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JOURNAL OF SOUND AND VIBRATION

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Review

CEAS-ASC highlights 2006

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Received 28 February 2007; received in revised form 14 March 2007; accepted 14 March 2007

Abstract

The Council of European Aerospace Societies (CEAS) Aeroacoustics Specialists Committee (ASC) supports and promotes the interests of the scientific and industrial aeroacoustics community on a European scale and European aeronautics activities internationally. In this context, "aeroacoustics" encompasses all aerospace acoustics and related areas. Each year the committee highlights some of the research and development projects in Europe.

This paper is a report on some highlights of aeroacoustics research in Europe in 2006, compiled from information provided to the ASC of the CEAS.

During 2006, numerous research programmes were funded by the European Union. Some of the contributions submitted to the editor summarize selected findings from these programmes, while other articles cover issues supported by national associations. Furthermore, a concise summary of the workshop on "Aeroacoustics of Jet Noise" held in Dublin in September is included in this report. Enquiries concerning all contributions should be addressed to the authors who are given at the end of each subsection.

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doi:10.1016/j.jsv.2007.03.029

1. CEAS-ASC Workshop

The 10th CEAS Aeroacoustics Committee workshop was held in Trinity College, Dublin, Ireland on 28 and 29 September, 2006. It was also the 1st Scientific workshop of the EU coordination action X3-Noise. The topic of the workshop was "Jet Noise Prediction Methodologies—Recent Developments" and it was organised by Professor John Fitzpatrick and Dr. Gareth Bennett of the Mechanical Engineering Department. There were 68 delegates who participated in the various sessions. These represented most EU countries including aspirant states, Japan, China, Brazil and the US with a good attendance from the industry sector including Boeing, Airbus, Rolls Royce, Snecma and Volvo. There were two keynote lectures and six paper presentation and discussion sessions. The keynote papers were "Large Eddy Simulation for Jet Noise Prediction" delivered by Professor Christophe Bailly from ECL, France and "Jet Noise Measurement Techniques" by Dr. James Bridges from NASA Glenn, USA. There were three sessions on CFD/CAA with 9 papers, and one on each of Experimental Studies (4 papers), Analytical & Semi-Empirical Methods (3 papers) and Source Modelling (3 papers). Although there was intense debate on a range of issues, a general consensus that there was an urgent need to use a combination of computational and experimental methods to seek to identify the most important mechanisms of sound production in jets. Information on the presentations can be obtained on the X3-Noise website or by contacting John Fitzpatrick.

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2. European-funded projects

2.1. MESSIAEN

MESSIAEN (Methods for the efficient simulation of aircraft engine noise) is an FP6 project integrating the work of three SMEs (Free Field Technologies, VIBRATEC and Odegaard & Danneskiold-Samsoe), three universities (Université Catholique de Louvain, TU Eindhoven and Southampton University's Institute of Sound and Vibration Research) and five leading industrial companies (Airbus, Rolls-Royce, Aermacchi, Turbomeca and Liebherr Aerospace) in view of producing and benchmarking a new simulation software for predicting the sound generated by aircraft engines. The resulting software, named ACTRAN/DGM, solves the linearized Euler equations (LEE) using a discontinuous Galerkin method (DGM) in the time domain and has been proven to work on complex 2D, 2D axisymmetric and full 3D problems including all relevant physical features like complex non-isothermal background flow including shear layers, realistic liners, excitation defined in terms of incident duct modes, non-reflecting conditions at the end of the computational domain and calculation of far-field radiation.

