATED BY BOUNDARY-LAYER INSTABILITIES, AIAA Paper 2006-2514

Comparison of R212 propeller broadband noise with experiment data

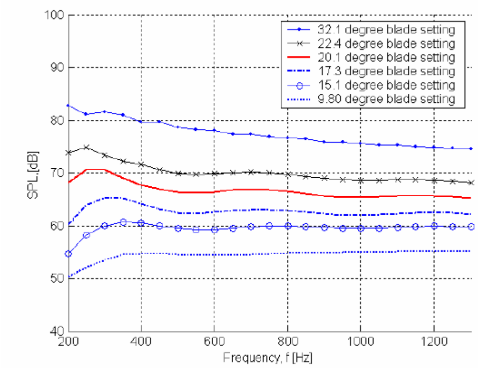




Experimental propeller

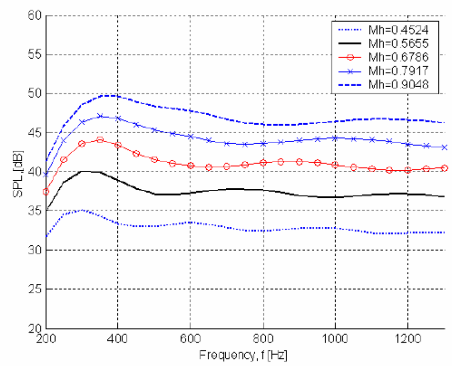
Blade angle and Mach number

Blade setting angle



$SPL \propto 1.4$ dB/degree

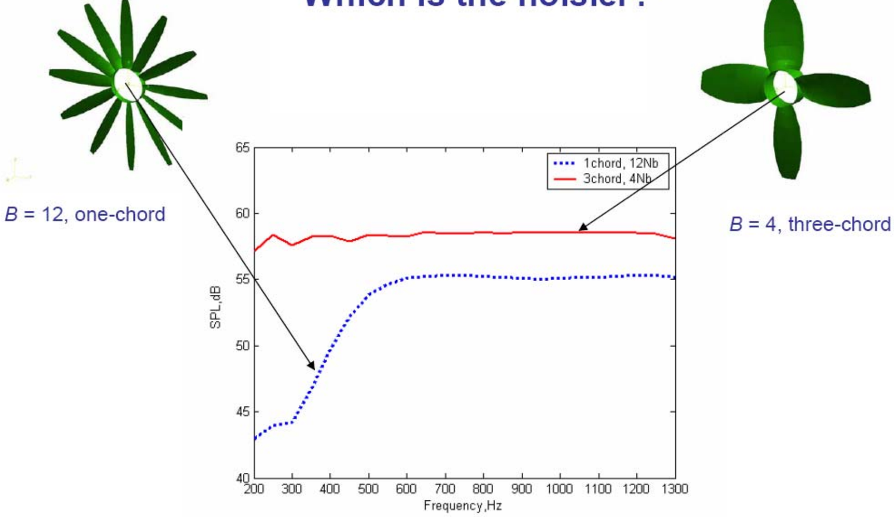
Blade tip Mach number



$SPL \propto 50\log_{10} M_h$

Two propellers with the same 'thrust-area'

Which is the noisier?



Propeller with the smallest chord develops thinner, less turbulent boundary layers and hence radiates less noise

Conclusion

- Fan broadband noise appears to be stubbornly robust to *most* changes in the engine that can be made realistically
- Large changes to the engine produce only small changes to the *bb* noise
- Significant reductions in noise can only be made by modifying the source of turbulence.
- In nearly all *bb* sources, the source of turbulence originates on the rotor
- Broadband noise may therefore be reduced by modifying the rotor

Suggestions for noise control:

More rotor blades – smaller chord?

leading edge treatments?

Wake management?

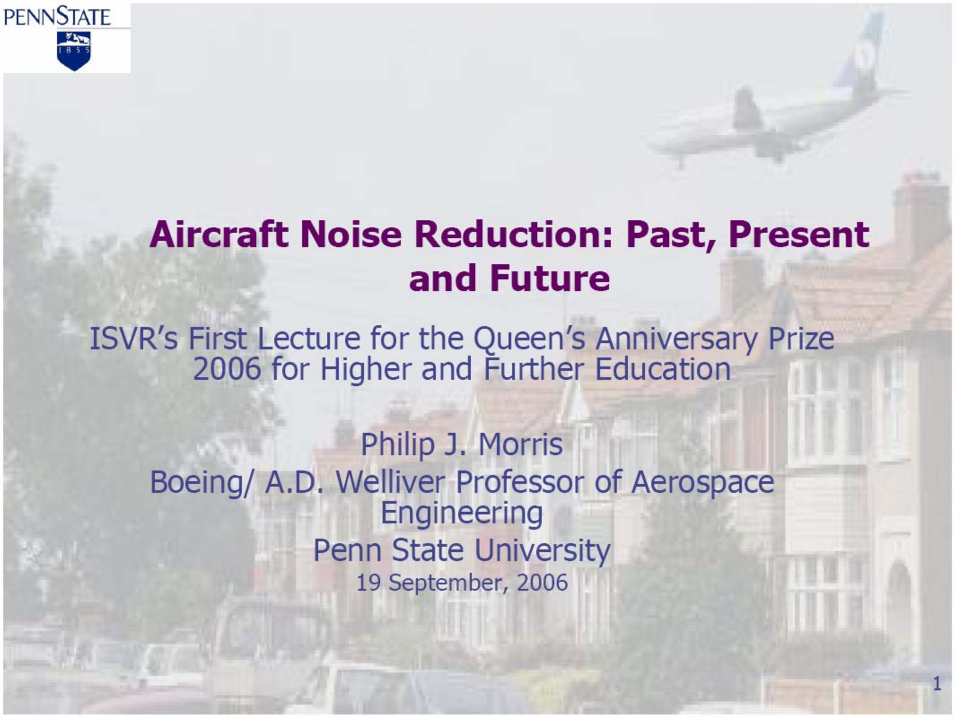
APPENDIX

The Queen's Anniversary Prize Lecture

Given by

Philip J. Morris
Boeing/ A.D. Welliver Professor of Aerospace Engineering
Penn State University

19th September 2006



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- Queen's Anniversary Prize 2006 for Higher and Further Education

- "Sustained excellence and outstanding achievements in research in the field of sound and vibration"

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The Institute of Sound and Vibration Research

