AEROACOUSTIC RESEARCH IN EUROPE: THE CEAS-ASC REPORT ON 2000 HIGHLIGHTS

Sandro Ianniello*
INSEAN – Italian Ship Model Basin
Via di Vallerano, 139 - 00128 Rome, Italy

This paper summarizes the highlights of aeroacoustics research in Europe in 2000, 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 Committee (ASC) is to to serve and support the scientific and industrial aeroacoustics community in Europe. Here "Aeroacoustics" is to encompass all aerospace acoustics and related areas. Each year the Committee will highlight some of the research and development activities in Europe. This is the report of the 2000 highlights; contributions to this report have been made by the following people: S. Oerlemans, P. Sijtsma J. Delfs, T. Lauke, W. Dobrzynski, W. Neise (*DLR*), Peter Költzsch (*Technical University Dresden*), H. Batard (*EADS*), C. Bogey, C. Bailly, D. Juvé (*Ecole Centrale de Lyon*), W. Just and I. U. Borchers (*Dornier GmbH*), D. Gély, G. Elias, C. Bresson, S. Lewy, J. Prieur, G. Rahier, P. Spiegel, P. Malbéqui (*ONERA*), H. Foulon (*CEAT*), G. Guidati, S. Wagner (*IAG, University of Stuttgart*), F. Kennepohl (*Münich Technical University*), A. Roure, A. Albarrazin, M. Winninger (*LMA*), A. de Boer, H. Tijdeman, F. van der Eerden, T. Basten (*University of Twente*).

2 AIRFRAME NOISE

2.1 Effects of wind tunnel side-plates on airframe noise

The effects of wind tunnel side-plates on airframe noise measurements with phased arrays were investigated both experimentally (in NLR's Small Anechoic Wind Tunnel) and theoretically [1]. In a previous set-up, with acoustically hard side-plates and a cross-shaped array, calibration measurements with a monopole source showed differences between array output and actual source strength up to 10 dB, with strong dependence on frequency and source location. Theory predicted much better results when the cross-shaped array was replaced by a sparse array and the hard plates by acoustically lined plates. After application of these modifications in the test set-up, new calibration measurements indeed showed impressive improvement in the ability to determine absolute levels with a phased array (within 2 dB), independent of frequency or source position (Figure 1) (by S. Oerlemans, P. Sijtsma).

2.2 CAA simulation of sound generation by linear interaction of vorticity with a wedge

The study of airframe noise is intimately connected with the interaction of flow with edges. In this context the question arises, whether linearized conservation equations describe such sources. Lilley's aeroacoustic wave equation states that in a subsonic parallel steady mean shear flow $\vec{u}^0 = [u_1, u_2, u_3]^0 = [u_1^0(x_2), 0, 0]$

*Research Engineer, Phone: +39-06-50299311, E-mail: s.ianniello@insean.it

sound is generated by nonlinear processes only, because the respective aeroacoustic source term $\frac{\partial u_i}{\partial x_l}\frac{\partial u_k}{\partial x_i}\frac{\partial u_l}{\partial x_k}$ vanishes upon linearization about the basic state $\vec{u}^0$. The linear dynamics of whatsoever small perturbations $\vec{u}'$, e.g. due to small fluctuations of the vorticity, will therefore not contribute to the generation of noise. In order to verify the above statement a numerical simulation of the linear dynamics of a purely vortical perturbation evolving in a free parallel shearlayer was carried out using DLR's CAA Chimera code [2], see also [3]. The shearlayer is located in $-1.1 \leq x_2 \leq 1.1$; below there is no flow and above there is a constant flow of Mach number $M = 0.4$. Localized vorticity is introduced at simulation time $t = 0$ and position $x = x_1 = 2, y = x_2 = -0.5$. As a result a downstream convecting unstable wave packet evolves representing the classical Kelvin-Helmholtz instability. The left part of Figure 2 shows the respective linear pressure field $p'(x, y, t = 70)$, which consists of purely hydrodynamic (i.e. non-propagating) components indicating complete silence and thus confirming the statement of Lilley's equation. The right part of Figure 2 shows the pressure field if a sharp vertical wedge with vertex at $x = 10, y = -1.4$ is originally placed below the shearlayer. In this case sound is generated by scattering of the wave packet's linear hydrodynamic pressure field at the wedge although the mean flow does not even touch the wedge. The example shows that in the presence of edges the sound generation by vorticity becomes a linear problem even in the presence of a parallel shear flow (by J. Delfs, T. Lauke).

Figure 1: Monopole source levels determined with phased microphone array, in an anechoic environment (i.e. actual source strength), in the previous set-up (hard side-plates/cross array), and in the new set-up (lined side-plates/sparse array).

Figure 2: Pressure of wave packet evolving along shearlayer. Left: free, right: with edge.