The project, which started in December 2003, was finalized in February 2007. It consisted in the following tasks:

- WP1—Specifications: all partners defined reference test cases that the final deliverable had to be able to tackle.
- WP2—CFD to CAA interfaces
  - Task 2.1—Recovery of background flow from standard CFD software program and interpolation on the DGM mesh;
  - Task 2.2—Calculation of acoustic sources from pressure distribution in a set of plane immediately upstream or downstream from the fan; this is a generalization to more complex flows and to lined ducts of work that had been done by TU/e in an earlier project (TurboNoiseCFD).
- WP3—Near field sound prediction (minor tasks are not listed)
  - Task 3.1—Application of DGM to the solution of LEE in time domain.
  - Task 3.3—Non-reflecting boundary conditions based on a buffer zone technique were developed and implemented in ACTRAN/DGM.
  - Task 3.4—The same buffer zone technique was also used to excite the acoustic domain with incident duct modes, possibly obtained from Task 2.2.
  - Task 3.5—One of the central difficulties of time-domain approaches in acoustics is related to the translation of the frequency-domain concept of impedance into an equivalent time-domain concept. This was done in a very elegant way documented in detail by S.W. Rienstra, see Section 6.1.
- WP4—Far-field sound prediction
  - Task 4.1—A Ffowcs–Williams and Hawkings integral method was developed to predict the acoustic far field from near field results obtained in WP3.
  - Task 4.2—An analytical code named TEARS was further developed to provide reference solutions for ACTRAN/DGM.
  - Task 4.3—A specific, simplified, methodology was developed for environmental control systems applications.
- WP5—Applications: the resulting software program was applied to the industrial problems defined in WP1.

The project was very successful even if some (physical) instability problems still need to be adequately tackled and if computational performance does not yet match the initial expectations. Work will continue on these topics in the TURNEX project (see next section). The results of MESSIAEN will be exploited by all partners in there respective business and are commercially available from Free Field Technologies.

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2.2. TURNEX

TURNEX (Turbomachinery Noise Radiation through the Engine Exhaust) is a 6th Framework EU-project comprising a consortium of 12 partners and is aimed at an improved understanding and a reduction of turbomachinery noise radiation through the jet exhaust. The project spans 3 years (2005–2007). Turbomachinery noise radiating from the bypass and core nozzles is becoming the dominant noise source on modern aircraft, but, while recent EU research programmes have made significant progress in reducing both the generation of turbomachinery noise and the radiation of noise from the intake, little work has been conducted on reducing the radiation of turbomachinery noise from exhaust nozzles. TURNEX will address this shortfall by delivering improved understanding and validated design methods, and by evaluating a number of low-noise exhaust nozzle configurations aimed at a source noise reduction of 2–3 dB. The project is divided into three workpackages:

- WP 1: Turbomachinery noise radiation experiments on an engine exhaust rig in a Jet Noise Test Facility.
- WP 2: Improved Models and Prediction Methods.
- WP 3: Assessment and Industrial Implementation of Results.

Main achievements at the Mid-term:

- Preliminary experimental tests have been completed to test simulated turbomachinery noise sources and measurement techniques, including (a) a Mode Synthesiser for fan tone noise and (b) arrays of incoherent actuators for fan broadband noise, at realistic jet Mach numbers.
- An Afterbody Liner has been manufactured and tested on a no-flow rig with a broadband noise source. The results show that the exterior Afterbody Liner yields significant broadband noise attenuation at certain far-field angles, over and above that achieved by the bypass liner. Future application of an Afterbody Liner as a 180-degree ‘Happy Afterbody Liner’ is illustrated in Fig. 1; also shown is an afterbody type-liner applied to the center plug or tail-cone.
- An analytical solution for the radiation of annular duct modes through a vortex sheet model of an exhaust jet has been extended to include the effects of (a) an acoustic lining on the centerbody and (b) an acoustic lining on the afterbody only. Both will be invaluable in the understanding and development of models of the Afterbody Liner concept described above. Expected results TURNEX will deliver validated industry-exploitable methods for predicting turbomachinery noise radiation through exhaust nozzles.

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2.3. SEFA

Within the project Sound Engineering for Aircraft (SEFA) sound engineering practices are used to define optimum aircraft community noise shapes (target sounds). SEFA is therefore going to answer how the noise annoyance of aircraft can be reduced, not just by lowering noise levels, but also by improving the characteristics of aircraft noise signatures in the context of airport operations (Fig. 2).