Elfyn J. Richards

- First director – 1963
- Chief aerodynamicist at Vickers-Armstrong
- 1950 – first Professor of Aeronautical Engineering at University College, Southampton
- Joined by Alan Powell, 1951 – 1956.
  - Shock noise, screech, acoustic fatigue
- Vice-Chancellor of Loughborough University 1967-1975

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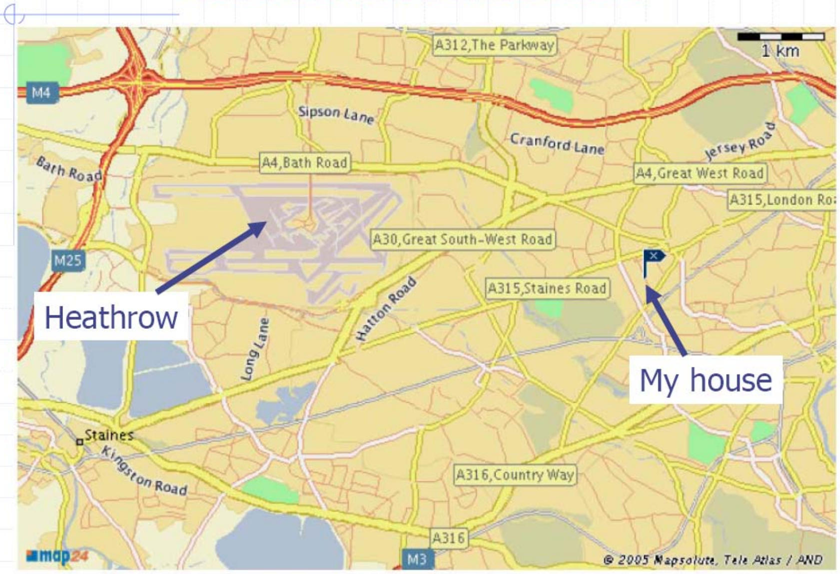
Interest in Aircraft Noise



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A Common Occurrence

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Outline

- Jet engine basics
- Some early activities
- Quantifying aircraft noise
- Sources of aircraft noise
  - Jet noise
  - Fan noise
  - Airframe noise
- The need for additional noise reduction
- Current research
- Future plans

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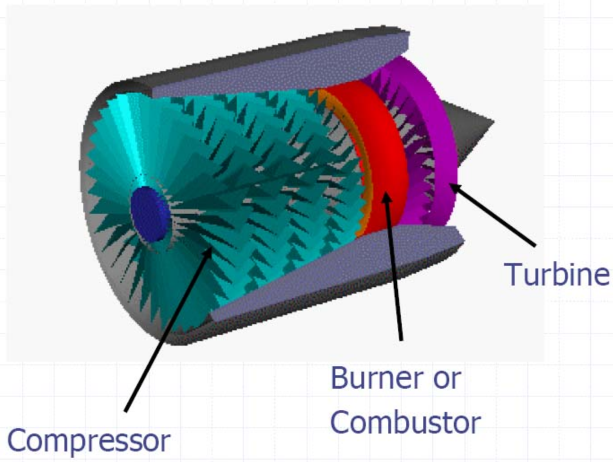
Core Engine



Credits: NASA Glenn Research Center

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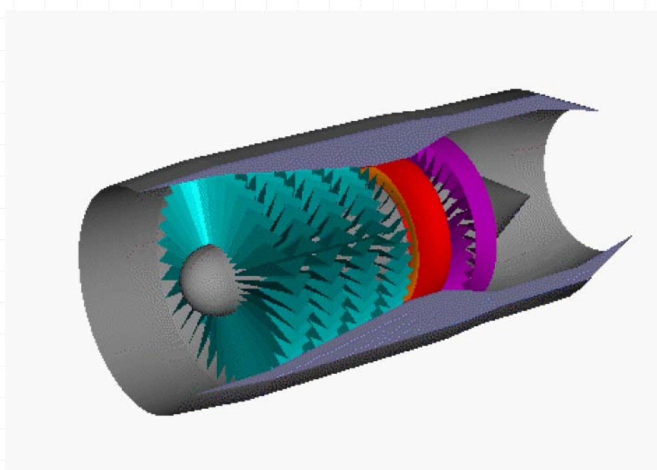
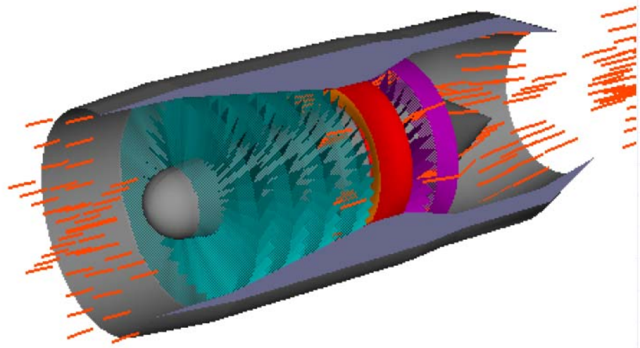
Turbojet Engine



Credits: NASA Glenn Research Center

8

Turbojet Engine



Credits: NASA Glenn Research Center

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Early Jet Aircraft

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Early Short Haul Aircraft


De Havilland Trident


Boeing 737-200


BAC-111


Sud Aviation Caravelle

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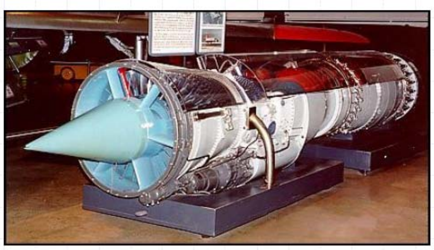
Early Jet Engines



- Pratt & Whitney, JT3
- 10,000 lbs thrust
- Turbojet

- A turbojet engine generates thrust from its exhaust jet
- The thrust is proportional to the square of the jet exhaust velocity
- Exhaust velocity $\simeq$ 2000 fps (650 m/s)

Very Noisy !!!

