AEROACOUSTICS RESEARCH IN EUROPE:
THE CEAS-ASC REPORT ON 2001 HIGHLIGHTS

Authors:	Dr M J Fisher and Dr R H Self
Address:	Institute of Sound and Vibration Research
	University of Southampton
	Highfield
	Southampton
	Hampshire SO17 1BJ, UK

Short running headline:	Aeroacoustics Research in Europe

No. of pages: 40

No. of tables: 0

No. of figures: 24

AEROACOUSTICS RESEARCH IN EUROPE: THE CEAS-ASC REPORT ON 2001 HIGHLIGHTS

M. J. FISHER and R. H. SELF

Institute of Sound and Vibration Research, University of Southampton,

Southampton SO17 1BJ, UK

This paper summarises some highlights of aeroacoustics research in Europe in 2001, compiled from information provided to the CEAS Aeroacoustics Specialists Committee (ASC). The CEAS (Confederation of European Aerospace Societies) comprises the national Aerospace Societies of France (AAAF), Germany (DGLR), Italy (AIDAA), The Netherlands (NVvL), Spain (AIAE), Sweden (FTF), Switzerland (SVFW) and the United Kingdom (RAeS).

1. INTRODUCTION

The role of the CEAS Aeroacoustics Specialists Committee (ASC) is to serve and support the scientific and industrial aeroacoustics community in Europe. Here "Aeroacoustics" is to encompass all aerospace acoustics and related areas.

This paper summarises events in 2001. During that year four major programmes of research, namely RESOUND, RANNTAC, RAIN and DUCAT supported by the European Union, were concluded and a brief summary of each is therefore included in Section 2. The extension of that work is funded under three new European supported programmes, SILENCE(R), TurboNoise CFD, and JEAN; their objectives are outlined in Section 3.

The remainder of this article comprises contributions by European researchers as submitted to the editors. Enquiries regarding all contributions should be directed to their principal authors who are identified at the end of each subsection.

2. EUROPEAN PROGRAMMES COMPLETED IN 2001

2.1. RESOUND (Reduction of Engine Source Noise through Understanding and Novel Design)

2.1.1. *Introduction*

Despite significant progress in reducing aircraft noise over the past thirty years, further improvements are required if passenger growth is to continue without an increase in noise exposure around airports Increased bypass ratios have reduced jet noise from the dominant levels of the first jet engines, so that now further progress in reducing aircraft noise requires research on a broad range of noise sources, including turbomachinery noise (especially fan noise), combustor noise, jet noise (still very important at aircraft departure) and airframe noise (often the dominant source on aircraft arrival).

RESOUND is a 9 MEuro European research programme launched in 1998 involving 18 partners from industry, research establishments and universities across Europe, with financial support from the European Union. The objective of RESOUND is to acquire the technology necessary to support the design of derivative and new aero-engines with noise levels that are 4 dB quieter than those of aircraft currently entering service. Conventionally turbomachinery noise reduction is achieved by increasing rotor/stator gaps increased to reduce interactions, and by selecting rotor and stator numbers so that sound from rotor/stator interaction decays rapidly. The RESOUND programme investigated advanced methods of reducing turbomachinery noise, namely fan noise reduction through reduced tip speed and rotor/stator design, low-pressure (LP) turbine noise reduction through exit guide vane design, and turbomachinery noise reduction through active stator design. Other elements of the programme, including combustor noise and the control of fan noise by aerodynamic devices, are not presented here.

2.1.2. *Fan noise reduction through reduced tip speed and rotor/stator design*

A model fan test programme was conducted in the Rolls-Royce anechoic chamber at Ansty in the UK. Far-field measurements were taken in the controlled environment of a large anechoic chamber. The 0.85 metre diameter model fan operating at supersonic fan tip speeds was driven by a 10 MegaWatt electric motor, and installed with a turbulence control screen to simulate intake flows relevant to the flight case.

Two designs of fan rotor were investigated in RESOUND. Low Noise Rotor 1 – LNR1 – was acoustically designed with a 15% tip speed reduction using 3-dimensional (3D) Computational Fluid Dynamics (CFD). The rotor was designed to have the same pressure ratio versus mass flow relationship as the datum blade with no reduction in efficiency and adequate stability margin. The rig was tested in November 1999, and demonstrated more than 4 dB improvement in rotor tone noise, as well as reductions in rotor-stator interaction tones (corrected to the same gap/chord ratio). Broadband fan noise benefits were not realised.

LNR2 was designed using 3D CFD to match the datum blade pressure ratio versus mass flow relationship, with the same tip speed as the datum rotor. LNR2 was swept forward to swallow the shock at the tip and stop it propagating forward as noise. 2-4 dB noise improvement was predicted using steady and unsteady Noise CFD for rotor-based tone sources. The rig was tested in July 2000 demonstrating more than 4 dB improvement in rotor tone noise.

In addition to low-noise rotor designs, a low-noise fan swept outlet guide vane (OGV) was evaluated. The OGV axial sweep noise benefits were evaluated, and a 20 degree sweep selected with 3-4 dB benefit on interaction tones predicted. The swept OGV was aerodynamically designed using 3D CFD Navier-Stokes methods to have the same overall aerodynamic loss as the datum OGV. The swept OGV was tested in July 2000, and demonstrated a rear-arc tone reduction of more than 4 dB.

2.1.3. *LP turbine noise reduction through exit guide vane design*

A number of turbine exit guide vane variants were tested on a LP turbine rig at MTU, Germany. The blades were designed to reduce rotor-stator interaction noise using CFD predictions of linear perturbations to non-linear steady mean flow.

2.1.4. *Turbomachinery noise reduction through active stator design*

Tests were conducted on two different concepts of active stator design, introducing either anti-noise or aerodynamic disturbances to cancel out the fan noise sources. In one test, loudspeakers were located on the duct walls between the stators, while in the other ten of the stators in the ring were modified to incorporate piezo-actuators

In the tests at SNECMA, both concepts gave significant (~10 dB) overall tone reduction for low frequencies, with an angular sector of 'silence' achieved at high frequencies.

2.1.5. *Conclusions*

RESOUND has delivered technology for aero-engine noise reduction that is suitable for application in the short term to fan rotor and outlet guide vane designs, and LP turbine exit guide vane designs and in the longer term to active stator designs.

[By A.J. Kempton, Rolls-Royce plc, Derby, UK]

2.2. RANNTAC

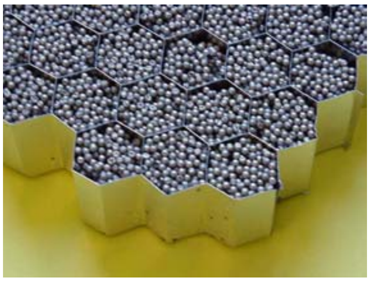
RANNTAC is a European Research Project devoted to the study of new low noise nacelle technologies. Started in January 1998 and completed in December 2000, this project coordinated by AIRBUS-FRANCE has allowed investigation into both passive and active concepts.

In the family of passive concepts, the following new absorbers have been studied: Hollow sphere liner of METRAVIB, SAA concept of DORNIER, Variable cavity depth sequence liner of University of Salford, 3DOF concept of SNECMA, bulk and spiralling liners of NLR. Most of these technologies have exhibited promising results and the benefit of two of them has been confirmed by engine tests performed by Rolls-Royce Deutschland.

Also in the category of passive technologies the negatively scarfed intake has been investigated with the aim of diverting noise toward sky rather than ground thanks to a longer lower lip. Aerodynamic study and scale model tests carried out by Rolls-Royce have allowed a much greater understanding of the acoustic benefit of this concept, and have highlighted the aerodynamic difficulties that must be addressed.

Between passive and active means, adaptive liners have been studied with the aim at highlighting their versatility with respect to the incoming acoustic wave. Different approaches have been investigated by Ecole Centrale De Lyon in collaboration with Metravib and Eads CRC based on acoustic or mechanical adaptation respectively.

In parallel of the study of liners, active noise control systems have been investigated with special attention given to the actuator positioning, algorithm and actuator technology. MTU and ISVR have suggested theoretical rules defining the best position for actuators so that an optimum control is achieved. EADS CRC and CNRS/LMA developed two algorithms based on in-duct or far field control. Positioning and algorithms have been tested at SNECMA's facility and effects on modes have been measured by DLR. Associated to these configuration studies, actuator technologies have also been investigated with the aim at achieving high levels with low bulk / low weight devices. Bertin, CTTM, Dornier, METRAVIB, Ferroperm, LC-EPFL and Cambridge Concept have studied various concepts the most mature of which were tested at CTTM facility by LEMA-EPFL. Even though some of these concepts have showed very high performances, the studies devoted to ANC configurations have demonstrated the need to improve again the output level/dimension ratio.

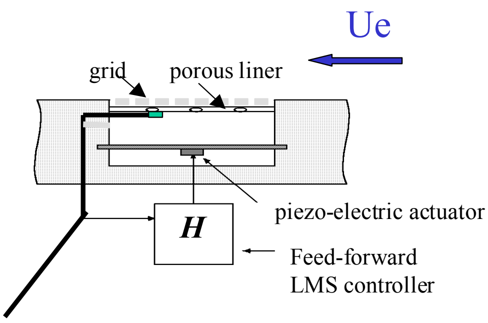


Example of new passive liner concept

(Hollow sphere concept developed by METRAVIB).

The Negatively Scarfed Intake

(Scale model flare manufactured by RR).



Example of adaptive liner concept

(Acoustically adaptation developed by ECL and METRAVIB).

Example of new actuator for ANC

(Electrodynamic direct radiator of CTTM).

Figure 2.1 Showing examples of RANNTAC technology.

[By Hervé Batard, AIRBUS-France]

2.3. REDUCTION OF AIRFRAME AND INSTALLATION NOISE (RAIN)

RAIN is one of the aircraft noise reduction research projects partly funded by EC under the Brite-Euram fourth framework. The airframe noise is an important contributor to the total noise level perceived on ground for large aircraft in an approach configuration. This source has to be reduced if the annoyance around airports is to be lower. The installation effects on the engine noise and particularly its interaction with the airframe is another area which requires better understanding in order to achieve further noise reduction. The objectives of RAIN are to identify the noise source mechanisms, to develop noise reduction solutions, to generate noise database and to improve/validate prediction models.

An A340 flight test has been performed to determine the important aerodynamic noise sources. These are from landing gears and the high lift devices. A noise source localisation tool was successfully applied during this test campaign. Detail studies of the noise sources have been conducted in separate wind tunnel tests. For the landing gears, the most important radiation areas have been identified using full scale tests in the DNW tunnel. The results have been used to improve noise prediction models and to design noise reduction treatments. A significant noise reduction has been achieved.

For the wing noise sources, an A320 and A321 1/11 scaled model tests have been performed in the CEPRA 19 tunnel. The identification of the noise sources allowed the development of noise reduction treatments. The efficiency of the treatments has been validated at model and full scale in CEPRA 19 and DNW tunnel respectively. Very good noise reduction has also been achieved.