2.3 Airframe Noise from Wing High-Lift Devices: Successful Prediction of Full-Scale Flyover Noise from (DNW) Model-Scale Studies

A good knowledge of aircraft noise characteristics (spectra and directivities) is indispensable to predict noise immission contours around airports. Since during landing approach the total aircraft noise is not solely determined by the engines, but much rather by flow around the entire airframe, the specific characteristics of both engine and airframe related noise components need to be determined.

Engine noise signatures are well documented by the manufacturers. In contrast, airframe noise characteristics (specifically related to landing gears and wing high lift devices) were yet unknown to the necessary detail. Within a dedicated German national program high lift device (HLD) airframe noise signatures were determined from scale-model experiments on complete aircraft configurations in the German-Dutch Wind Tunnel (DNW) both in terms of spectra and of directivities in longitudinal and azimuthal directions. After transformation to full-scale the wind tunnel results compare well with flyover noise data for an aircraft with its HLD fully deployed.

An example is provided in Figure 3 showing wing HLD noise spectra in the "vertical" radiation direction (i.e. for the aircraft directly overhead). While at low frequencies flyover- and wind tunnel data exhibit excellent agreement, an increasing offset is observed at higher frequencies. This could well be expected since accompanying wind tunnel tests on a full-scale aircraft wings showed conclusively that excess noise occurs from small structural components, whose detailed geometry simply cannot be reproduced at model scale. It is worth mentioning that good agreement between flyover- and wind tunnel data is also obtained with respect to the noise directivity, exhibiting maximum levels in the rear arc as a result of noise radiation from the deployed wing slats (by W. Dobrzynski).

Figure 3: Comparison of wing high lift device airframe noise spectra from fly-over and scale-model wind tunnel tests.

2.4 First Phase of German Research Initiative into the Computation of Airframe Noise Successfully Completed

The aim of the co-operative national research initiative SWING (Simulation of Wing-flow Noise Generation) is the computation of airframe noise generated at the high-lift devices of modern transport aircraft at approach conditions. Within the first three years of the project the partners from three German universities

(Aerodynamisches Institut RWTH Aachen, Institut für Aerodynamik und Gasdynamik University Stuttgart, Institut für Akustik und Sprachkommunikation University of Technology Dresden) and DLR (Institut fr Entwurfsaerodynamik) have developed and validated computational approaches based on (a) the numerical solution of an acoustic wave equation (BEM) in combination with statistical source modeling and (b) the high accuracy numerical solution (CAA) of 3D linearized Euler equations (LEE) for a direct simulation of perturbations about the mean flow field and thus the sound generation process.

In this first project phase the methods were successfully tested against CAA benchmark problems and problems of edge noise generation (leading edges, trailing edges). Respective aeroacoustic validation tests were carried out in the aerodynamic wind tunnels of University Stuttgart as well as the anechoic tunnels of TU Dresden and DLR Braunschweig employing microphone arrays and acoustic mirrors for source localization. Moreover, source data were also generated by means of Large Eddy Simulation of the turbulent fluctuations near a trailing edge in order to validate the statistical source model of the acoustic analogy approach as well as the stochastic fluctuation model used in the LEE.

The project was funded partially by the Deutsche Forschungsgemeinschaft DFG, the ministry of research and education (BMBF) as well as DLR. The research progress was documented within two international colloquia held in Dresden 1999 and Braunschweig 2000, the proceedings [4, 5] of which are available through either of the two authors (by P. Költzsch and J. Delfs).

3 FAN & JET NOISE

3.1 Research on the nacelle devices to reduce the fan noise

The RANNTAC project started on January 1998 and finished as planned on December 2000. The objective of this project was to acquire the technology necessary to support the design and the manufacturing of turbofan engine nacelles featuring innovative noise reduction devices. During these three years, the following families of concepts have been studied:

- Passive liners including an investigation of non locally reacting concepts,
- Adaptive liners,
- Negatively scarfed intake,
- Active noise control including actuator technology.

Figure 4: Sketches of concepts developed in RANNTAC project.

In view of the large number of concepts (see Figure 4), a special effort has been devoted to the definition of technical objectives and to the set up of final assessment procedure in order to guide development towards industrial but feasible solutions. A procedure based on performance checklists, including acoustic but also integration criteria, has been defined for each concept. Three issues of these check lists were requested during the project in which developers provided themselves targets, predicted and consolidated figures respectively for their concepts. In addition, and in order to carry out predictions of aircraft noise in flight, specialists were asked to send the performance of their concepts in terms of either impedance, in-duct attenuation or directivity pattern spectra in approach and take-off conditions.