Credits – U.S. Air Force Museum

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Early Jet Noise Experiments

- UK
  - Cranfield: Lilley and Westley (1952)
  - Southampton: Powell (1953)
- USA
  - Wright Patterson Air Force Base: von Gierke (1953)
  - NASA Langley Research Center: Hubbard (1953)

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Early Jet Noise Theory

- Sir James Lighthill introduced an "acoustic analogy"
  - Recast the equations of motion into an inhomogeneous wave equation in a uniform medium at rest
  - Identified "equivalent sources" with a "quadrupole" character
  - Deduced simple scaling laws
  - The acoustic power radiated by a jet is proportional the eighth power of jet velocity
  - Provides a good correlation of noise measurements
  - The conversion of kinetic energy into acoustic energy is very inefficient

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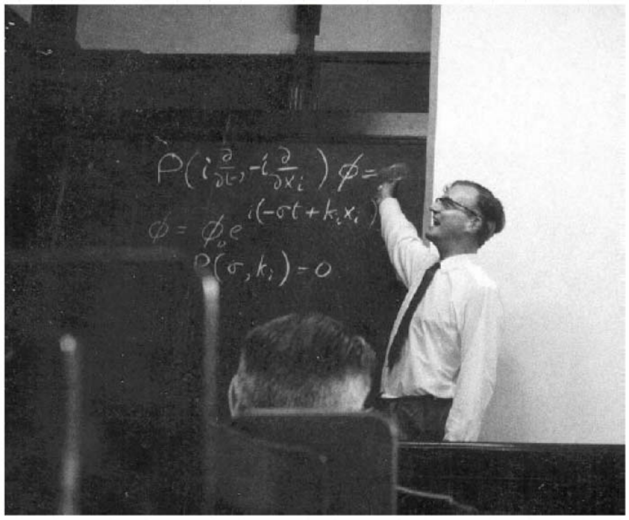
Sir James Lighthill



Credits: Malcolm Crocker, "SIR JAMES LIGHTHILL AND HIS CONTRIBUTIONS TO SCIENCE"

Lighthill's Eighth Power Law

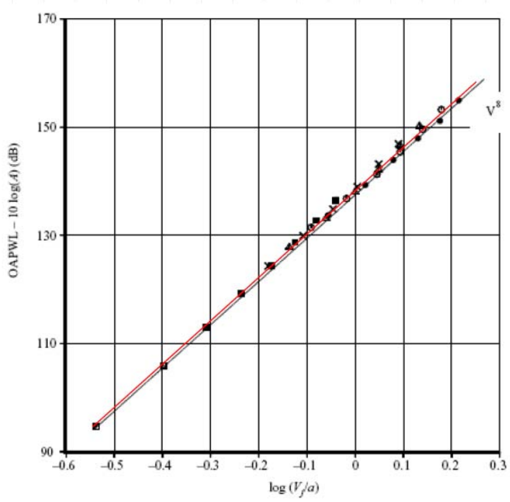


FIGURE 23. Variation of OAPWL with jet velocity, $D = 2.45$ in. Solid line: V^8. □, ■, $T_t/T_a = 1.0$; ×, 1.8; △, 2.2; ○, 2.7; ●, 3.2.

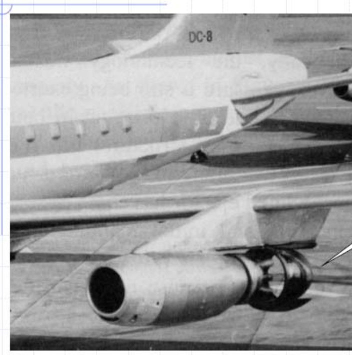
Credits – Viswanathan (2006)

Early Jet Noise Suppressors

8 corrugated silencers for Conway engines on a 707-420

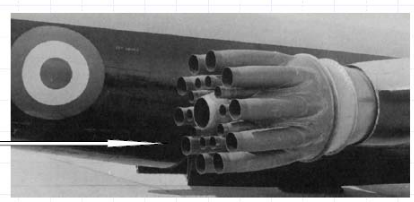
Credits – Michael J. T. Smith, "AIRCRAFT NOISE"

Early Jet Noise Suppressors



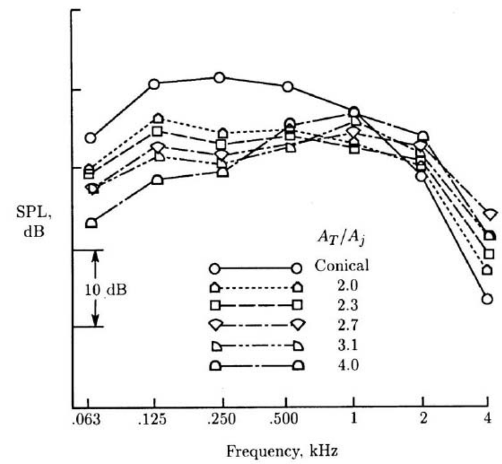
Ejector-suppressors on a 1960's DC-8

21-tube nozzle for a 1960's Boeing 707



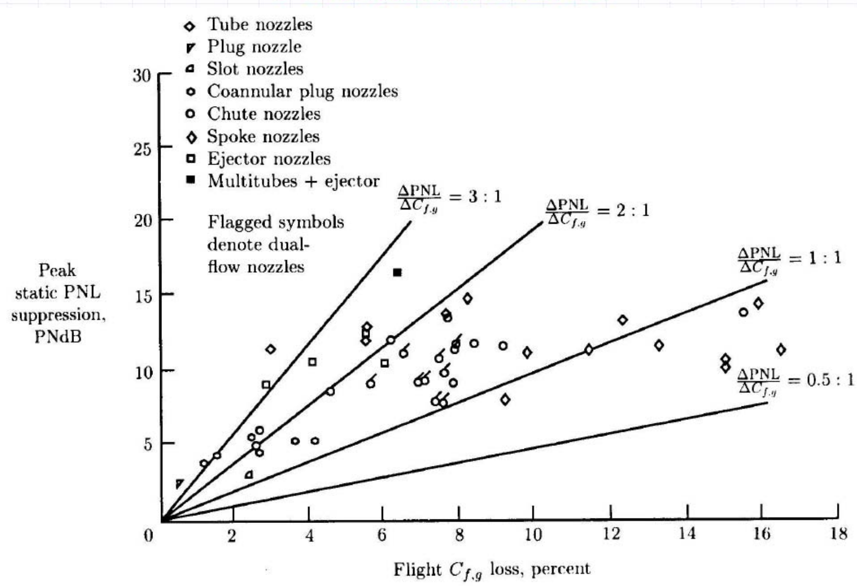
Credits – Michael J. T. Smith, "AIRCRAFT NOISE"