The engine installation effects have been studied separately for fan, jet and core noise. Wind tunnel tests at model scale have been performed for fan and jet noise in the CEPRA 19 tunnel, whilst for core noise the DERA (now QinetiQ) tunnel was employed. Good databases have been generated. The results obtained have clearly demonstrated a significant increase of the level of these sources due to the installation on the aircraft model.

[By L.C. Chow, Airbus UK, Filton, Bristol, England]

2.4. DUCAT

2.4.1. *Introduction*

DUCAT is a European Research Project aiming to develop and validate duct acoustics models, which with confidence after validation, can be used as industrial design tools for the optimisation of liners and actuators. The project started in January 1998 and was completed in December 2000. Main objectives of the project are:

- development, extension and validation of various duct acoustics models;
- reduction of the computational effort required by the models to obtain results up to dimensionless frequencies of 40;
- constitution of a firm experimental database for present and future applications;
- demonstration of the improved design capability on a low noise nacelle of a generic turbofan and assessment of the applicability of the models.

Prior to the development of the models, the industrial partners (Rolls-Royce, Rolls-Royce Deutschland, Turbomeca and EADS Airbus) raised the industrial specifications for the duct acoustics models. In the work programme, it was anticipated that not all aspects could be addressed in a single duct acoustics model. Therefore a small number of numerical models has been developed, based on various methods as FEM (NUIG), BEM (DTU), coupled FEM/BEM (UTC), non-linear propagation (ISVR), ray-acoustics (ONERA) and a 2-port matrix method for a duct lined with a bulk absorber (KTH). These models are partially complementary and partially overlapping, which offers the possibility to find the best modelling for each aspect of duct acoustics. Three validation experiments were carried out to constitute a database for current and future applications (UTC, NLR and ISVR). After validation and a liner design study, the range of applications of the models and the restrictions for use as industrial design tools for nacelle acoustic optimisation was established.

2.4.2. *Modelling and validation*

NUIG improved the computational efficiency of their FEM-model by using a pre-conditioned solution matrix, which can be re-used for subsequent calculations and which gives a CPU-time reduction of more than 50%. An existing infinite wave envelope element formulation has been modified to calculate fan noise radiation. Good agreement between model predictions and benchmarks and experimental results was found. Furthermore, a liner design method based on a gradient optimisation routine was implemented. DTU extended the BEM-modelling for uniform flow to a model for potential flow, first proposed by Astley and Bain in 1986 for flows at low Mach number. An improved variant of this model seemed to be considerably more accurate.

UTC developed a coupled FEM-BEM model to study the problem of acoustic propagation and radiation in a non-uniform mean flow. The inner domain close to the duct with non-uniform flow is calculated using FEM. The radiated acoustic field in the external domain is calculated using BEM (in the project considered as a no-flow region). The fluid is supposed to be perfect, compressible, and isentropic. The linear acoustic equations are obtained by the perturbation of the mass conservation and momentum equations, leading to the so-called Galbrun equation. The code is developed and validated with various comparisons as analytical benchmarks and experimental results. Good agreement was found (Figure 2.2).

The development of theoretical models of non-linear propagation of tones radiated forward of supersonic fans has been studied for many years at the ISVR, and this work has been successfully continued in DUCAT. A frequency-based model has been developed, so-called FDNS (Frequency Domain Numerical Solution), which predicts the non-linear propagation in a lined intake duct. The predictions were compared to FANPAC data (a previous Brite-Euram project) and data from a turbofan engine test at Hucknall. Generally, a good agreement between measured and predicted results was found.

As a high frequency approximation, ONERA developed a no-flow ray-model as an alternative to purely numerical methods. One of the objectives is to demonstrate the capabilities of the ray model to handle both in-duct propagation and far-field radiation. The model allows a coherent or incoherent contribution of the rays both at the source emission and at the observer in the far-field. Furthermore, the model can handle spinning modes and non-uniform liners. The model was validated using analytical benchmarks, for which good agreement was found.

KTH wrote, validated and documented a numerical code calculating the 2-port matrix for a duct lined with a bulk absorber in the case of negligible mean flow. The problem was handled by first analysing an infinite duct of arbitrary cross-section with extended reaction liners. The resulting eigenvalue problem was solved using the collocation technique. When the eigenmodes and wave numbers of the lined ducts were known a mode matching technique was used to solve the transmission properties of the finite duct. The starting point for this work was a code previously developed at KTH for analysing the infinite problem for automotive dissipative silencers. After validation comparisons were made between the transmission loss of an axisymmetric liner and one in which the depth varied azimuthally. The axisymmetric case, with constant liner depth, was predicted to give the higher transmission loss.

2.4.3. *Experiments*

NLR in September 1999 carried out an experiment with a model turbofan in the Large Low Speed Facility of the DNW-LLF (Figure 2.3). This test delivered a valuable database on fan noise generation, in-duct propagation and far-field radiation (kR_{max} = 10.0). UTC carried out a lined flow duct experiment on a locally and non-locally reacting liner. The acoustic fields at either sides of the liners were determined using a traversing pressure and velocity probe. Measurements have been conducted for an axial mean flow velocity of 20 m/s and *kR* values ranging from 2.0 to 8.0 and will be compared with predictions of the coupled FEM/BEM method. Rolls-Royce and ISVR carried out several no-flow experiments on complex duct geometries as turbine humps and buried exhaust cones. The use of a flexible non-locally reacting liner proved successful and allowed the complex geometry's to be wrapped in a simple and cost effective manner for the lined builds. The results are used for a first assessment on the influence of exhaust geometry on fan noise radiation.

2.4.4. *Concluding remarks*

The project was successful in the development and validation of various duct acoustics models and the execution of three validation experiments. However at the end of the project, it seemed that two industrial requirements could not be fully covered:

- The inclusion of 3-D non-uniform flow and liner geometry's.
- The ability to calculate the 3-D in-duct propagation and radiation at realistic frequencies (kR values ranging from 20 to 40, which are characteristic for 1 to 2 BPF of a modern turbofan).

Further developments and validations of the duct acoustics models towards more realistic nacelle conditions are required before the models can be used as mature industrial design tools.

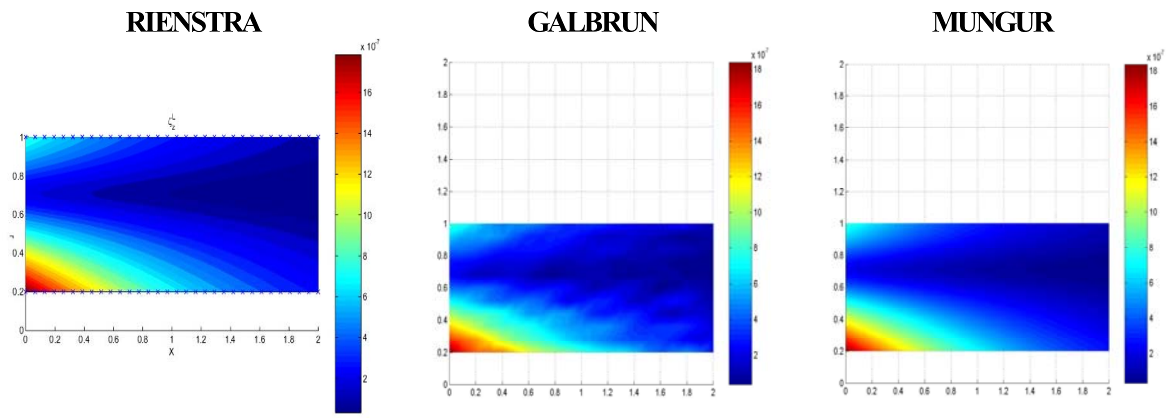


Figure 2.2 Comparisons results slowly varying duct: coupled FEM/BEM (Galbrun) and analytical benchmarks (Rienstra and Mungur).

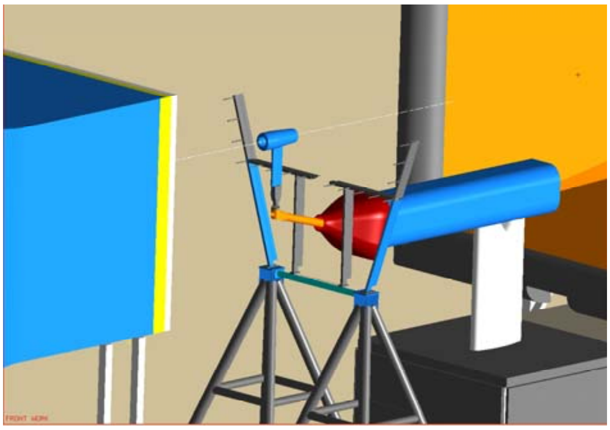


Figure 2.3 Test of NLR model turbofan in the DNW-LLF.

[By Edward Rademaker, NLR Department of Aeroacoustics, The Netherlands]

3. EUROPEAN PROGRAMS STARTED IN 2001

3.1. SILENCE(R) (Significantly Lower Community Exposure To Aircraft Noise)

On 1 April 2001, the largest ever European aircraft noise research program, called SILENCE(R), has been launched. A consortium of 51 companies will collaborate during 4 years to validate noise reduction technologies that will allow as of 2008 quieter aircraft operations by up to 6 decibels. The program is part of the 5^{th} framework program of the European Commission enabling a 50% funding of the total budget of more than 110 million Euro. The kick-off meeting took place in Copenhagen, from the 17^{th} to 19^{th} of April and finished with a public session on 20^{th} April involving presentations to the European Commission and major industrial partners on the objectives and technical content of the project.

SILENCE(R) will address the issue of aircraft noise, a major cause of concern around European airports, through three major objectives:

- Large scale validation of noise reduction technologies whose development was initiated by the European Commission and National projects in 1998.
- Assessment of the applicability of these technologies to current and future European products with minimum cost, weight or performance penalty.
- Determination of the associated achievable noise reduction.

Novel concepts to be validated include low-noise fans, LP turbines, scarfed intakes, novel intake, bypass and hot-stream liners, nozzle jet noise suppressors, active control techniques and airframe noise reduction technologies.

The SILENCE(R) program is linked to X-Noise, a European Thematic Network on External Aircraft Noise. Participating companies consist of aircraft, aero-engine and nacelle manufacturers, supported by research establishments and high tech engineering companies and SMEs (see http.www.x-noise.net/ SILENCER kickoff PR pdf).

For information contact the X-Noise/SILENCE(R) communication manager Dominique Collin at dominique.collin@x-noise.net .

3.2. TURBO-NOISE CFD

3.2.2. *Introduction*

This programme of research, which commenced in March 2000, is supported by the European Union and is divided into four Workpackages. Workpackage 1 identifies the key features of CFD codes that are required to model each type of turbomachinery noise source, including blade row transmission effects. This covers steady and unsteady flows, viscous and non-linear effects, boundary conditions, non-dispersive propagation and meshing. The methodology developed will be benchmarked against analytical results and a feasibility study will also be conducted into the CFD modelling of fan broadband noise sources.

In Workpackage 2 methods are being developed to link the source noise prediction methods, developed in Workpackage 1, with propagation models to carry the noise from the source to the far field.