A lot of activities concerned the development of innovative nacelle treatment concepts and included both liner studies and negatively scarfed intake investigations. Liners have been analysed in two subtasks for theoretical modelling and tests respectively. Extensive computations and tests carried out with various facilities on concept configurations, including full scale tests on a real engine, have allowed to draw the main features of each concepts. Investigations have also been devoted to the effect manufacturing processes and to the improvement of structural properties, namely weight and bonding quality. The ability of most of liner concepts to widen the frequency range of efficiency has been demonstrated thank to very promising behaviours of the imaginary part of impedance. The effect of the real part on the attenuation has also been confirmed and a need to improve manufacturing processes to get closer from optimum resistance was identified. The evaluation of the negatively scarfed inlet has allowed to quantify acoustic power and directivity changes due to the scarf angle with respect to an axisymmetric duct. Thanks to fan rig tests, it is now possible to draw the main characteristics of the negative scarf. First of all, a significant reduction of acoustic power toward ground in the flyover plane has been confirmed on both tone and broadband noise. In addition, the directivity pattern changes due to the scarf have been quantified. An other interesting result concerns the overall reduction of acoustic power in the whole flyover plane (the increase of noise toward sky is not as important as the decrease toward ground). This result leads to consider an additional diversion of noise sideways due to the scarf angle that will have to be studied further.

An entire task was devoted to the development of active noise control (ANC) technology for engine nacelles, and a significant work concerned the optimisation of set up and the improvement of algorithms. Theoretical studies on the optimisation of actuators/sensors number and positioning have been performed and most results, namely about number of actuators/sensors and their distribution on consecutive rings with respect to modal content in the duct, were confirmed during ANC test campaigns on a fan rig. These tests allowed to evaluate the accuracy of various algorithms, to analyse their robustness with respect to engine speed variations and to validate a new radial mode analysis. Significant noise abatements have been measured for low frequency tones (1 BPF) but tests and theoretical studies show that harmonics will be more difficult to reduce because of much higher number of propagating modes.

Actuators suitable in Nacelle Active Noise Control have been also thoroughly studied. Special specifications have been used by partners to test and improve their concept, from the acoustic point of view but also from their resistance to aggressive environment in nacelle. Very significant improvements have been achieved namely about weight, bulk and consumption needed to reach reasonable acoustic levels. For instance, the ability of some concepts to reach required acoustic levels has been demonstrated with very low thickness and weight. As a conclusion, it is important to note that the performance checklists and data provided by partners have allowed to build a firm data base concerning the maturity and the potential of each concepts. These results, in addition with aircraft noise impact computations carried out for both concepts during the last 6 months of the project, enable now to draw precisely ways of improvement or further studies for each concepts. These results will be key information for forthcoming industrial or research programs (by H. Batard).

3.2 Direct simulation of aerodynamic noise

The noise radiated by turbulent flows was investigated through direct simulation [6, 7, 8] with the two illustrations of a 2-D cavity and a 3-D jet. In order to obtain directly the acoustic field, a code solving the compressible Navier-Stokes equations was developed using specific numerical techniques, such as the DRP scheme of Tam & Webb for space integration and a fourth order Runge-Kutta algorithm for time advancement. The boundary condition of Tam & Dong are implemented in combination with a sponge region at the outflow boundary.

Firstly, a 2-D open cavity with a laminar incoming boundary layer with a Mach number of 0.5 was simulated by DNS [8]. Figure 5 presents the acoustic field generated by instability waves of the shear layer impinging the downstream corner (X. Gloerfelt Ph. D. Thesis). Secondly, a Mach 0.9, Reynolds number 6 $\times$ 10^4, 3-D round jet is simulated by LES [6] (Figure 6). The aerodynamic properties of the jet, such as meanflow parameters and turbulent intensities, are in very good agreement with experimental data. The sound field generated by the jet is obtained directly in the simulation and investigated. Acoustic sources in the jet are located around the end of the potential core, consistently with experimental observations. Radiation directivity and sound levels are compared successfully with corresponding measurements (by C. Bogey, C. Bailly, D. Juvé).

Figures 5: Visualization of the dilatation field in the upper part and of the vorticity field in the lower part for two successive times with a ratio $L/\delta_{\theta 1} \simeq 63$.

Figures 6: Snapshot of the dilatation field $\Theta = \nabla \cdot \nu$ in the acoustic region, and of the vorticity field ω_{xy} in the aerodynamic region, in the $x - y$ plane at $z = 0$. The dilatation color scale is defined for levels from -90 to 90 s^{-1}.

3.3 Successful testing of Active Stators for Turbofan Engines in Europe

Within the EC funded project RESOUND (Reduction of engine source noise through understanding and novel design) very promising results in testing of Active Stators for reduction of tonal rotor/stator interaction noise in the fan of aeroengines could be achieved. The Active Stators were developed by Dornier GmbH/Germany and successfully tested in a model scale fanrig of SNECMA/France in co-operation with EADS Deutschland Corporate Research Center (Figure 7). The actuators are flush mounted on and integrated in the stator vanes of a model scale fan rig to act as control devices nearest to the source of the rotor-stator interaction noise caused by the viscous wakes of the rotor (see small picture in Figure 7). Results of a first test campaign show averaged reductions of up to 15dB at BPF in a selected area of interest in the upstream farfield at lower frequencies (1500 Hz, see Figure 8). In the remaining upstream farfield the control is nearly global. Furthermore the SPL maps gathered with an upstream moving farfield antenna show that a good reduction at high angles to the machine axis is achieved in nearly each test case (by W. Just and I. U. Borchers).