Effect of Multitube Nozzles on Spectrum



Credits – Harvey Hubbard (Ed.), "AEROACOUSTICS OF FLIGHT VEHICLES" 19

Performance Loss



Credits – Harvey Hubbard (Ed.), "AEROACOUSTICS OF FLIGHT VEHICLES" 20

Quantifying Aircraft Noise

- Many different metrics
- Aircraft certification is based on the Effective Perceived Noise Level (EPNL)
  - Accounts for perceived annoyance: measured in NOYS
  - Takes account of the presence of tones
  - Includes a duration factor
  - Three measurements:
    - Sideline noise (take-off)
    - Take-off (cutback)
    - Approach

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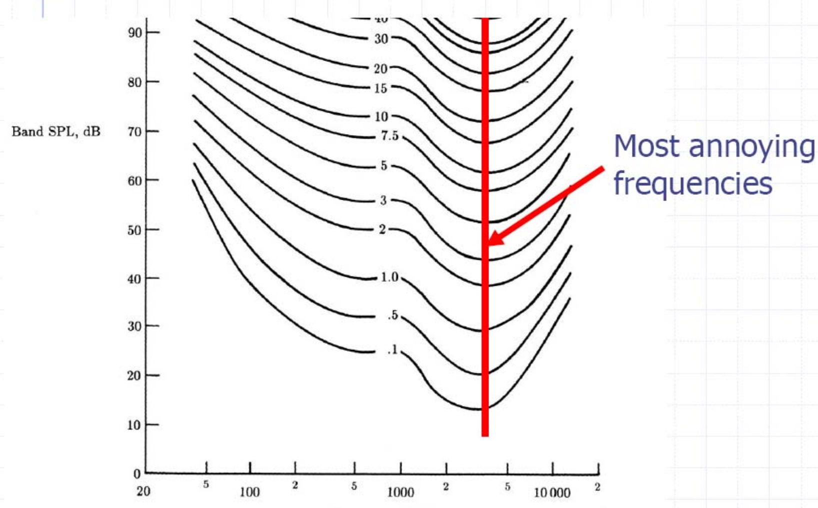
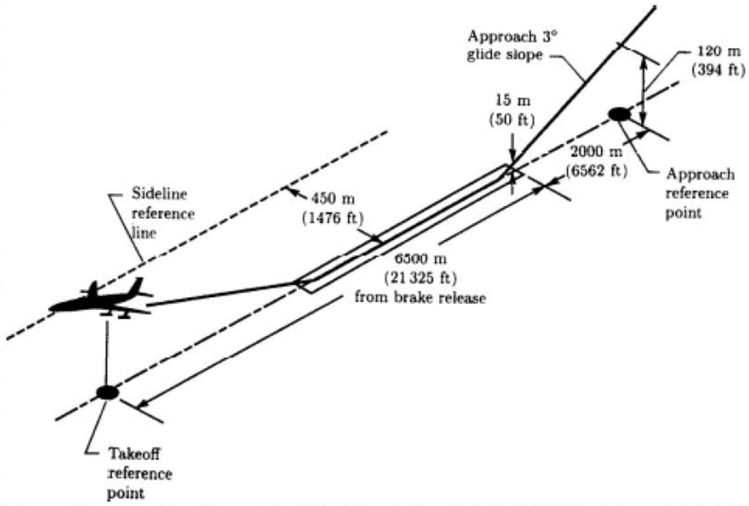
Curves of Equal Annoyance



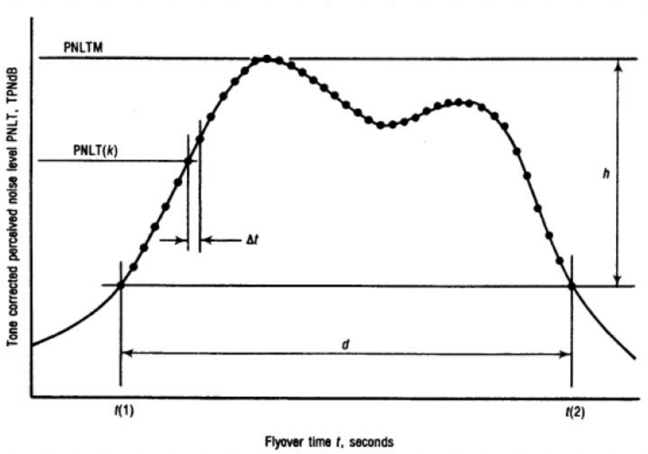
Credits – Harvey Hubbard (Ed.), "AEROACOUSTICS OF FLIGHT VEHICLES" 22

FAA Certification Flight Path



Credits – Harvey Hubbard (Ed.), "AEROACOUSTICS OF FLIGHT VEHICLES" 23

Example of Perceived Noise Level as Function of Time



Credits – FAA Federal Aviation Regulations Part 36, "NOISE STANDARDS" 24

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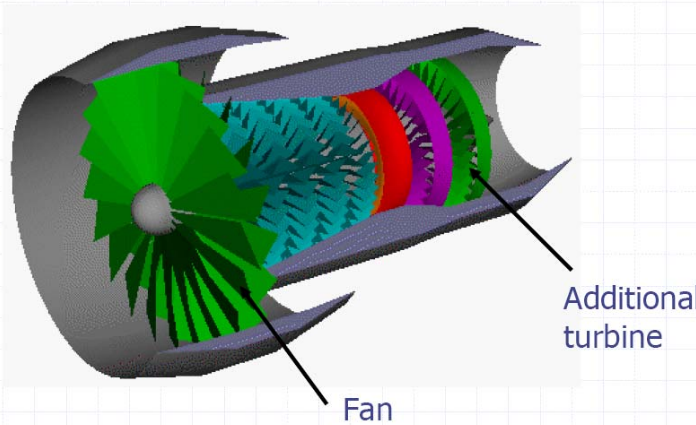
The Turbofan Engine



Credits: NASA Glenn Research Center

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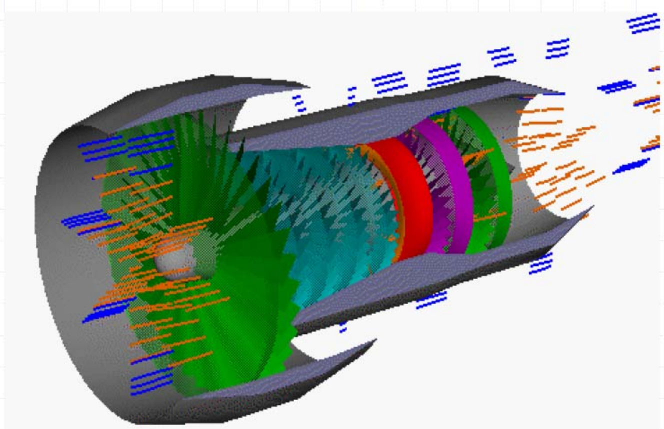
The Turbofan Engine