Workpackage 3 will benchmark the methodology developed above against experimental data from:

- Rotor/Stator viscous wake interaction
- Potential interaction
- Fan rotor –alone and buzz-saw tones
- Rotor and Stator transmission and reflections.

Workpackage 4 will prove and refine the new methodology through a case study of low noise design concepts identified in RESOUND and elsewhere, to develop the tools in a working environment prior to exploitation and to recommend low noise concept improvements.

[By A. J. Kempton, Rolls-Royce plc, Derby, UK]

3.3. JEAN (Jet Exhaust Aerodynamics and Noise)

A research contract to develop new techniques for the prediction of Jet Noise has been awarded under the European Commission's Competitive & Sustainable Growth or 5th Framework Programme. The JEAN project will be for three years and will be co-ordinated by Professor John Fitzpatrick and Dr. Craig Meskell of the Mechanical & Manufacturing Engineering Department, TCD. The work involves 13 partners from across Europe representing the University, Research Centre and Industry sectors.

The objectives of JEAN are to develop methodologies for the prediction of noise generated by jets including the effects of mixing enhancement and co-axial configurations. The long term aim is to provide for design tools for the development of low noise nozzles for HBR engines. The specific technical objectives of the project are

- to identify and develop optimal CFD methods for the calculation of the velocity characteristics of jet flows of relevance to aircraft technology;
- to develop aeroacoustic methods which use the CFD results as input for the prediction of acoustic fields generated by exhaust flows;
- to validate the prediction techniques thus developed;
- to identify the optimum prediction methodologies for particular applications.

The principal objectives of this project are:

- development of predictive tools to assess future jet noise reduction techniques;
- to quantify effects of flow distortion and co-axial configurations.

[By J. Fitzpatrick, Trinity College, Dublin]

4. AIRFRAME NOISE

4.1. AIRFRAME NOISE FROM HIGH LIFT WING SLATS – SOURCE MODELLING

Airframe noise constitutes one important component of aircraft noise in the approach phase. As an outcome of numerous (world wide) experimental airframe noise studies Handley Page type slats were identified as one of the dominating sources of airframe noise. Therefore both scale-model and full-scale slat noise data – as obtained within recent dedicated experiments – were analysed, aiming at the development of an engineering source noise prediction model. As a result upper slat trailing-edge noise was found to represent the dominating source mechanism. Both local edge-flow turbulence and slat noise levels turned out to increase with decreasing wing angle-of-attack – while level maxima shift towards lower frequencies – due to a corresponding increase of the rear slat cove vortex size. Accordingly noise level spectra scale with the vortex dimension which in turn (in a first approximation) can be replaced by the slat chord (c_s). Squared sound pressures were found to increase with flow speed (v) corresponding to a $v^{4.5}$ power law which is slightly less compared to the v^5 law known from trailing-edge noise theory. This difference is assumed to originate from superimposed unsteady mean slot flow fluctuations (monopole source).

A non-dimensional representation of noise spectra from slats of vastly different scale (Figure 4.1) exhibit excellent agreement, when based on a simple linear geometric scaling law (SF = scale factor; R = radiation distance), inherently accounting for the linear dependence of slat noise on wetted trailing-edge length.

Measured slat noise polar directivities feature a shape similar to that of a compact dipole with orientation perpendicular to the slat chord.

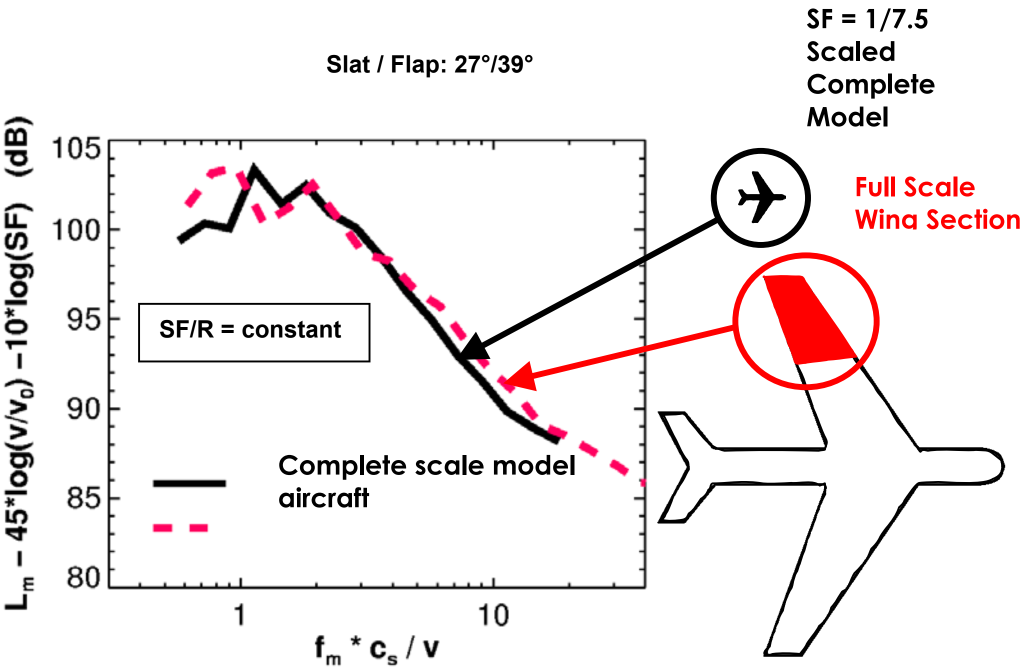


Figure 4.1 Comparison of non-dimensional wing high lift far field slat noise spectra from 1/7.5 model-scale and full-scale wind tunnel experiments.

[By Werner Dobrzynski and Michael Pott-Pollenske,) DLR, Institut für Aerodynamik und Strömungstechnik, Braunschweig/Göttingen, Germany]

4.2. AIRFRAME NOISE REDUCTION BY ACTIVE FLOW CONTROL

Airframe noise contributes significantly to the total sound radiated during landing approach. One dominant source is situated at the side-edge of the extended wing-flap. Oscillation of the vortical structure at the flap side-edge leads to pressure fluctuations at the rigid surface and thus to sound radiation into the far field [4.2.1], [4.2.2]. The objective of the present study is to reduce this noise by blowing air into the vortical structure. The basic idea behind this concept is to displace or destroy the vortical structure, reducing the surface pressure fluctuations and thus the amplitude of the radiated sound.

In order to investigate the physical mechanism in detail, experiments on a swept constant chord half-model were carried out in a wind tunnel with closed test section. The angles of incidence and the flap- and slat angles of the model can be varied. At the flap side-edge, air can be blown out with different velocities. Firstly, flow visualization with particle image velocimetry (PIV) was performed to investigate the flow field at the flap side-edge. The spatial vorticity distribution with and without blowing was measured. Secondly, the change of the sound pressure level (SPL) due to the blowing was measured with a single microphone. Furthermore, the distribution of the sound sources on the model was measured with a microphone-array.

The PIV measurements without blowing yield a rather complicated unsteady vortical structure which confirms the assumption of a noise source at the flap side-edge. The reason for the unsteady motion of the vortices is the special geometry of the flap-wing configuration. The swept main wing generates disturbances that influence the flow field at the flap side-edge, thus generating vortex instabilities. This mechanism can also be expected on a wing of a real commercial aircraft. The measurements with the microphone array show that the flap side-edge noise is present over a broad range of frequencies in agreement with [4.2.3]. The angle of incidence determines if the slat- or the flap- noise is dominant.

The vortical structure can be almost completely dispersed by the blowing and the maximum vorticity in the vortex core is reduced. Furthermore, the SPL measured with a single microphone is reduced by 3 to 4 dB above 1.25 kHz.

[By L. Koop, K. Ehrenfried, A. Dillmann TU Berlin; and U. Michel, DLR Berlin]

5. DUCT ACOUSTICS

5.1. A CLASSIFICATION OF LINED FLOW DUCT MODES

For the relatively high frequencies relevant in a turbofan engine duct the modes of a lined section may be classified in two categories: genuine acoustic 3D duct modes resulting from the finiteness of the duct geometry, and 2D surface waves that exist only near the wall surface in a way essentially independent of the rest of the duct. The number and location of the surface waves depends on the wall impedance Z and mean flow Mach number (see Figure 5.1).

The figure shows a typical case, corresponding to acoustic modes in a cylindrical lined duct with uniform mean flow (m = 1, Helmholtz number = 5, Mach number = 0.5). Displayed are trajectories in the complex plane of the eigenvalues (reduced axial wave numbers) as a function of wall impedance Z. Re(Z) = 0.5 is kept fixed, while $Im(Z)$ varies from ∞ to – ∞. It is seen that most modes are genuine acoustic. They start and finish at a hard-wall value (when $|Z| = \infty$), and stay near these hard-wall values for finite Z. Four modes, however, move away from these hard-wall values, and become of surface type (their existence physically is limited to the neighbourhood of the wall). Two of these surface waves (located outside of the "egg") disappear to infinity when $Im(Z) \rightarrow -\infty$.

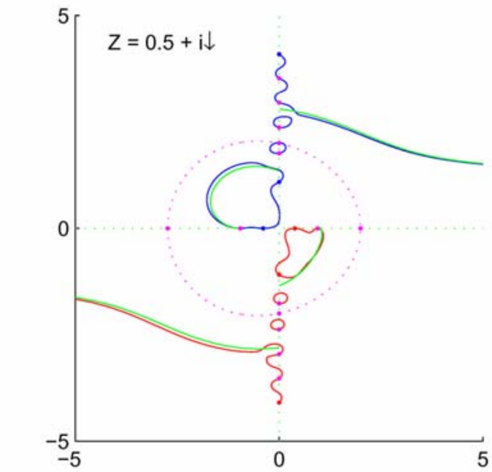


Figure 5.1 Trajectories of reduced wave number (m = 1, ω = 5) for $Im(Z)$ varying from ∞ to – ∞ and fixed Re(Z) = 0.5. The 2D surface wave limits are seen to be a very close approximation of the actual duct mode. The "egg" separates the regions of occurrence of the surface waves.

[By S.W. Rienstra, Eindhoven University, The Netherlands]

5.2. ON THE AZIMUTHAL MODE PROPAGATION IN AXISYMMETRIC DUCT FLOWS

One of the main sound sources in aeroengines is the tone noise of the rotor stator interaction. CAA is part of a three-stage procedure that is developed to predict the sound audible in the far field. The tone noise is generally dominated by only a few cut-on duct modes, at the blade passing frequency and it's harmonics. It is much more efficient for numerical computations to treat these few two-dimensional azimuthal Fourier components (m). Therefore, under the assumption of axisymmetric mean flow without swirl and with axisymmetric acoustic boundary conditions, the three-dimensional linearised Euler equations in cylindrical coordinates, can be decomposed into a Fourier series in the azimuthal direction. This involves less restriction than the finite element method (FEM) and the multi-scale method (MS) assume for their solution. The computational aeroacoustic (CAA) procedure applied for the time and spatial discretisation is based on a seven-point 4th-order Dispersion-Relation-Preserving (DRP) scheme and a 2N storage form Low-Dissipation and Low-Dispersion Runge-Kutta (LDDRK) scheme respectively. Appropriate boundary conditions are prescribed for the solid wall, inflow and outflow boundary [5.2.1].