Figure 7: Monitor microphones and Active Stator vane for Active Stator testing.

Figure 8: Active Stator testing. Selected sound pressure levels measured at Dornier static farfield microphones.

3.4 Sound pressure level reduction around the Ariane 5 launch vehicle

The vibroacoustic tests made during the last V503 qualification flight of the Ariane launcher (October 1998) confirmed the need to reduce, specially in the 31.5 Hz octave band, the acoustic levels underneath the fairing when the launcher goes through the altitude 10m to 20m. Based on the relative levels of the Solid Rocket Booster (SRB), the central engine sources and the NR indexes, it appeared necessary to reduce the acoustic sources at the outlet of the two solid booster ducts by at least 6 dB to achieve the required noise reduction inside the fairing.

A test campaign was conducted in the MARTEL facility in 1999 to test systems which could satisfy this requirement. Two methods were investigated. The first consisted in attempting to improve the efficiency of the water injection systems even more by focusing on the incriminated source regions. Unfortunately, despite a few improvements observed in certain configurations, the noise reductions in the frequency band concerned did not exceed 2 dB and were therefore too low to implement this type of solution. The second method investigated was an extension of the SRB ducts (Figure 9).

Figure 9: Ariane 5 launch pad mock-up with duct extension in MARTEL facility.

Figure 10: Duct extensions effect.

The noise spectra measured for three extensions 10m, 15m and 30m are shown in Figure 10. These results were obtained for a critical altitude of 10m. In each case, a noise reduction was observed over a wide frequency band. The noise reduction increases with the duct extension lenght. However, based on results not presented herein, the reduction decreases as the launcher climbs. Indeed, the extension of the duct gradually masks the jet near the final section.

The noise attenuations observed are due to the masking effect of the duct and to the change in the direction of the jet subsequent to the horizontal extension of the duct. The main jet emission direction is thus farther from the top part of the launcher. Quantification and extrapolation of the attenuation predictable at full scale in the 31.5 Hz octave are based on :

- the geometric scale (1:47),
- the Strouhal reduced number, which takes the velocity and temperature effects into account (1:42),
- the velocity ratio at the duct outlet based on flow rate conservation (1:29).

It appeared that a 30-meter horizontal extension of the solid booster stage ducts satisfies the stated requirement. The building on the Kourou site were performed just before the V504 flight as it can be seen in Figure 11.

Figure 11: SRB duct extension in Kourou site.

Figure 12: V503-V504 Ariane 5 flights. Acoustic data comparison.

The comparison between V503 and V504 flights appears in Figure 12. The mean sound pressure level of microphones located on the fairing has been plotted between H0 + 4s and H0 + 18s. Between H0 + 4s and H0 + 7s, when the central engine (Vulcain) is running alone, before the SRB ignition, no difference is observed. In contrast, a reduction of about 5 dB appears from H0 + 7s to H0 + 12s (60m in altitude). It is interesting to quote that with the new extended ducts, the contribution of the SRB to the noise during this time seems to have disappeared, the levels being the same before and after their ignition. This result is confirmed by noise source localization. A full microphone array consisting in twelve flush mounted microphones has been implemented around the fairing, in order to perform noise source localization during lift-off. An example of the results is presented in Figure 13. The V504 acoustic map, compared to the V503 one, shows that no acoustic source remains at the SRB duct outlets at an altitude of 20m. The full-scale measurements fully agrees with the predictions made using the MARTEL facility and the final noise reduction objective is reached. The MARTEL facility and expertise in advanced signal processing techniques prove to be excellent, invaluable, performing tools for successfully conducting experimental studies designed to reduce the noise level of a launcher at lift-off (by D. Gély, G. Elias, C. Bresson, H. Foulon).

Figure 13: Acoustic sources localization V503 - V504 flights. Top view.

3.5 Active Control of Noise from Turbomachines

Active noise control of turbomachinery tones up to ka = 10 was successfully demonstrated with a fan model of 1m diameter, using 32 actuators and 32 error sensors wall-mounted in the inlet duct section.

Figure 14: Fan rig at DLR with active noise control equipment: 1.Fan casing 2.Actuators 3.Sensors

In this project – supported by the German Ministry for Research and Technology (BMBF) in the framework of AG Turbo – DLR provided the test stand and executed the radial mode analysis of the sound field, EADS provided and operated a 32 channel controller using filtered-x-LMS-algorithms and MTU Aero Engines developed a computer code to simulate the ANC sound field in the duct and specified the optimum locations of actuators and sensors. Total sound power reductions of 27 dB at 340 Hz, where 8 duct modes are propagational in both directions in the duct, have been achieved and 11 dB at 680 Hz, where 28 modes are propagational, using the control concept of minimising the squared sound pressures measured at the error sensor positions. Additionally, a modal control concept was successfully applied, which allows cancellation of selected azimuthal mode orders (by F. Kennepohl, W. Neise).