Credits: NASA Glenn Research Center

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Early Turbofan Engines

General Electric TF39

Lockheed C5

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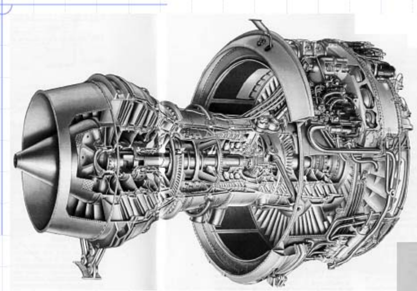
Early Turbofan Engines



RB211-22B

Rover
Barnoldswick

Test on VC10

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Rolls Royce Trent 1000

Credits – Rolls Royce, Media Room

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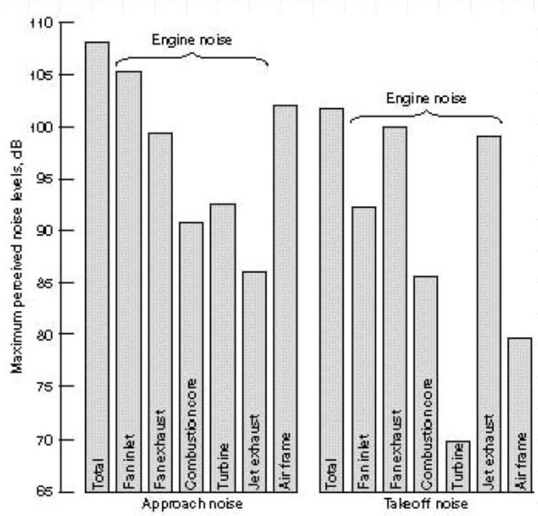
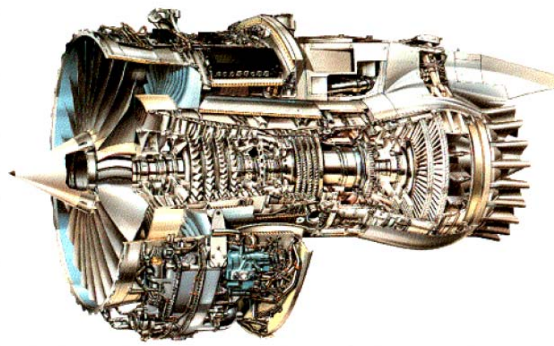
Engine Noise Components



30

Sources of Fan Noise

- Tonal
- Broadband
- "Buzz-Saw"



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Tonal Fan Noise

- If the tip Mach number of an isolated fan is subsonic then the pressure field it generates does not propagate out of the fan inlet or exhaust
- The interaction between the spinning pressure field generated by the fan and the outlet or exit guide vanes can result in pressure patterns that sweep the duct wall at supersonic speeds
  - Tyler-Sofrin interaction modes

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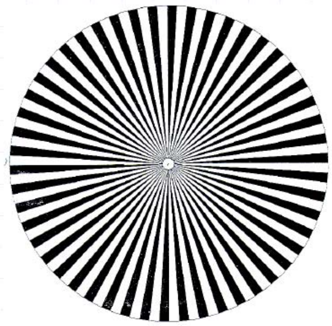
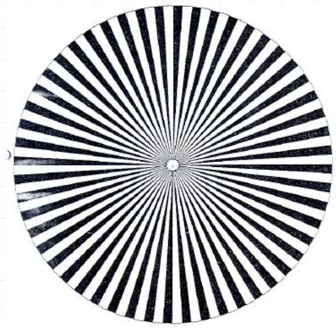
Rotor and Stator



Rotor with 50 blades



Stator with 52 blades

Interaction pattern spins at -25 times the rotor speed

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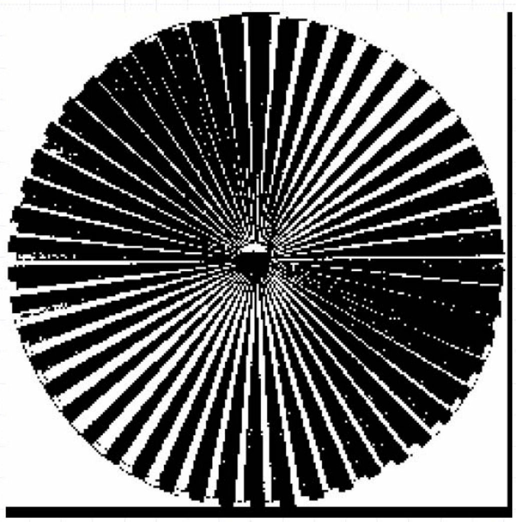
Rotor-Stator Interaction



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Broadband Fan Noise

- Interaction of the fan tip vortex with the turbulent fan inlet duct boundary layer
- Fan self noise including noise generated by the turbulent eddies passing the fan blade trailing edges
- The impingement of the rotor wakes on the outlet guide vanes
- Outlet guide vane self noise

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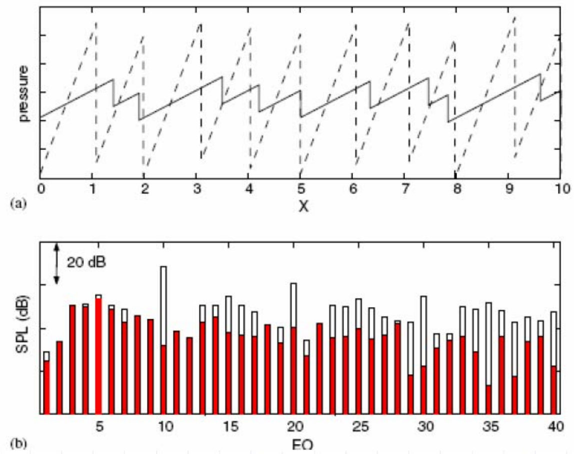
"Buzz Saw" Noise