The approach based on the Fourier decomposition is employed to the duct geometry of Rienstra and Eversman [5.2.2], similar to a generic aeroengine inlet. The results (m = 10, n = 1, ω = 16) are in reasonable agreement with FEM and MS without as well as with Euler based mean flow (Ma = – 0.5). Although the CFD calculated flow field is different from the FEM potential flow and the MS assuming a 1D potential flow, the CAA calculated sound field agrees rather well with FEM and MS. At the same time CAA is much more applicable for future problems, and the CAA results also provide a good basis for the far field integration using the approach based on Ffowcs-Williams and Hawkins, that also is in development.

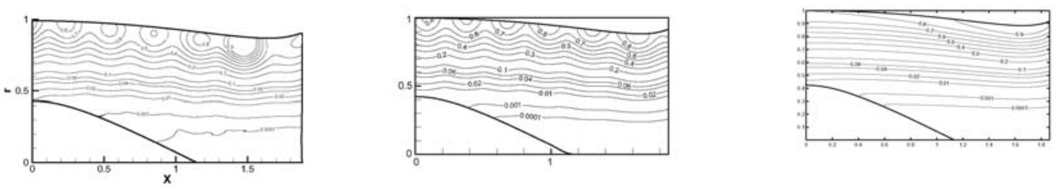


Figure 5.2 (a) Comparison of normalised pressure contours by CAA, FEM and MS, m = 10, n = 1, σ = 16, and Ma = 0.

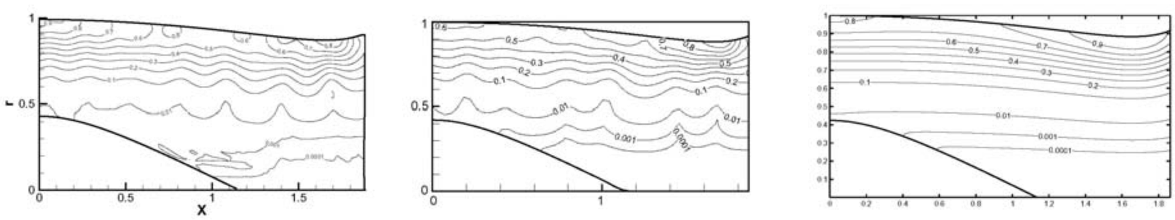


Figure 5.2 (b) Comparison of normalised pressure contours by CAA, FEM and MS, m = 10, n = 1, σ = 16, and Ma = 0.5.

[By C. Schemel, F. Thiele, TU Berlin; U. Michel, DLR Berlin; and X. Li, BUAA Beijing]

5.3. BUZZ-SAW NOISE

One of the most significant sources of fan tonal noise from modern high-bypass-ratio aero-engines, at high power operating conditions, is “buzz-saw” noise (also known as “combination tones” or “multiple pure tones”). Aero-engines operating at supersonic fan speeds generate an acoustic signature in the forward arc containing energy at harmonics of the engine shaft rotation frequency, known as Engine Order (EO) tones. These tones are generated by the steady (in the frame of reference) “rotor-locked” pressure field attached to a ducted fan. At subsonic fan speeds this pressure field is “cut-off” and decays evanescently upstream of the fan, however at supersonic fan speeds the “rotor-locked” pressure field propagates upstream of the fan, sweeping around the duct in a helical path. The acoustic signature measured close to the fan will be dominated by energy at the Blade Passing Frequency (BPF) harmonics. However the energy in the EO harmonics will be redistributed amongst these tones during the *nonlinear* propagation of the pressure field. This leads to a more ‘ragged’ and low-pitched noise referred to as the buzz-saw signature of a supersonic fan.

Recent work, carried out at the ISVR on the X-Noise EC projects RESOUND and DUCAT, has been concerned with prediction methods regarding buzz-saw noise, with particular emphasis on the prediction of buzz-saw noise in acoustically lined engine inlet ducts. A simple, ‘engineering’, numerical method has been developed which calculates the nonlinear propagation of the “rotor-locked” pressure field in a lined inlet duct.

Also on the RESOUND project, Rolls-Royce plc carried out a model fan test (with a lined inlet duct), and generated a large experimental database containing measurements over a wide range of operating speeds. These measurements include many in-duct “buzz-saw” frequency spectra, and have provided an excellent source of experimental data to benchmark, and further develop, the numerical prediction scheme.

The effect of an acoustic liner on the “buzz-saw” tones is largely dependent on the fan operating speed. At fan speeds slightly above sonic the liner is predicted to significantly attenuate a broad band of the EO “buzz-saw” tones. However as the fan speed increases the predicted attenuation falls, and there is less benefit obtained from the acoustic liner. Comparisons between measurement and prediction of “buzz-saw” noise show encouraging agreement.

[By A. McAlpine, Institute of Sound and Vibration Research, University of Southampton, UK]

6. THEORETICAL METHODS

6.1. SOUND RADIATION OF THE VORTEX FLOW PAST A GENERIC SIDE-MIRROR MODEL

The noise generated by the flow over blunt bodies and its propagation to the far field plays a major role in many engineering applications. Presently various concepts are under consideration to calculate the sound radiation into the far field such as combination of flow field simulation and sound radiation integration. Based on the Navier-Stokes equations the unsteady vortex shedding past blunt bodies can be numerically simulated. Using the pressure fluctuations on the body, the noise radiated to the far field is obtained by an integral solution of the equation of Ffowcs Williams & Hawkings (FWH) [6.1.1]. The investigations performed are related to the unsteady flow around a side-mirror model placed on a flat plate which leads to the formation of trailing vortices and pressure fluctuations on solid surfaces.

Unsteady Reynolds-Averaged Navier-Stokes calculations (URANS) allow the computation of high Reynolds number turbulent flow in engineering applications such as the side mirror but have difficulties to compute unsteady coherent structures due to a misrepresentation of the interaction between turbulent/transient phenomena. The predictive inaccuracy is particularly pronounced in conjunction with high frequency and broad-band phenomena. Since the wall-resolving Large Eddy Simulation (LES) remains rather unfeasible for high Reynolds number flows in the near future, Detached Eddy Simulation (DES) [6.1.3] has recently become an attractive tool to investigate aerodynamic flows. DES avoids the high near-wall resolution by applying the RANS approach in the vicinity of the wall and a modified Spalart-Allmaras one-equation turbulence model in the far-field. In the overlap region, DES blends from a statistical to a subgrid-scale model without the use of shape functions.

For the validation of the FWH integration procedure the radiation of a sound source into the far field is considered in a first step. For this purpose, an elliptical surface encloses monopole and dipole sources, which provide the boundary conditions for the FWH procedure for field integration. Compared to the analytical solution the FWH results are in excellent agreement with the pressure perturbation.

The capability of unsteady flow simulations in providing accurate pressure fluctuations on body surfaces is investigated in a second step for the complex unsteady vortex flow over a generic side-mirror model [6.1.2]. Numerical simulations have been performed for various grid arrangements, approximation schemes and modelling approaches (URANS, DES). The results of the mean pressure distribution, the fluctuating pressure levels as well as the surface pressure spectra are in fairly good agreement with the experimental data available (Figures 6.1 and 6.2). Compared to URANS, the results for the sound spectra demonstrate that the DES-FWH approach is more suitable to capture the main features of noise generation and sound propagation to the far field.

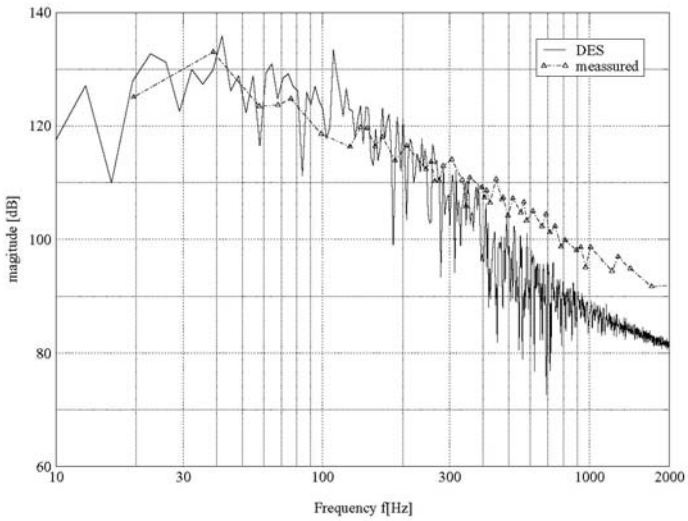


Figure 6.1 Measured and calculated surface pressure spectra at a selected sensor location based on DES.

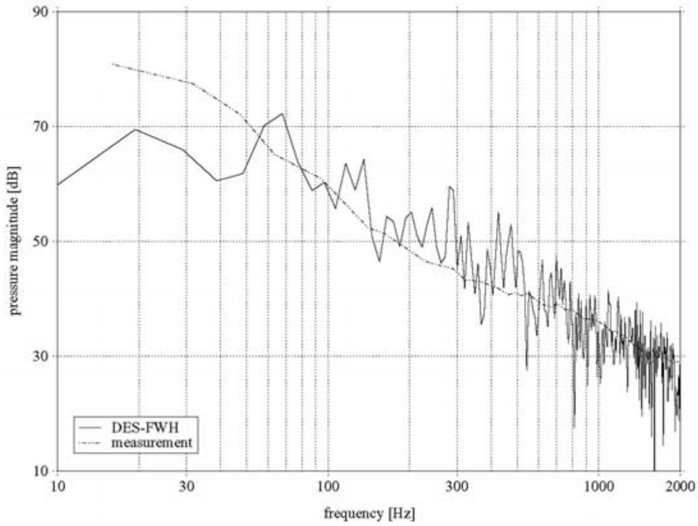


Figure 6.2 Measured and calculated sound spectra at a selected position.

[By D. Eschricht, J. Yan, F. Thiele, TU Berlin; and T. Rung, Bombardier, Hennigsdorf]

6.2. AEROACOUSTIC COMPUTATIONS OF UNSTEADY FLOWS USING CFD AND ACOUSTIC ANALOGY

The reduction of sound emission gains increasing importance in a variety of technical fields such as fluid machinery construction. Expensive after-design action can be avoided by applying pre-design sound prediction methods. In the field of climatisation systems and fans current prediction methods are mainly empiric or half-empiric solutions. Our present research is focused on a numerical prediction method based on Computational Fluid Dynamics (CFD) and Acoustic Analogy.