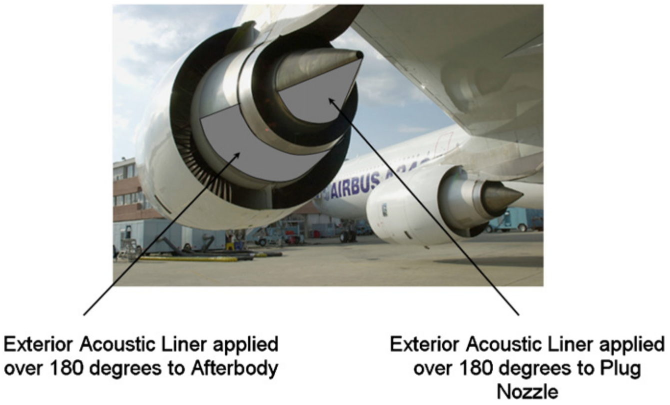

Fig. 1. Happy afterbody liner used in Turnex.

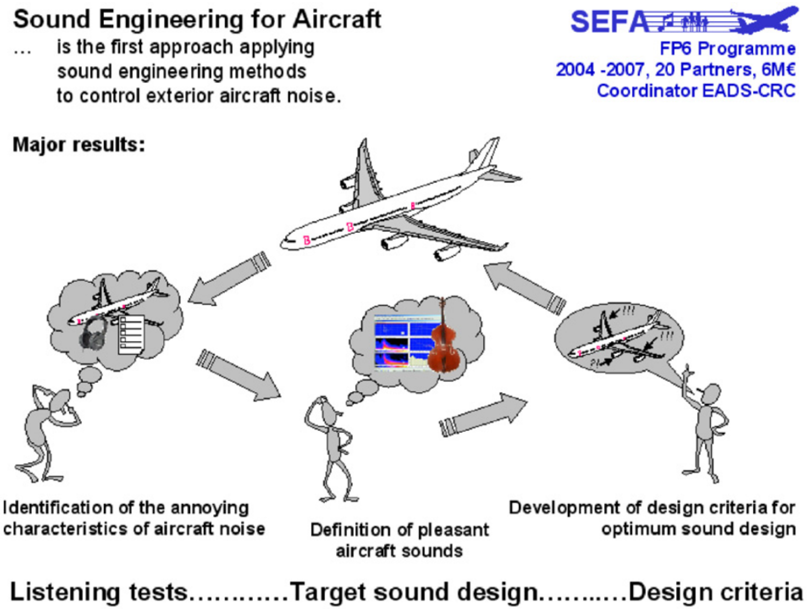

Fig. 2. SEFA project.

In the current stage of SEFA several important results have been achieved:

- Psychometric listening tests methods based on active hearing have been developed. More than 100 different aircraft flyovers have been evaluated within paired comparison and semantic differential tests, each flyover by more than 30 subjects.
- Sound design procedures including source analysis, re-synthetisation procedures and filtering procedures have been established and used for the target sound design exercises. The target sounds itself are clearly related to aircraft source components.
- A virtual aircraft tool has been set up able to produce audible realistic flyover sounds according to a virtually defined aircraft configuration.
- Three different approaches have been developed to generate a virtual resident tool which simulates the subjective response of an active listener to flyover sounds.

In the current final project phase the designed target sounds are validated within a final large psychometric test campaign. Finally, the virtual aircraft tool shall be used for identification of the related engineering design criteria related with the optimized target sounds. For more detailed information please refer to the literature, a selected number of papers is given in Refs. [1–5].

The SEFA project (2004–2007) takes place with the financial support of the EC, 6th framework program and involves 20 partners from 8 different countries.

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2.4. Significantly lower community exposure to aircraft noise—SILENCE(R)

SILENCE(R) is the largest project ever devoted to aircraft noise, supported by the European Commission. As part of the 5th Framework "Growth" programme, the project started in April 2001 and is expected to finish mid 2007. SILENCE(R) has a budget of 111 Million Euros and consists of a consortium of 51 partners. Research activities are being carried out in various fields, such as Engine Source Noise, Nacelle Technologies, and Airframe Source Noise and Active Control Applications. More than 35 prototypes are to be tested during the SILENCE(R) programme.