- Most notable at take-off and climb
- Fan tip speeds can become supersonic
  - Rotor alone pressure field
- Pressure pattern consists of sharp shocks and expansions
- Propagate forward through the jet inlet
- Small differences in each blade result in an irregular pattern
- As the pattern propagates nonlinearity transfers energy to the higher harmonics
- Dissipation occurs at higher frequencies

36

"Buzz Saw Noise"



Credits - McAlpine, Fisher and Tester (2006)

37

Fan Exhaust Noise

- Fan tonal and broadband noise propagates through the fan exhaust duct and the fan exhaust shear layer
- Predictions have been made using
  - Analytical methods
    - Limited to simple geometries
  - Finite element and finite difference methods
    - Able to deal with more complicated, realistic geometries
    - Sometimes with simplifying assumptions such as fully irrotational flow
    - Sometimes based on the linearized Euler equations, with fewer assumptions

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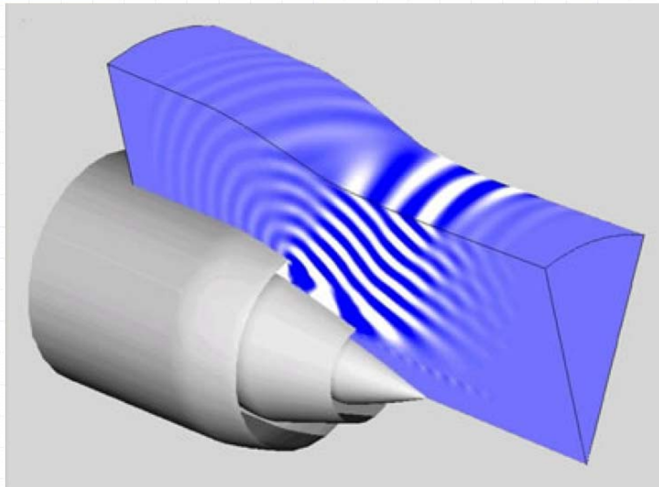
Fan Exhaust Noise Propagation



Credits - ONERA 2006, Low Noise Aircraft 2

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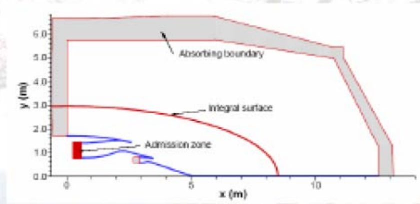
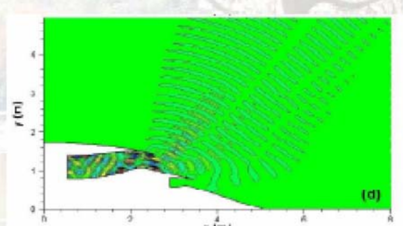
Fan Exhaust Noise Propagation

Credits – Zhang, Chen, Morfey, Tester (2003)

Source model :	analytic – modal input
Mean flow:	RANS
Propagation:	LEE – time domain (high order compact)
NRBC:	Buffer zone
Far-Field :	FW-H





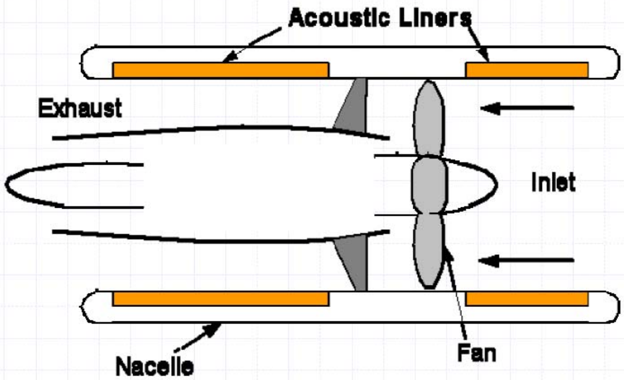
Near field instantaneous pressure

isvr

UK-Japan Bilateral Workshop, Aircraft Emissions and Noise
Tokyo, January 17-19 2006

Rolls-Royce

Acoustic Treatment: Liners



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Acoustic Treatment: Liners

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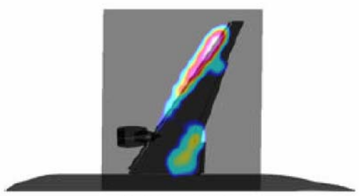
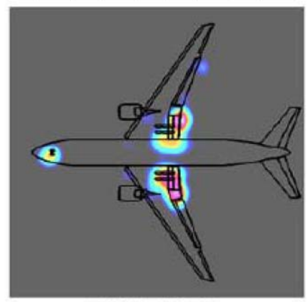
Airframe Noise

- Noise made by the non-propulsive components of the aircraft
- High-lift devices
  - Slats and flaps
- Landing gear

Full Scale Frequency: 800 Hz



6.3% Scale Model



Full-Scale Model

Credits – Stoker, Guo, Street & Burnside (2003)