The method is implemented into the institute‘s research CFD solver. The parallelized, compressible solver is able to do 3-dimensional, unsteady Reynolds Averaged Navier-Stokes (RANS) as well as Large Eddy Simulations (LES). Algebraic, one-equation, two-equation models can be chosen for RANS calculations, the Smagorinsky, the Function-Structure or a new two-equation model for LES. The acoustical module is based on the Ffowcs-Williams Hawkings equation. It extracts the necessary information out of the unsteady CFD computation, performs the Ffowcs-Williams Hawkings integration and computes time dependent density and pressure fluctuations as well as the related frequency spectra. The acoustical module is steadily optimized concerning computing resources, e.g. CPU time and memory needs. The acoustical computations within each time step require presently an overload of about 12% of memory compared to the pure CFD computation, whereas the additional CPU time per time step is negligible.

Presently the acoustical module is tested with a turbulent, unsteady flow around a 3-dimensional circular cylinder. The corresponding mesh consisted of about 3 million cells. In the laminar case the sound emission results from the von Karman vortex street and is dominated by pressure fluctuations inducing mainly lift and drag force fluctuations and emitting a dipole sound field with its specific directionality. The third-octave spectrum (Figure 6.3) was calculated from a turbulent flow of Re ≈ 59,000 using unsteady RANS. The main peak was expected according to the observer position and the directionality at a frequency of about f = 1170 Hz. Compared with experiments the computed main frequency is slightly higher. The computed main peak is higher than the experimental peak but agrees fairly well with the one theoretically predicted for these experiments.

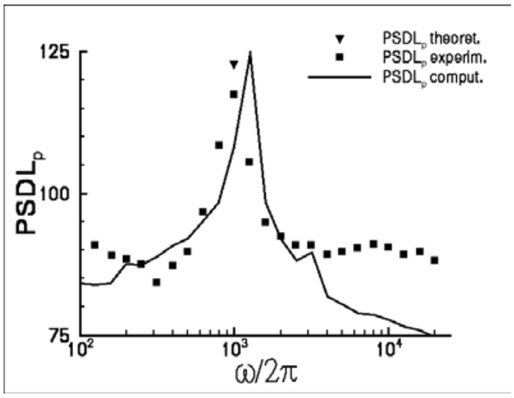


Figure 6.3 Third-octave spectrum of the sound emission of an unsteady flow around a circular cylinder (Re ≈ 59,000).

[Dipl.-Phys. I. Pantle, Dr.-Ing. F. Magagnato, Prof. Dr.-Ing. M. Gabi, University of Karlruhe, Germany]

6.3. RESEARCH ON OPEN – AND DUCTED-ROTOR NOISE USING CAA-MULTIDOMAIN METHOD

The prediction of open or ducted rotor noise is a challenging problem as there are large difference in scales between the noise source near the rotor and the sound field. The sound field generated by an open rotor and that radiated by the same rotor placed inside a semi-infinite duct is simulated at DLR using a CAA multi-domain method. The linearized Euler equations in cylindrical coordinates are used as governing equations in solving this problem. Both Tam's radiation and PML far field boundary conditions are used. A multi-domain Cartesian grid system is used so that the number of grid points can be kept as a minimum. A combination of DRP and a specially optimized cell-centered high order differencing scheme is implemented in the area of two Cartesian grid interfaces. Figure 6.4 gives the directivity obtained computationally in comparison with the exact solution for an open rotor with rotational speed of $\Omega = 0.85$. There is good agreement between the numerical simulation and the analytical solution. Figure 6.5) shows the pressure contour radiated from the open end of the duct at $t = 40$ for the case $M = 0.5$ and its enlarged plot close to the grid interface. It was demonstrated that the effect of a mean flow in the duct may cause the propagation of acoustic modes which are cut-off for vanishing mean flow. The results also prove the numerical treatment is successful. The effect of mean flow including a shear layer on the noise radiation off the ducted rotor is studied.

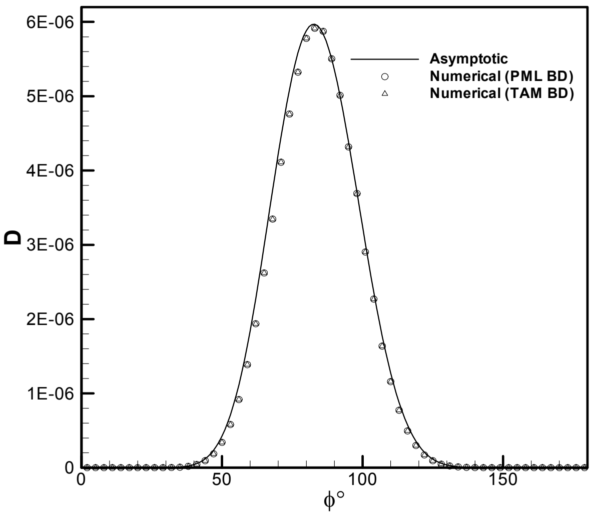


Figure 6.4 Comparison of the numerically obtained directivity at R = 15.0 and the exact solution for Ω = 0.85 with two different far-field (PML and TAM) boundary conditions (BD).

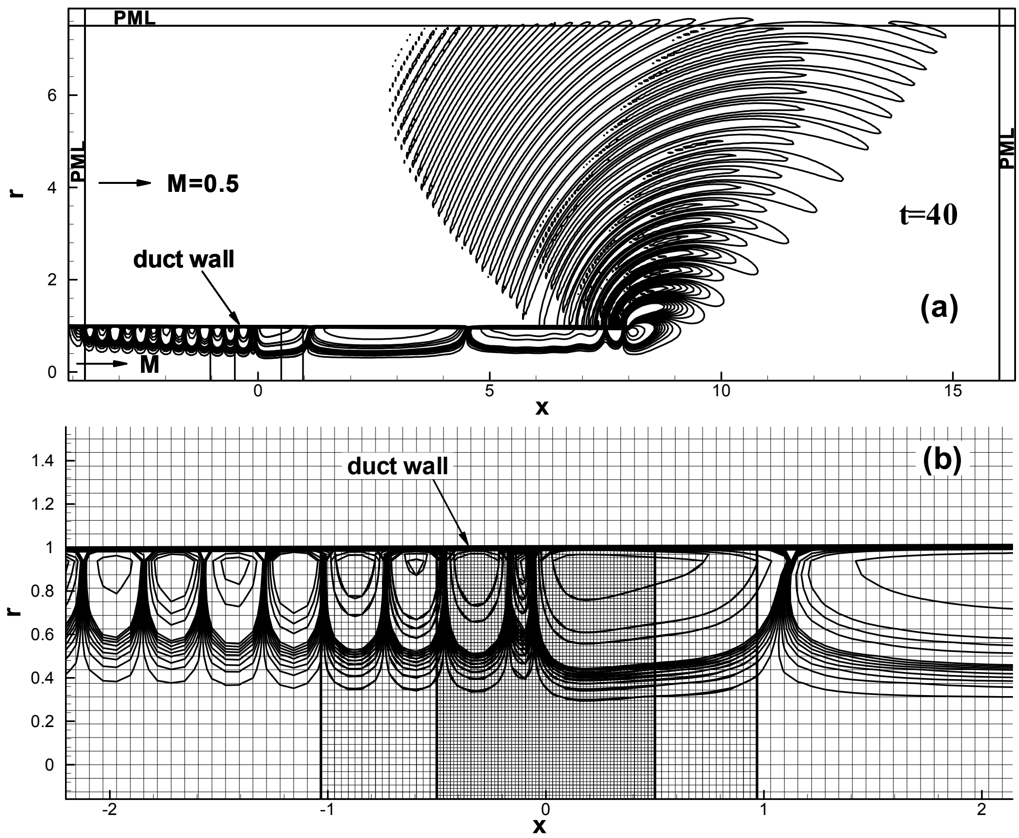


Figure 6.5 Pressure contour at t 40 and its enlarged plot close to grid interface; ducted rotor case with M = 0.5 and Ω = 1.15.

[By J. Yin, J. Delfs, DLR, Braunschweig, Germany]

6.4. AEOLIAN TONE SIMULATION USING HYBRID CFD/CAA METHODS

A hybrid CFD/CAA method is validated for the problem of a cylinder in a cross-flow at M_∞ = 0.3 and Re = 200. In the first step of the hybrid method the unsteady compressible flow field in the immediate vicinity of a sound producing geometry is computed. The acoustic field is computed with acoustic perturbation equations (APE) in a second step using sources determined from the unsteady compressible flow field. The APE system has been derived to solely describe the propagation of the acoustic modes. Due to the excluded vortical eigenmodes the excitation of instabilities in global unstable mean flows is prevented. Furthermore, the separation of the analysis of the flow field and the acoustic field offers the possibility to take advantage of the disparity of the turbulent and acoustic length scales at low Mach numbers. The left-hand side of the APE system can be shown to be equivalent to the wave operator of Pierce [6.4.1], which agrees with the linearized operator of Möhring's acoustic analogy.

A high resolution CFD simulation of the unsteady compressible flow around a circular cylinder was carried out as a reference solution and as a basis to evaluate source terms for acoustic perturbation equations. The CFD simulation was based on an O-grid with a coarsest resolution of approx.~20 points per wavelength (PPW) at the outer circumferential. The acoustic simulation was carried out on a coarsified O-grid with approx. 8 PPW far-field resolution since the high order low dispersion and dissipation CAA methods used for the discretization of the acoustic perturbation equations have clearly improved limits for the highest resolved wavenumber. With the same radial extension of r/d=80 cylinder diameters, the acoustic grid has 8 times less points.

Figure 6.6 depicts a snapshot of the acoustic field, obtained from the CFD simulation. Figure 6.7 shows the result using the APE system. It can be seen that no vortex street occurs in the wake of the cylinder. Both simulations take into account convection effects, which can be seen qualitatively due to the two lobes tilted in upstream direction.

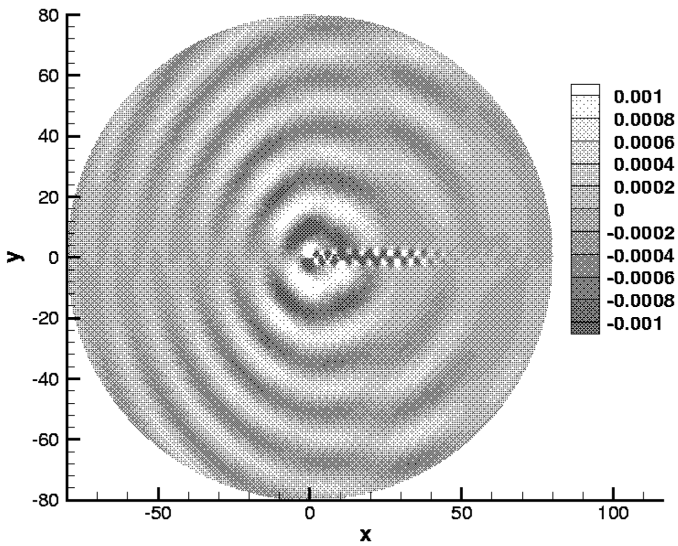


Figure 6.6 Unsteady perturbation pressure from high resolved CFD simulation.