3.6 Successful testing of low-noise airfoils on model wind turbine in DNW

The EU-funded project DATA (Design and Testing of Acoustically Optimized Airfoils for Wind Turbines, JOR3-CT98-0248) aimed at the reduction of broadband aerodynamic noise from wind turbines. The work focused on the major noise mechanism, namely turbulent-boundary-layer-trailing-edge-interaction noise.

A prediction model developed by TNO-TPD allowed to design airfoils which minimize this type of noise. In a series of wind tunnel tests on cylindrical airfoil sections it could be shown that reductions in the order of 2-4 dB are possible. This was confirmed during a test in the Large Low-speed Facility of DNW. The results indicate that noise reductions in the same order of magnitude can be expected for both tripped and untripped flow conditions, without negative effect on the power production. The approach of designing low-noise airfoils may also be applied in related areas such as fan noise (Partners: IAG, LM Glasfiber Holland, NLR, TNO-TPD, ECN) (by G. Guidati, S. Wagner).

3.7 Studies on Acoustics of Turbofans

Main achievements at ONERA on turbofan noise have been related to broadband noise. Work has been performed in the framework of the European project RESOUND. Further analyses of the FANPAC tests made by Rolls-Royce in their anechoic facility enabled us to get more information on broadband noise [9].

Figure 15: Left figure shows the relative overall sound power level vs rotation speed, N rpm (logarithmic scale); right figure shows the reduced broadband sound power level vs the flow angle of attack on rotor blades.

Figure 15 (on the left) shows the total (including the tones) and broadband overall sound power levels, OAPWL, radiated upstream of the fan (the reference of the dB-scale is arbitrary). The difference between both curves is about 2 dB at subsonic rotation tip Mach numbers, Mtip, which proves that broadband noise is higher than the blade passing frequency, BPF, and its harmonics. The large increase of total OAPWL in transonic is due to multiple pure tones, MPT, which are not completely removed from the broadband component. The departure from the theoretical law in 50 log10 (Mtip) suggests there is another important parameter. On the right of Figure 15 a plot of reduced OAPWL versus the flow angle of attack on the rotor blades is shown (Mhel is the tip helical Mach number). Values collapse on a single straight line in subsonic, with a slope of 1.6 dB/degree. It can be inferred from this result that rotor self-noise dominates in upstream broadband radiation. The part at supersonic tip speeds has not the same shape, but this can be due to remaining MPT. Indeed, other test series with an acoustic lining on the duct wall well absorbs the MPT, and broadband curves are continuous around Mtip = 1 which means that the generation mechanisms should be similar in subsonic and in supersonic. Next steps consist in comparing with RESOUND tests on low-noise research fans, and in developing a prediction method to compute fan broadband noise (by S. Lewy).

4 HELICOPTER NOISE

4.1 Main achievements in the field of helicopter rotor noise research

4.1.1 Code development and validation

The Kirchhoff code KIM [10] and the code FIM [11] based on the generalized Ffowcs Williams-Hawkings (porous surface) formulation respectively designed at ONERA in 1997 and 1998 have a high numerical efficiency thanks to the original integration technique [10]. They have been extended to deformable grids for proper adaptation to currently implemented CFD grids. Furthermore the unsteady version of FIM, the last to be developed (for forward flight simulations) has been fully validated. In view of applications to acoustic flight tests and future design of low-noise flight procedures, the validation of the code CONGA [12] able to predict BVI noise using blade pressures measured by a small number of sensors has been completed on the basis of W.T. results [13].

It is intended to be applied to 2001 flight tests of the DLR BO105 helicopter for which unsteady main rotor blade pressures together with ground noise will be measured. In the framework of the ERATO cooperation with DLR, a low noise rotor geometry (with emphasis on low BVI noise and performance/dynamic constraints) was designed [14] and a highly instrumented model rotor manufactured and tested (together with a reference rotor) in the ONERA S1 Modane-Avrieux (S1MA) wind tunnel at high speed and in the DNW at moderate and low speed. Though the very satisfactory results reported in [15] verify the quiet rotor methodology applied, there is still room for improvement of the wake predictions particularly. The high quality comprehensive data base acquired including extensive blade pressure, strain gauge, microphone and wake measurements (at DNW using LLS and PIV), is currently used for prediction/experiment correlations.

Figure 16: Characterisation of BWI noise sources by wavelet analysis of HART test data (sample rotation) [16].

4.1.2 Study of Blade Wake Interaction (BWI) noise of the main rotor

A statistical analysis of HART BWI-related blade pressure fluctuations have been performed by means of the wavelet transform (see Figure 16). The study shows that BWI should be related to coherent structures expected to develop in the vicinity of the rotor vortices [16]. This conclusion is in opposition with current approaches which consider BWI as the result of an homogeneous and stationary random phenomenon. The next step of the study consists in numerical simulations of the development of such structures using a Navier-Stokes code, in cooperation with *Le Havre* University.