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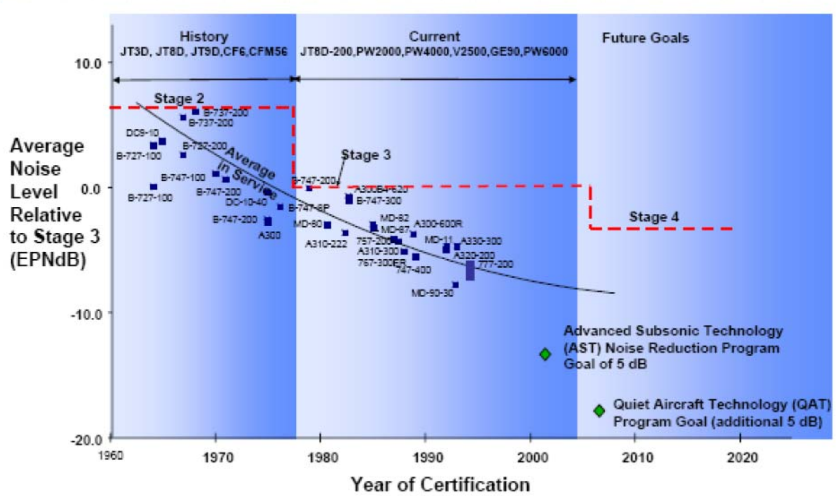
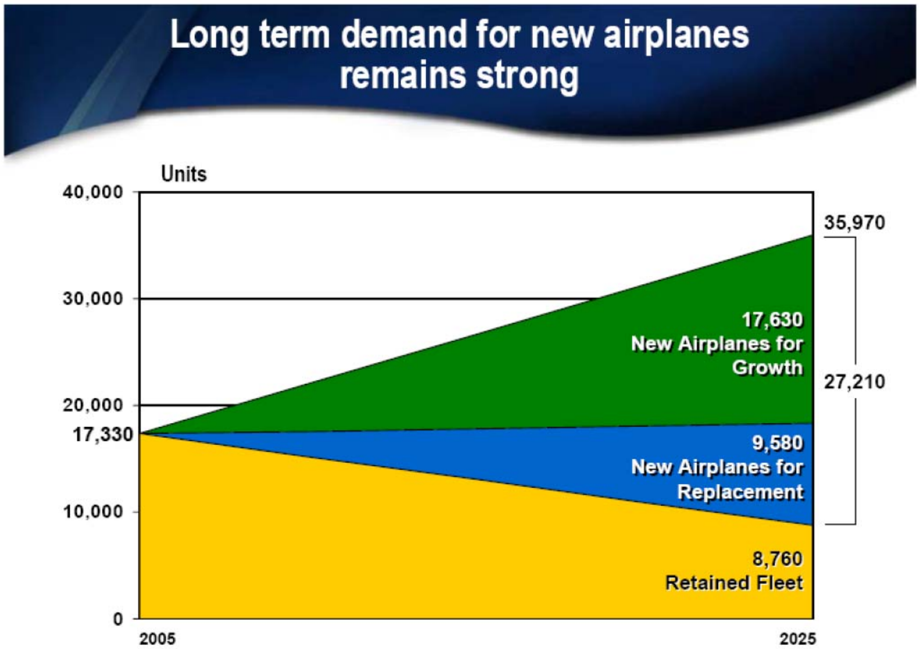
Aircraft Noise Reduction Trend



Credits – Dennis Huff (2204), "TECHNOLOGIES FOR TURBOFAN NOISE REDUCTION 44



Credits – Randy Baseler (2006), "BOEING MARKET OVERVIEW"

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Recent Technologies for Noise Reduction

- Jet noise
  - Increase bypass ratio further
  - Chevrons
- Fan noise
  - Changing relative locations of fan and OGV
  - Spliceless liners
- Airframe Noise
  - Fairings on landing gear

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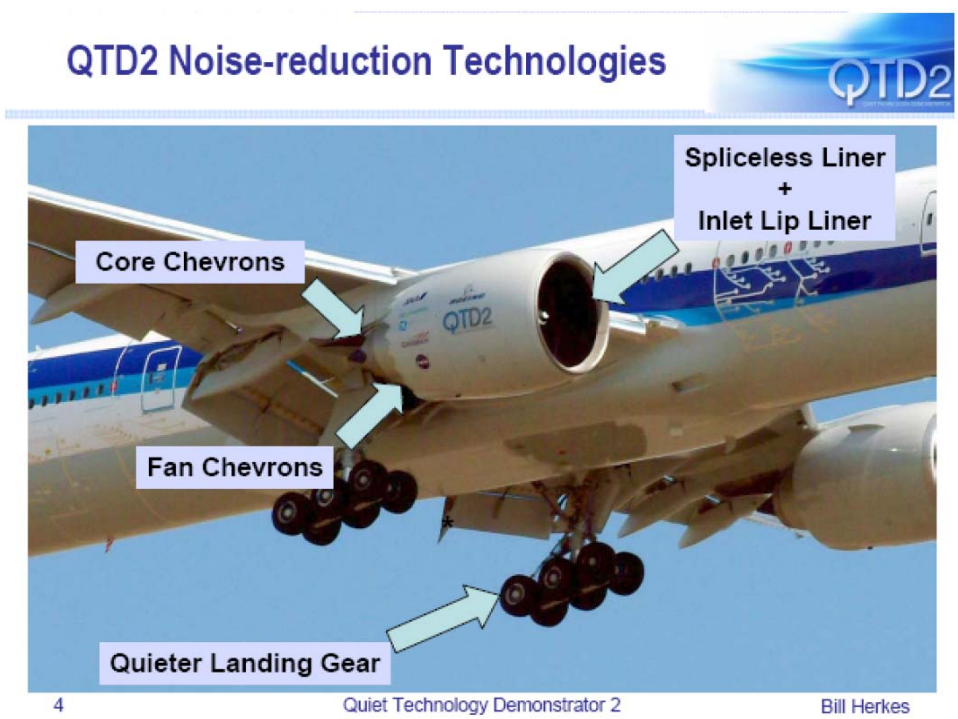
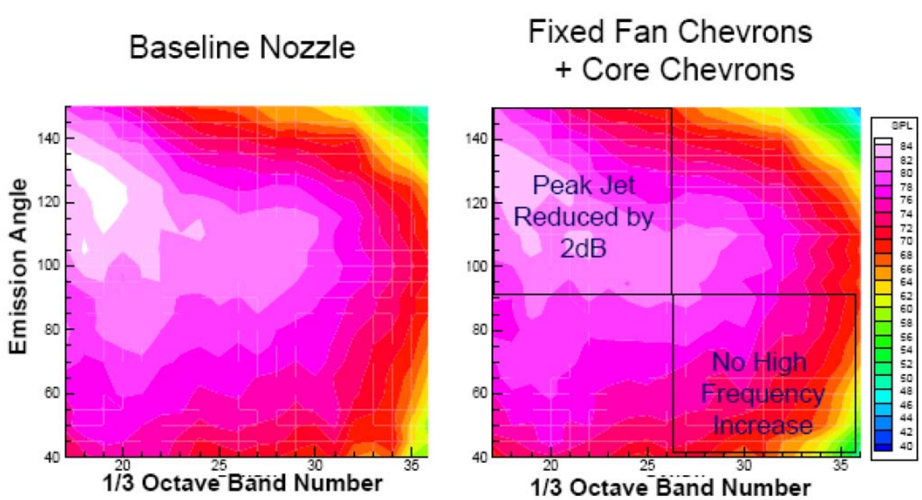
The Quiet Technology
Demonstrator 2 Flight Test
Bill Herkes
Boeing Commercial Airplanes
The Aviation Noise & Air Quality Symposium
Palm Springs CA - March 7, 2006


QTD2 Noise-reduction Technologies
Spliceless Liner
+
Inlet Lip Liner
Core Chevrons
Fan Chevrons
Quieter Landing Gear
4
Quiet Technology Demonstrator 2
Bill Herkes