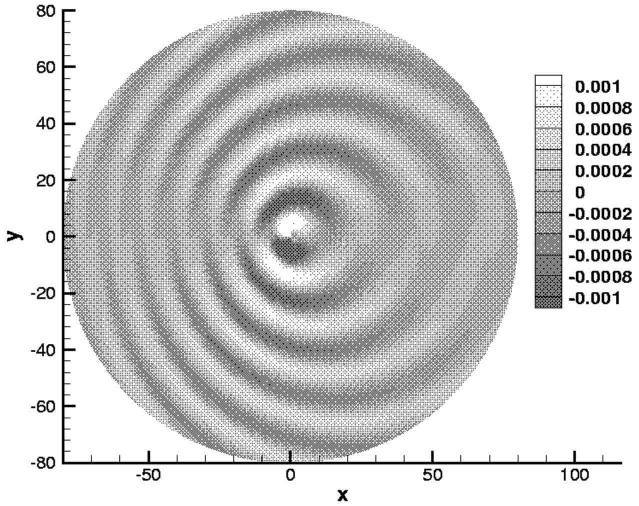


Figure 6.7 Unsteady pressure field using acoustic perturbation equations (APE) with source term.

[By R. Ewert, M. Meinke, W. Schröder, Aerodynamisches Institut, RWTH Aachen, Germany]

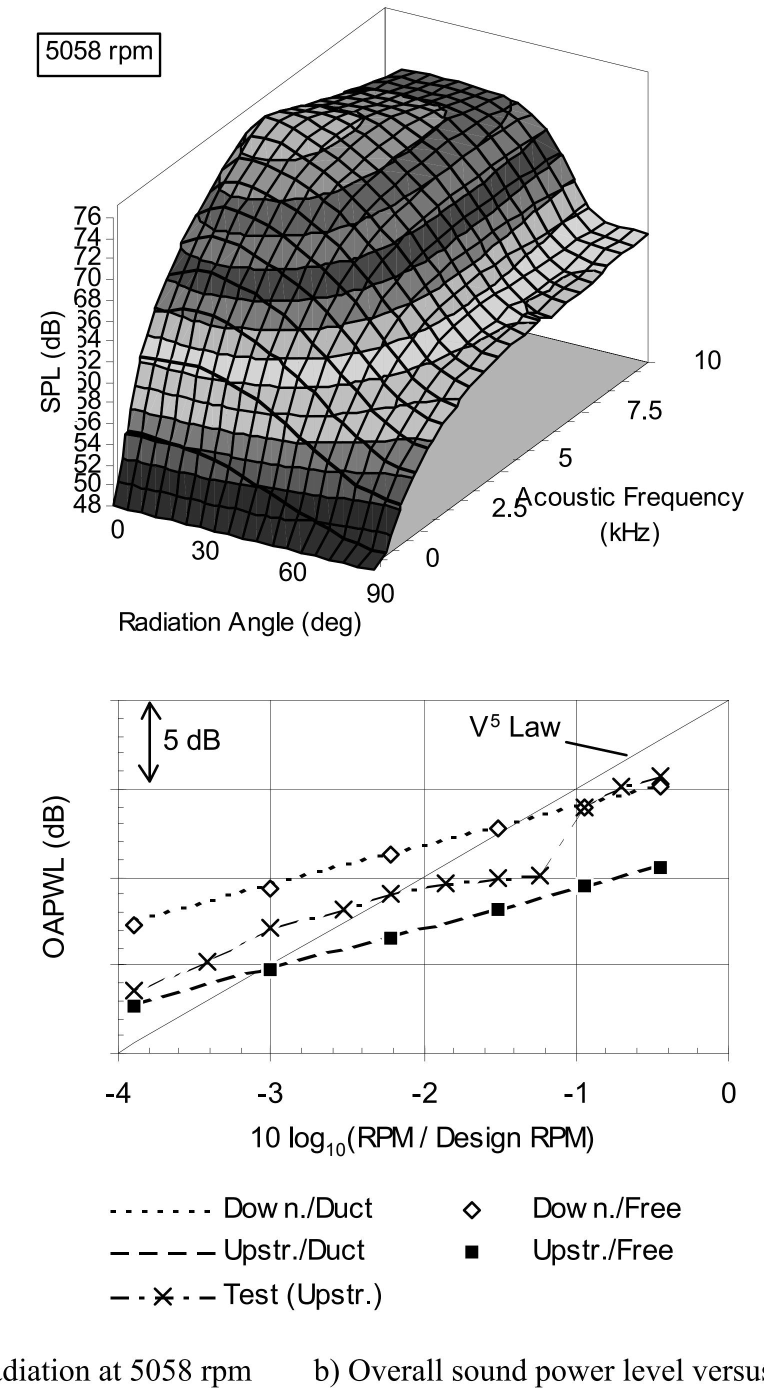
6.5. ANALYTICAL PREDICTION OF BROADBAND NOISE RADIATED BY A DUCTED FAN

The main difficulties for predicting fan broadband noise arise from the facts that there are several competing noise generation mechanisms, and that input data are generally poorly known. Present study has been performed within the framework of the European project RESOUND *(Reduction of Engine Source Noise through Understanding and Novel Design)*.

The method proposed here aims at avoiding these drawbacks, and at being fast and easy to implement on a PC. It is devoted to random-dipole radiation from a ducted rotor. It starts from an assumed flat blade loading spectrum, according to previous tests in a SNECMA facility. This hypothesis is also physically consistent with ECL tests made on a low-speed cascade of highly-loaded airfoils to investigate its unsteady aerodynamic behaviour. In-duct sound pressure is computed using the Ffowcs Williams and Hawkings equation in which the free-space Green's function has been replaced by the Green's function in a cylindrical hard-walled duct. Free-field radiation is derived using the Tyler and Sofrin model.

Applications are based on the data of the fan tested by Rolls-Royce in its anechoic Ansty Noise Compressor Test Facility (ANCTF) during a previous European project FANPAC. An example of the computed sound pressure levels in the fan forward arc, at approximately 50% of the fan design speed, is shown in Figure 6.8. The theoretical model predicts good agreement between the in-duct and free field sound power levels if one neglects the mean flow in the duct. These comparisons are shown in Figure 6.8 for a range of fan speeds together with the measured forward arc sound power levels. The sharp rise in the latter at transonic speeds (abscissa around -1) is due to the fact that the multiple pure tones could only be partially separated from the broadband noise component in the measured spectra. Subsequent FANPAC tests, in which an acoustic liner effectively absorbed these buzz-saw noise tones, showed that the broadband level then varied continuously from subsonic to supersonic fan speed in accordance with the present model.

Spinning mode content of broadband noise computed at a given acoustic frequency has also been analysed to better understand how sound waves propagate inside the duct and radiate into the far field. Finally, the effect of the radial turbulence length scale along the blade span can be predicted, and well duplicates an approximate closed form expression derived by Mugridge for an airfoil in a turbulent flow (Figure 6.9).



a) Upstream radiation at 5058 rpm b) Overall sound power level versus rotation speed
Figure 6.8 Computation of upstream and downstream broadband noise radiation: In-duct flow neglected, Drag/Thrust = 0.398.

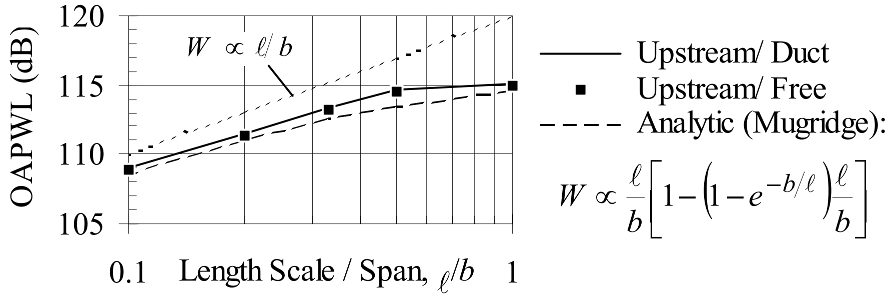


Figure 6.9 Effect of radial turbulence length scale on upstream radiation at 5058 rpm: In-duct flow neglected, Drag/Thrust = 0.398.

[By S. Lewy, ONERA]

6.6. AEROACOUSTIC COMPUTATIONS OF INTERACTION NOISE RADIATED BY FAN INLETS

Discrete-frequency tones due to wake interaction between rotor wake and outlet guide vanes (OGV) are of particular concern in the design of advanced fans. For this reason, CFD and CAA are strongly required for modeling interaction noise problems. Based on existing codes available at ONERA, a computation chain is at present investigated in the framework of the European Project TurboNoiseCFD.

CFD RANS codes are expected to provide the pressure disturbance field upstream of the fan, or the unsteady blade loads, required respectively by each of the two acoustic models proposed. These are semi-analytical based routines, interfaced to a commercial BEM scattering code. For both methods, the time-dependent acoustic problem is transformed into the frequency domain, and acoustic solution is split into spinning modes.

In the first model, the analytical solution of convected Helmholtz equation in an infinite annular duct is used to match the unsteady fluctuating pressure computed by CFD. The CFD solution is expanded into spinning and radial modes using a Hankel-Fourier transform, and converted into equivalent monopoles using an inverse method. These adapted monopoles are then entered as input sources into the BEM code to compute the radiated field solution of the scattering problem in the presence of the fan inlet. The second model is based on the loading noise term of the Ffowcs Williams and Hawkings equation, which gives the interaction noise due to the unsteady blade loads, to be provided by CFD. The analytical Green's function of the infinite duct, commonly used, is replaced here by the Green's function of the fan duct, computed by BEM.

Although the present models are rather simple, they may be an alternative to more advanced fan computations involving less restrictive assumptions for acoustics (linearized-potential or linearized-Euler CAA solvers, direct Navier-Stokes/Kirchhoff hybrid solvers), but still limited by high numerical difficulties. Validation of the computation chain is underway. It aims to be first applied to representative test cases, modeling rotor/OGV configurations with simplified geometry, which have been tested in the framework of DUCAT and RESOUND European projects.

[By C. Polacsek, ONERA, France]

7. TECHNIQUES AND METHODS IN AEROACOUSTICS

7.1. LOCATION OF ROTATING SOURCES BY MICROPHONE ARRAYS

The applicability of phased arrays for acoustic source location has been extended to the location of rotating sources, like broadband noise sources on helicopter and wind turbine blades. A source reconstruction technique was developed that takes account of the effects of source motion and Doppler frequency shift. Low signal/noise ratios can be dealt with and the shear layer of an open jet wind tunnel does not form a serious hindrance. The technique was implemented in the computer program ROSI ("Rotating Source Identifier"). [7.1.1]

ROSI was successfully applied to rotating whistles, blades of a helicopter in hover and wind turbine blades. The test with the rotating whistles demonstrated convincingly the capability to reconstruct the emitted sound. On the helicopter blades, rotating broadband noise sources were made clearly visible. On the wind turbine blades, noise emitted from the leading and trailing edge could be distinguished well.