4.1.3 Study of fenestron noise

A comprehensive numerical and experimental programme to study the noise generation mechanisms of Eurocopter helicopter fenestrons has been launched. The year 2000 has been devoted to the design of a pressure instrumented Dauphin fenestron in view of aeroacoustic flight tests (cooperation with Eurocopter and Istres Flight Test Center).

4.1.4 Active rotor blade studies

In cooperation with DLR and Eurocopter, numerical parametric studies of a scale-one rotor with active trailing edge flaps have been performed with respect to performance, noise and dynamics [17]. Studies of a model-scale rotor with such flaps have also been performed in view of future wind tunnel tests (by G. Rahier, J. Prieur, P. Spiegel).

4.2 Developments of the K-Algorithm in the computation of emission surfaces

At CIRA the K-Algorithm, developed to integrate the Ffowcs Williams-Hawkings equation on a supersonic rotating domain [18] and to evaluate the high-speed impulsive (HSI) noise from helicopter rotors at high transonic regime [19], has been deeply revised and improved.

Figure 17: On the right: plan-view and 3D-view of the numerical meshes used to test the K-Algorithm capability in computing a supersonic emission surfaces (Mach number between 0.95 and 1.3) and, (left figures) the thickness noise signatures as determined at hovering condition and for an observer placed at 3 radii from rotor hub. Top: UH-1H untwisted blade. Center: BERP-like blade. Bottom: Propeller blade.

At present the algorithm is able to determine the time evolution of a subsonic/supersonic emission surface, without any requirement about the geometrical simmetry of the rotating body and/or the microphone location, and in a very limited CPU time. This aim has been achieved by changing the structure of the code and through the development of a numerical procedure (named CIS: *Crossed Iteration Scheme*) devoted to the evaluation of the multiple emission times for supersonic sources [20]. The CIS is based on a double time loop sweeping forward and backward the time period corresponding to the noise prediction of a source point and compared to the full iteration scheme required to find the roots of the *retarded function* (corresponding to the emission times) can obtain a CPU time reduction greater than 95 %. In order to test the capability of the K-Algorithm in computing the emission surface area and the different noise terms of the Ffowcs Williams-Hawkings equation, some critical test has been treated. Figure 17 shows (on the left) both a plan- and a 3D-view of three blades, corresponding (from top to bottom) to a UH-1H untwisted blade with a uniform spanwise distribution of NACA0012 profile, a BERP-like blade with a complex tip shape and a high-speed propeller blade characterized by a significant variation of twist angle and chord along span. The same Figure 17 shows (on the right) the thickness noise component as determined through the K-Algorithm, by accounting for a microphone placed in the rotor plane at a distance of 3 radii from the hub, and a range of the rotational Mach number between 0.95 and 1.3 (thus forcing the code to treat the critical region overlapping the sonic cylinder). Despite the occurence of multiple emission times and the corresponding difficulties in modelling the emission surface, the signatures appear very smooth, thus proving the effectiveness of the procedure (by S. Ianniello).

5 TECHNIQUES AND METHODS IN AEROACOUSTICS

5.1 Application of the ray-model to duct acoustics

In the framework of the European Brite-Euram DUCAT project, complementary methods have been developed for duct acoustics: BEM, FEM, coupled FEM/BEM, ray-acoustics, non-linear propagation model, extended reaction liner model. In practice, due to CPU time consuming and to large memory requirement, the analysis of 3D problems with numerical techniques is restricted to the low and mid frequency ranges. As a high frequency approximation, the ray-model is an alternative method. Its capabilities to handle both in-duct propagation and radiation have been studied in the project [21]. Figure 18 illustrates a benchmark solution concerning the directivity pattern of a point source inside a duct. The comparisons with the LINDA modal approach [22] show that the ray model is valid when kr = 7 for rigid walls (Figure 18a), and when kr = 35 for lined walls (Figure 18b) (by P. Malbéqui).

Figure 18: Directivity pattern of the sound radiation from a point source inside a duct.

5.2 Sound reduction methods with passive and/or active means

Within the Applied Mechanics group of the Department of Mechanical Engineering at the University of Twente research is carried out on coupling of structural vibrations and acoustics. The main objective is to investigate sound reduction methods with passive and/or active means. Overview is focused on the research on passive methods.

5.2.1 Noise reduction with coupled prismatic tubes

It is efficient to predict the effect of sound absorbing materials in advance for specific noise problems. For conventional sound absorbing materials, such as glass wool or foams, this is not an easy task. Therefore a well-defined model of a wall with a uniform distribution of resonators has been developed and validated experimentally. With the help of resonators, which consist of coupled tubes, a broadband absorption can be created for a predefined frequency range. Besides, in aggressive environments or at high temperatures special materials can be used [23, 24].