Variable Geometry Chevrons

Jet Noise Reductions due to Chevrons



“Acoustically Smooth” QTD2 Inlet

McAlpine and Fisher (ISVR)

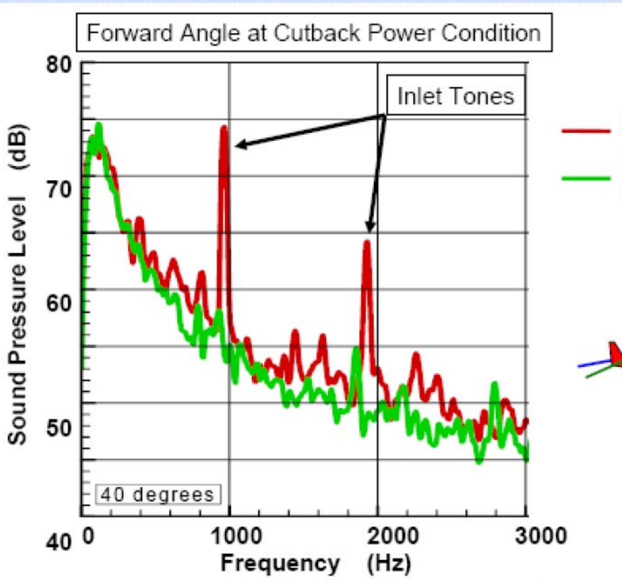
Baseline Inlet

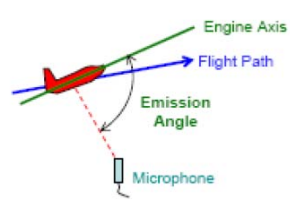
QTD2 Inlet:

- Axial splices eliminated
- Treatment extended fore and aft
- Treated inlet lip
- 78% increase in treated area

11 Quiet Technology Demonstrator 2 Bill Herkes

Community Noise Reduction due to Spliceless Inlet



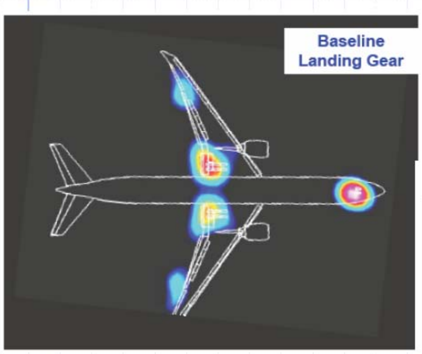


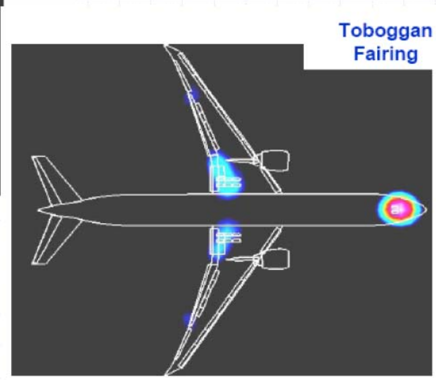
12 Quiet Technology Demonstrator 2 Bill Herkes

Toboggan Landing Gear Fairing

24 Quiet Technology Demonstrator 2 Bill Herkes

Toboggan "Shows Promise"





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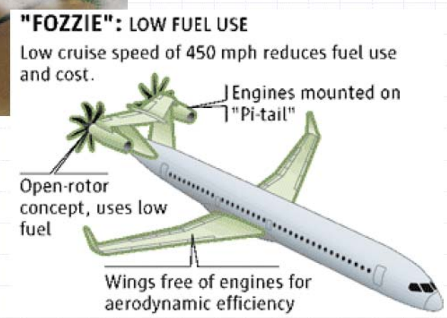
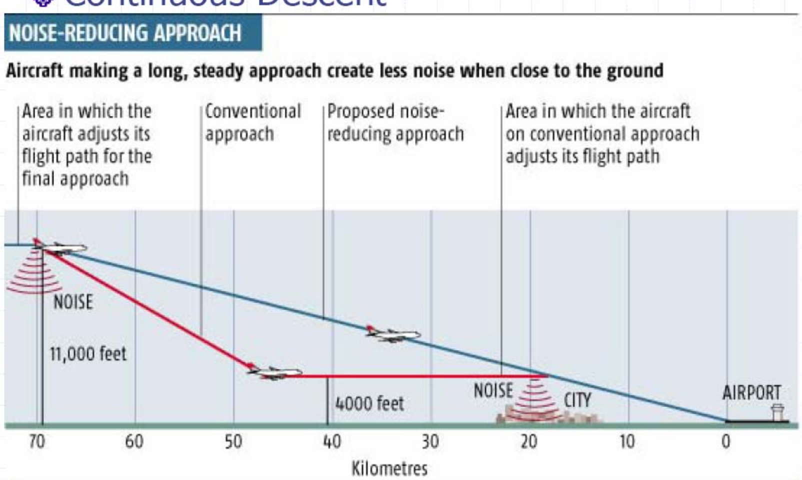
Future Possibilities



Operational Procedures

- Continuous Descent



Credits – New Scientist, November 2003

European Research Programs

- Turbomachinery Noise radiation through the Engine Exhaust (TURNEX)
- Computation of Coaxial Jet Noise (CoJeN)
- Methods for the Efficient Simulation of Aircraft Engine Noise (MESSIAEN)
- Improvement of Fan Broadband Noise Prediction: Experimental Investigation and Computational Modelling (PROBAND)
- Environmentally Friendly High-Speed Aircraft (HISAC)
- Environmentally Friendly Aero-Engine (VITAL)

The Rolls-Royce University Technology Centre (UTC) in Gas Turbine Noise

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AIAA Aeroacoustics Award

- Southampton connections
  - **Shon Ffowcs Williams**
    - (PhD Southampton)
  - **Alan Powell**
    - (1951-1956)
  - **Geoffrey Lilley**
    - (Professor and Head of Aeronautics and Astronautics)
  - **Philip Doak**
    - (Emeritus Professor – ISVR)
  - **Krish Ahuja**
    - (Postgraduate research)
  - **Philip Morris**
  - **Chris Morfey**
    - (Emeritus Professor – ISVR)
  - **Stewart Glegg**
    - (PhD Southampton)
  - **Mike Fisher**
    - (Emeritus Professor – ISVR)

9/26 = 35%

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Congratulations to the ISVR on the award of the Queen's Anniversary Prize 2006 for Higher and Further Education

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