An example of the difference between ROSI and conventional array software is shown using array measurements on a model wind turbine in the DNW-LLF. Typical results, at 8000 Hz, are shown in Figure 7.1 (conventional) and Figure 7.2 (ROSI). These tests were set up to demonstrate (amongst others) the effects of trailing edge serrations on the reduction of trailing edge noise. Using plots like Figure 7.2, it was shown that sound radiation from the trailing edges was significantly reduced. The leading edge source, which can be seen near to the spinner on one of the blades in Figure 7.2, appeared to be due to the junction of two different blade shapes.

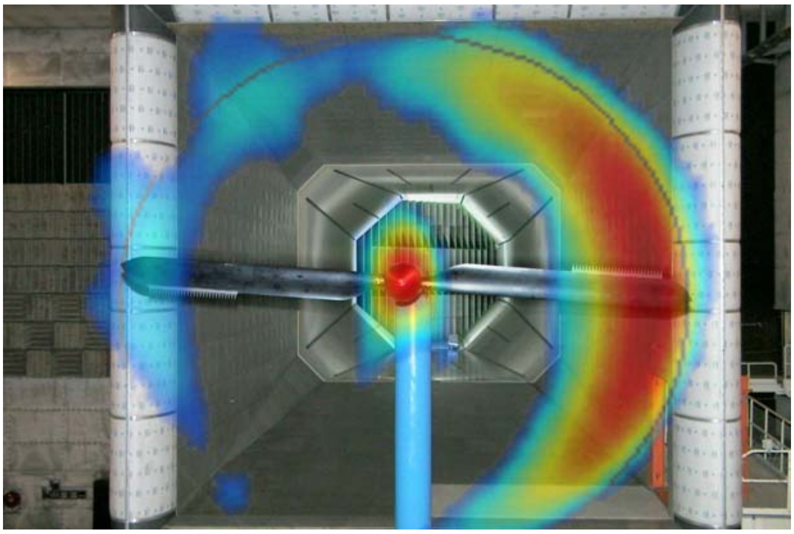


Figure 7.1 Acoustic image of model wind turbine at 8000 Hz, obtained with conventional array software.

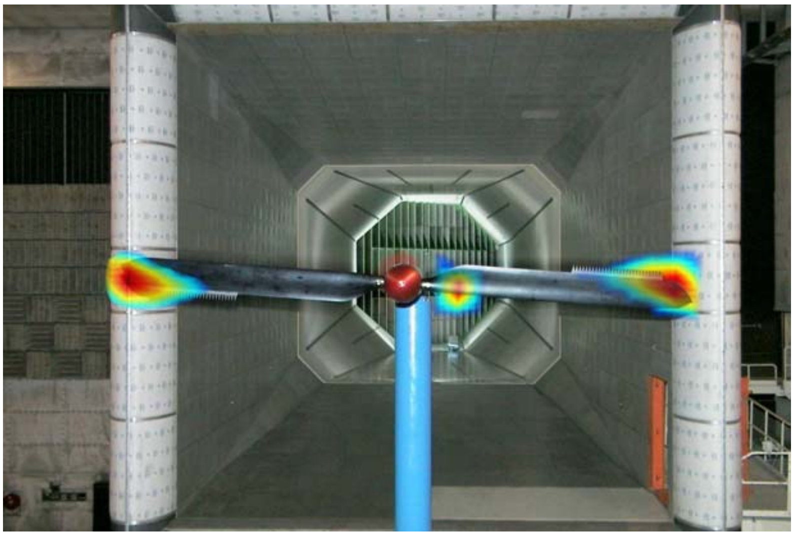


Figure 7.2 Acoustic image of model wind turbine at 8000 Hz, obtained with ROSI.

[By P. Sijtsma, NLR, The Netherlands]

7.2. TURBINE BLADE/VANE INTERACTION NOISE: ACOUSTIC MODE DECOMPOSITION IN UP TO 1500 RADIAL MODES

The sound field in the outlet of a high-speed low-pressure turbine was studied. The experiments aimed at a better understanding of the sound generating mechanisms inside the three-stage turbine. Special attention was given to the acoustic impact of different types of exit guide vanes (EGV) downstream of the turbine. Six radial rakes carrying ten Kulite-sensor probes each were mounted downstream of the EGV's in the cylindrical duct section of the turbine exit. The rakes were traversed azimuthally over 180 degrees in steps of 1.5 degrees to give a total of 240x30 measurement points. Acoustic measurements were made at operating conditions from 63% to 99% rotor design speed resolving the blade passing frequencies (BPF) of the three turbine rotors

The chosen experimental setup allows the decomposition of the sound field into azimuthal and radial modes for frequencies up to 6 kHz, Figure 7.3, with a total amount of 1500 propagating radial modes. The results of the mode analysis permit the calculation of the downstream radiated sound power. Using an extension of the theory of Tyler & Sofrin [7.2.1], the dominant noise sources can be separated into rotor/stator- and rotor/stator/EGV-interactions with associated azimuthal modes.

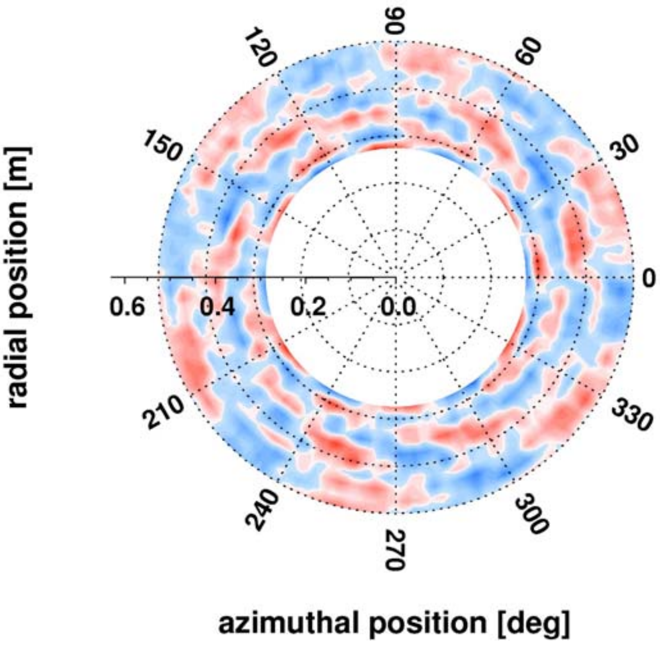


Figure 7.3 Instantaneous sound pressure pattern in the measurement plane for BPF_1 at 6 kHz, $M = 0.3$.

The investigation was conducted in the framework of the Brite/Euram project RESOUND (Reduction of Engine Source noise through Understanding and Novel Design).

[By L. Enghardt, U. Tapken*, W. Neise*, F. Kennepohl**, K. Heinig** *DLR (German Aerospace Center), Institute of Propulsion Technology, Department of Turbulence Research, Berlin **MTU Aero Engines, Munich]*

7.3. STATISTICAL APPROACH TO TURBULENCE INDUCED NOISE AND PHASED MICROPHONE ARRAY MEASUREMENTS

The noise prediction model SATIN (Statistical Approach to Turbulence Induced Noise) was developed at IAG (Institute of Aerodynamics and Gasdynamics, University of Stuttgart) in the framework of SWING (Simulation of Wing Noise Generation), a German research project sponsored by DFG (Deutsche Forschungsgemeinschaft). SWING deals with noise caused by high-lift devices of airplanes (airframe noise).

The formulation of SATIN is based on Lighthill's Acoustic Analogy and allows predicting both the far field noise radiation as well as near-field wall-pressure fluctuations. The latter is important for many practical problems because far-field noise radiation may result from the scattering of wall-pressure fluctuations at geometrical discontinuities.

The two building blocks of SATIN are a tailored Green's function and a statistical description of the turbulence. The first is computed for arbitrary geometry using a boundary-element method (BEM) and represents the influence of a solid body on the sound field. The structure of the turbulence is defined via correlations of the turbulent velocity fluctuations The required input values of SATIN are local properties of turbulence, namely the turbulent kinetic energy and the integral length scale which can be obtained from steady solutions of the Reynolds-averaged Navier-Stokes equations or for simple cases, e.g. boundary layers, from measurements.

Validation measurements were carried out using a phased microphone array (AAS). It consists of 48 to 96 microphones. Data acquisition, processing and visualization is performed with a normal PC. The data can be recorded over all 96 channels continuously over 15 s with a sampling rate of 48 kHz and 18 bit resolution.

Measurements of trailing-edge noise from a thin flat plate were performed in the acoustic wind tunnel at the Institute for Acoustics and Speech Communication of Dresden University of Technology (AWD) (see Figure 7.4).

Figure 7.5 shows a good agreement between the predicted and measured sound spectra. The turbulence quantities were obtained from a RANS calculation.

Figure 7.4 Experimental set-up for measurements of trailing-edge noise of a thin flat plate (AWD).

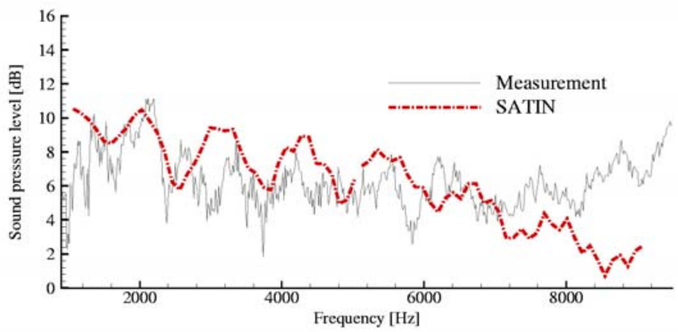


Figure7.5 Measured and predicted sound spectra of a thin flat plate (U_∞ = 36.3 m/s, c_f = 0.0037, δ = 4.8 mm).

[By Jasmin S. D. Ostertag, Sandro Guidati, Gianfranco Guidati, Siegfried Wagner Institute of Aerodynamics and Gasdynamics, University of Stuttgart, Germany]

8. FLIGHT TESTING FOR NOISE

8.1. QUIET NOISE DEMONSTRATOR

Boeing and Rolls-Royce have completed a noise reduction flight test program, known as the Quiet Technology Demonstrator (QTD), in which a Rolls-Royce Trent 800 engine was modified with a package of noise reduction technologies developed collaboratively by the two aerospace companies. Using a Boeing 777-200ER the three week flight-test demonstrated noise levels significantly below those of a standard 777: takeoff jet exhaust noise was reduced by up to four decibels and inlet fan noise was reduced by up to 13 decibels. Engineers used saw-tooth-shaped aerodynamic devices at the rear of the nacelle and on the exhaust nozzle to control the mixing of the hot jet exhaust, the bypass stream and the ambient air, the shape of the devices being determined by computational fluid dynamics modelling and wind tunnel testing using scale models. Fan noise also was reduced with extensive acoustic improvements to the redesigned engine nacelle inlet, in which a new technology called Amax (area maximisation) increased by 30 percent the area of acoustic treatment in the inlet casing, and a new lining design was used that reduces objectionable "buzz saw" noise passengers often hear during takeoff and climb.

Figure 8.1 The quiet technology demonstrator.