5.2.2 Structural damping with double wall panels

The vibrational behaviour of light weight structures, such as a thin flexible panel, is strongly influenced by narrow air layers (Figure 19). Structural vibrations and structure borne sound can be reduced via this so-called squeeze film damping through viscous and thermal effects in the air layer. Analytical and FEM tools were developed. It is shown, both numerically and experimentally, that high damping coefficients for double wall panels can be obtained. The damping can be increased by placing barriers in the layer (Figure 20). The vortices formed behind the barriers increase the dissipation of vibrational energy [25, 26] (by A. de Boer, H. Tijdeman, F. J. M. van der Eerden, T. G. H. Basten).

Figure 19: Sound absorbing samples with resonators and corresponding sound absorption coefficients (... quarter-wavelength resonators, – two coupled tubes, - three coupled tubes).

Figure 20: Experimental set-up for double wall panel measurements (left) and increased damping through vortices due to the presence of barriers (right).

6 AIRCRAFT INTERIOR NOISE

6.1 The Remote Microphone Technique for Nacelle Active Noise Control

During the RANNTAC project, the Laboratoire de Mécanique et d'Acoustique (L.M.A.) of CNRS worked on the concept of Remote Microphone Technique (RMT) for actively reduce the nacelle engine noise. The RMT algorithm is an Active Noise Control algorithm [27] allowing minimisation of an acoustic field in some areas where error sensors cannot be located (far field of the engine noise by example). It needs a preliminary identification phase where microphones are located in these "forbidden" areas and where transfer functions are measured between these "virtual" microphones and those of the control system (nacelle by example). During the control phase, an estimate of the instantaneous virtual field was done with the measured error sensor signals of the controller and with the identified transfer functions. A classical filtered x-LMS algorithm is then applied on this virtual acoustic field. During the ASANCA projecti [28], this algorithm had been implemented in aircrafts to reduce turbofan noise in cabin and had given significant results during flying tests. In the RANNTAC project, the RMT algorithm has been tested on the SNECMA fan rig schematically shown in Figure 21. The virtual microphones were located on a far field antenna at about 3 meters of the inlet of the duct or on the turbulent control screen of this inlet. The secondary sources and the error microphones of the controller were put all around the duct surface. The controller used was a multichannel (16 outputs x 18 inputs)-multiprocessor (17 DSP) system, but the real-time computations needed by the RMT algorithm limited the control to only narrow bands of frequencies.

Figure 21: Transducer locations on the Snecma fan rig.

Figure 22: On the left: acoustic level measured on the virtual microphones for a RMT control of a 1320 Hz pure tone produced by a loudspeaker. On the right: Mean spectrum of the acoustic field on the virtual microphones for a RMT control of the 1320 Hz pure tone produced by the nacelle engine.

The difficulties in this experiment came from the high frequencies to control (1500 to 3000 Hz), the high order of the modes propagating in the duct (> 7) and the large fluctuations of the engine speed during the control tests ($> 4\%$). The main conclusions of the tests were that the RMT algorithm is a valid concept for stationary fields as shown in the left Figure 22, in which the engine noise was replaced by a primary loudspeaker. With 12 secondary sources, 6 errors microphones and 12 virtual microphones located on the far field antenna, 15 to 20 dB reduction of the directivity pattern of the primary field was obtained in a solid angle crossing the far field antenna. With the engine noise and with the same transducers, the results are not so good (2 to 3 dB reduction only) due to the low tracking capability of the RMT algorithm when the primary noise fluctuates (right Figure 22). Recent investigations allow to drastically reduce the calculation needed by the RMT algorithm. With these new improvements, broadband control should be possible that will probably authorise a better robustness of the RMT algorithm to speed changes (by A. Roure, A. Albarrazin, M. Winninger).

References

[1] Oerlemans, S., Sijtsma, P., "Effects of wind tunnel side-plates on airframe noise measurements with phased arrays", *6th AIAA/CEAS Aeroacoustics Conference*, Lahaina, Hawaii, 12-14 June 2000.

[2] Delfs, J. W., "An overlapped grid technique for numerical simulation in Aeroacoustics", submitted to *Journal of Computational Physics*, 2001.

[3] Grogger, H. A., Delfs, J. W., Lauke, T. G., Lummer, M., Yin, J., "Simulation of leading edge noise of airfoils using CAA based on body fitted grids", *International Congress of Sound and Vibration ICSV7*, Garmisch, Germany, 2000, (submitted to *International Journal of Acoustics and Vibration*).

[4] Költzsch, P., Kalitzin, N., "Proceedings of Aeroacoustics Workshop SWING", Institut für Akustik und Sprachkommunikation, University of Technology Dresden, Germany, October 1999.

[5] Körner, H.; Delfs, J. W., "Proceedings of Second Aeroacoustics Workshop SWING", Institut für Entwurfsaerodynamik, Deutsches Zentrum für Luft- und Raumfahrt, DLR Braunschweig, Germany, October 2000.

[6] Bogey, C., Bailly, C., Juvé, D., "Computation of the sound radiated by a 3-D jet using large eddy simulation", *AIAA Paper 2000-2009.*

[7] Bogey, C., Bailly, C., Juvé, D., "Numerical simulation of the sound generated by vortex pairing in a mixing layer", *AIAA Journal*, 38(12). See also *AIAA Paper 99-1871.*

[8] Gloerfelt, X., Bailly, C., Juvé, D., "Calcul direct du rayonnemnt acoustique d'un écoulement affleurant une cavité", *C. R. Acad. Sci.*, t. 328, Série IIb.

[9] Lewy, S., "Experimental study of fan brodband noise on a turbofan model", *7th International Congress on Sound and Vibration*, Garmisch-Partenkirchen, Germany, July 2000, pp. 1251-1258.

[10] Rahier, G., and Prieur, J., "An Efficient Kirchhoff Integration Method for Rotor Noise Prediction Starting Indifferently from Subsonically or Supersonically Rotating Meshes", *53rd Annual Forum of the American Helicopter Society*, Virginia Beach, VA, April-May 1997.

[11] Prieur, J., and Rahier, G., "Comparison of Ffowcs Williams-Hawkings and Kirchhoff Rotor Noise Calculations", *4th AIAA/CEAS Joint Aeroacoustics Conference*, Toulouse, France, June 1998.

[12] Spiegel, P., "An Iso-Event Spanwise Interpolation Technique for Blade-Vortex Interaction Noise Prediction and Analysis", *24th European Rotorcraft Forum*, Marseilles, France, September 1998.

[13] Spiegel, P., "BVI Noise Prediction and Analysis Starting from Blade Pressures Measured on a Small Number of Points", *56th Annual Forum of the American Helicopter Soc.*, Virginia Virginia Beach, VA, May 2000.

[14] Prieur, J., and Splettstoesser, W., "ERATO: an ONERA-DLR Cooperative Programme on Aeroacoustic Rotor Optimisation" *25th European Rotorcraft Forum*, Roma, September 1999.

[15] Splettstoesser, W., Van der Wall, B., Junker, B., Schultz, K., Beaumier, P., Delrieux, Y., Leconte, P., and Crozier, P., "Wind Tunnel Test Results and Proof of Design for an Aeroacoustically Optimised Rotor", *25th European Rotorcraft Forum*, Roma, September 1999.

[16] Bouchet, E., and Rahier, G., "Structure of the Blade Pressure Fluctuations Generated by Helicopter Rotor Blade-Wake Interaction", *56th Annual Forum of the American Helicopter Society*, Virginia Beach, VA, May 2000.

[17] Leconte, P., and Kübe, R., "Main Rotor Active Flaps: Numerical Assessment of Noise and Vibration Reduction", *2nd ONERA-DLR Aerospace Science Meeting*, Berlin, June 2000.

[18] IANNIELLO, S., "An Algorithm to Integrate the FW-H Equation on a Supersonic Rotating Domain", *AIAA Journal*, Vol. 37, No. 9, September 1999, pp. 1040-1047.

[19] IANNIELLO, S., "Quadrupole Noise Predictions Through the Ffowcs Williams-Hawkings Equation", *AIAA Journal*, Vol. 37, No. 9, September 1999, pp. 1048-1054.

[20] IANNIELLO, S., "Developments of the K-Algorithm in the Computation of the HSI Noise from Rotors and propellers", *6th AIAA/CEAS Aeroacoustics Conference*, Lahaina, Hawaii, 12-14 June 2000.

[21] MALBIÉQUI, P., "Application of the ray-model to duct acoustics", DUCAT S.T1.5, ONERA *Technical Report*, RT 26/3641 DSNA/Y, October 1998.

[22] RIENSTRA, S. W., "Acoustic radiation from a semi-infinite annular duct in a uniform subsonic mean flow", *Journal of Sound and Vibration*, 94 (2), 1984, pp. 267-288.

[23] VAN DER EERDEN, F. J. M., "Noise reduction with coupled prismatic tubes", PhD thesis, University of Twente, 2000

[24] DE BREE, H. E., VAN DER EERDEN, F. J. M., VAN HONSCHOTEN, J. W., "A novel technique for measuring the reflection coefficient of sound absorbing materials", *ISMA 25 Conference on Noise and Vibration Engineering*, Leuven, Belgium, 2000

[25] BASTEN, T. G. H., TIJDEMAN, H., "Damping of structural vibrations by vortex shedding", *ISMA 25 Conference on Noise and Vibration Engineering*, Leuven, Belgium, 2000

[26] BASTEN, T. G. H., VAN DER HOOGT, P. J. M., SPIERING R. M. E. J., TIJDEMAN, H., " On the acousto-elastic behaviour of double wall panels with a viscothermal air layer", *Journal of Sound and Vibrationi* (accepted, July 2001).

[27] ROURE, A., ALBARRAZIN, A., WINNINGER, M., "The Remote Microphone Technique for Active Noise Control", *ACTIVE 99*, pp. 1233-1244.

[28] JUVÉ, D., "Aeroacoustic Research in Europe: the CEAS-ASC Report on 1998 highlights" *Journal of Sound and Vibration*, 227(2), pp. 321-342, 1999.