[By A. J. Kempton, Rolls-Royce plc, Derby, UK)

9. HELICOPTER NOISE

9.1. BREAKTHROUGH IN BVI NOISE REDUCTION OF HELICOPTERS BY ROTOR ACTIVE CONTROL

The active blade root control system installed on a BO 105 helicopter has been successfully tested in open loop configuration by EUROCOPTER DEUTSCHLAND GmbH (ECD). Flight tests have demonstrated the noise and vibration reduction potential of the individual blade root control (IBC) technology. The succeeding investigations therefore concentrated on the realization and the testing of a closed loop noise and vibration control using IBC technology.

The BO 105 IBC demonstrator (see Figure 9.1) uses proven electro-hydraulic blade pitch actuators with adequate authority for noise reduction from ZFL. This actuation system is controlled by an embedded digital computer in combination with high performance signal processing equipment for the data transfer between the rotating and non-rotating system from the DLR. For the exterior noise control a complex sensor system is installed consisting of blade pressure transducers and a landing gear mounted microphone array.

The applied BVI noise control is based on a newly developed concept for minimizing an appropriate BVI index using either blade pressure or microphone signals by applying a 2/rev IBC feedback. For the recent flight tests (performed Nov 01) only the microphones installed on the landing gear were used for BVI noise detection and generation of the BVI index based on sound pressure signals. Some details of this closed loop control system are presented in Figure 9.2. A "Golden Section" algorithm was applied for the optimisation of the 2/rev IBC phase angle towards the minimum of the BVI index. The IBC amplitude was not optimised during the tests and was therefore kept at a constant value of 1°. This approach was in accordance with open loop flight tests which generally have indicated that the IBC amplitude of 1° is most favourable for the reduction of the BVI noise emission. The evaluation of the flight tests in closed loop configuration is not finished at present, but first results are very promising. For example major BVI noise reductions in the range of 5-6 dB(A) could be achieved for the approach flight procedures with 6° and 8° slope angle (see Figure 9.3).

Figure 9.1 The BO 105 IBC demonstrator used for flight tests.

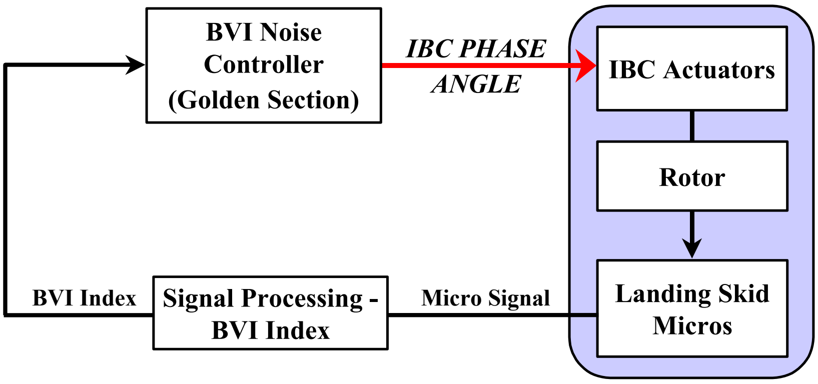


Figure 9.2 BVI noise control concept.

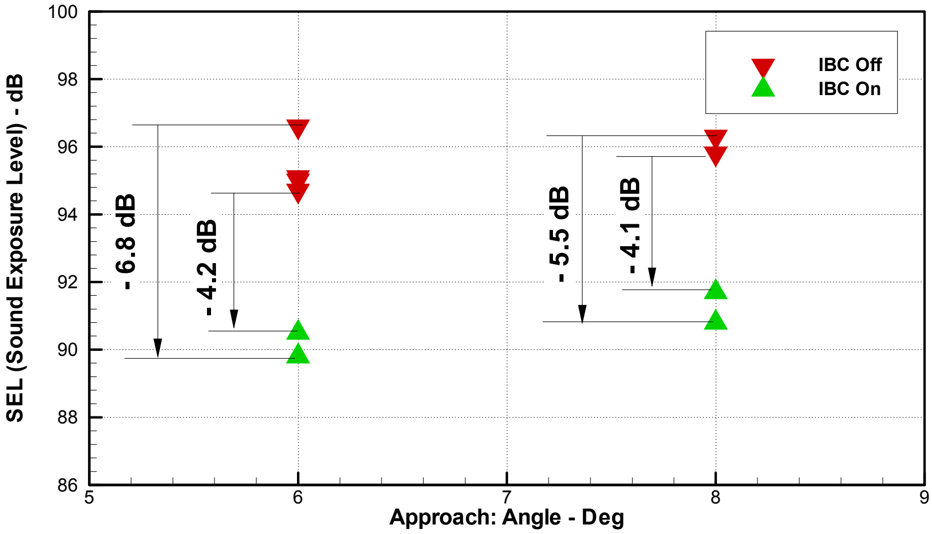


Figure 9.3 Reduction of sound exposure levels achieved by rotor active control for 6° and 8° approach flight procedures.

[By Dr Marius Bebesel / Dieter Roth EUROCOPTER DEUTSCHLAND GmbH, Munich, Germany]

10. COMMUNITY NOISE

10.1. DLR – PROJECT, QUIET AIR TRAFFIC – A CONTRIBUTION TO NOISE REDUCTION THROUGH INTEGRATED APPROACH IN RESEARCH

Aircraft noise is an urgent environmental problem. It will become more and more critical in the near future because the ongoing growth of air traffic will force an increase of the noise load around airports which cannot be overcompensated by the noise reduction techniques for airplanes currently available.

In the long term a technical potential of engine and airframe noise reduction of about 10 dB is given by experts. However short and mid-term measures are necessary to reduce noise as fast as possible. Such measures are the target of the DLR project “Quiet Air Traffic”. The objective is to realize a noise emission reduction of about 3 dB with respect to the current state in the extended environment of civil airports. Five workpackages which are linked with each other build an interdisciplinary research system covering human-specific, technical/operational as well as regulatory aspects of noise reduction. The targets of the different workpackages are:

- Definition of scientifically sound critierion for the assessment of nightly aircraft noise as a basis for noise reduction measures and legislation (sleep laboratory and field studies).
- Development of construction instructions for the aircraft industry to reduce engine and airframe noise (wind tunnel and engine test facility experiments, theoretical investigations).

- Improvement of currently used noise-abatement flight procedures for airlines, air-traffic control and airport authorities (simulation, flight experiments).
- Development of concepts for regulatory noise reduction measures for legislative and airport authorities.
- Definition of improved aircraft noise prediction procedures for environmental planning and for modeling of noise reduction strategies (computer simulation, validation experiments).

An effective abatement of aircraft noise cannot consist just in a technical and operational reduction of the physically measurable sound. Much more it must take into account the physiological and psychological effects of noise on people. In particular, our knowledge of the effects of nightly aircraft noise is still rather poor and needs to be considerably improved.

The straightforward way to minimise aircraft noise on the ground is to reduce the noise at the source. Since fan noise becomes more and more a dominating source with respect to decreasing jet noise the activities focus on the design of an optimised fan based on the reduction of fan rotational speed. Additionally the use of active noise control for the reduction of very disturbing discrete tones is investigated.

While engine noise has been reduced effectively during the last decades, airframe noise has increased due to the use of modern high-lift devices. Major sources of airframe noise are the landing gears, flaps and slats and the gear-wake/flap interaction. First wind tunnel studies were performed to identify source mechanisms, prediction schemes and reduction technologies. Flyover tests were realised to validate the windtunnel results as well as to generate airframe noise databases.

A further goal is to define operational quiet procedures with optimised altitude and speed-profiles for takeoff and landing of modern civil jet aircraft which can provide a noise reduction around civil airports. In a next step these procedures have to be integrated into modern air traffic management concepts.

As operational procedures transport political concepts for aircraft noise reduction are used to reduce interest conflicts between people living around airports, carriers, airport authorities and passengers. Possible measures are e.g. landing fees, noise quotas, steering of modal split, more effective certification regulations or airport co-operations.

Noise calculation procedures are an important tool for land-use planning and noise legislation as well as for the validation of the effects of different noise reduction strategies. An advanced simulation procedure based on a component source model (jet, fan and airframe noise) is currently under development. Such a procedure allows one to estimate a noise level time history at a given observer. Based upon that cumulative noise load expressed in long terms “noise descriptors” can be estimated. Additionally an advanced sound propagation model will be integrated. The approach is to couple meteorological models with sound propagation models thus giving a consistent description of the complex topography, atmosphere and sound field.

All these activities are performed in close contact to carriers, industries, legislators, agencies and associations as well as to universities and other research centers.

[By Burkhard Gölling, Ullrich Isermann DLR, Institute of Aerodynamics and Flow Technology, Göttingen]

REFERENCES

4.2.1 J. C. Hardin 1980 *AIAA Journal*. Noise radiation from the side edges of flaps **18**(5), 549-552.

4.2.2 C. L. Streett 1998 *AIAA* Paper 98-2226. Numerical simulation a flap edge flow field.

4.2.3 H. M. M. van der Wal and Pieter Sijtsma 2001 *AIAA* Paper 2001-2170. Flap noise measurements in a closed wind tunnel with a phased array.

5.1.1 S. W. Rienstra 2001 *7th AIAA/CEAS Aeroacoustics Conference, Maastricht, The Netherlands*. A Classification of Duct Modes Based on Surface Waves 2001-2180.

5.2.1 Li, Xd. Schönwald, N. Thiele, F. *AIAA/CEAS* 2001. Numerical Computation of Sound Propagation and radiation in a Duct 2001-2179.

5.2.2 S. Rienstra and W. Eversman 2001 *Journal of Fluid Mechanics.* A Numerical Comparison Between Multiple-Scales and FEM Solution for Sound Propagation in Lined Flow Ducts **437**, 367-384.

6.1.1 F. Farassat 1975 *NASA Technical Report R-451*. Theory of noise generation from moving bodies with an application to helicopter rotors.

6.1.2 R. Höld, R. Brenneis and A. Eberle *AIAA*-99-1896. Numerical Simulation Of Aeroacoustic Sound Generated By Generic Bodies Placed On A Plate: Part 1 – Prediction of Aeroacoustic Sources.

6.1.3 A. Travin, M. Shur, M. Strelets and P. Spalart 2000 *Journal of Flow, Turbulence and Combustion.* Detached eddy simulations past a circular cylinder **63**, 293-313.

6.4.1 A. Pierce 1990 *Journal of the Acoustical Society of America*. Wave equation for sound in fluids with unsteady inhomogeneous flow **87**(6), 2292-2299.

7.1.1 P. Sijtsma, S. Oerlemans and H. Holthusen 2001 *AIAA* Paper 2001-2167Location of rotating sources by phased array measurements.

7.2.1 L. Enghardt, U. Tapken, W. Neise, F. Kennepohl, and K. Heinig 2001 *7th AIAA/CEAS Aeroacoustic Conference*, Maastricht. Turbine Blade/Vane Interaction Noise: Acoustic Mode Analysis using in-duct Sensor Rakes, CEAS/AIAA Paper 2001-2153.

ACKNOWLEDGEMENT

The authors are pleased to acknowledge the contribution of Mrs Susan Brindle to the production of this paper.