Fig. 3. Low frequency liner in engine centerbody.

Alternative shapes of the exhaust nozzle to reduce jet noise were investigated for acoustic and aerodynamic performance using test facilities of ONERA (CEPRA19 and BD2), and QinetiQ (NTF) and on the A320. In 2006, a final test on an outdoor acoustic test bed concluded the nozzle test programme. The serrations at the nozzle influence the vortex shedding, thereby reducing the mixing noise generated in the jet.

In order to reduce turbine and combustor noise, significant effort has been devoted to the investigation of novel absorbing materials and concepts able to resist the high temperatures of the engine core exhaust flow. Several full-scale prototypes have been manufactured and tested at full scale on an outdoor acoustic test facility, implementing "hot stream" solutions in the primary nozzle and the engine centerbody (Fig. 3).

Several active technologies are under investigation. Some of these technologies are based on anti-noise cancellation techniques. Others are noise attenuation systems that adapt themselves to give maximum noise reduction depending on the flight conditions. Examples include active stator technology and active control of buzz-saw tones, for which large-scale tests have been carried out at the RACE and ANECOM anechoic fan noise facilities.

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3. Airframe noise

3.1. An integrated design approach to reduce slat noise

In the mainframe of the project LEISA [6] the German Aerospace Centre DLR investigates in a combined aerodynamic and aeroacoustic approach means for slat noise reduction of conventional slat configurations without loss of aerodynamic performance. Since slat noise is dominated by slat trailing edge noise the reduced flow velocity at the slat trailing edge may provide a noise source reduction according to a $p^2 \sim v^{4.5}$ power law [7]. Since the local flow velocity at the slat trailing edge is both a function of aircraft speed and of the local flow acceleration the design objective is either to increase the local flow pressure at the trailing edge and/or to increase the maximum lift coefficient, as aircraft speed scales with the square root of the lift coefficient [8]. Preliminary results show that an increased slat together with an increased overlap is able to improve the aerodynamic performance while slightly reducing the flow velocity at the upper slat trailing edge. Based on these findings a new slat design named VLSC (Very Long Chord Slat, 26.5% local wing chord, overlap 3% wing chord) was numerically optimized in order to keep with the above mentioned objectives and afterwards tested in the low speed wind tunnel DNW-NWB. The new device provides (i) a 3% increase in CLmax and

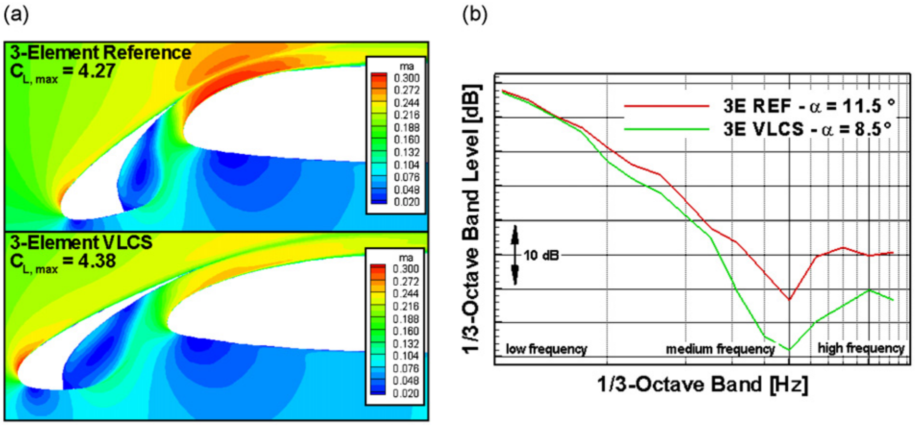

Fig. 4. VLCS slat performance.

(ii) a reduced local flow velocity at the slat trailing edge compared to the reference configuration (Fig. 4a). As given in Fig. 4(b) a broadband noise reduction of up to 5 dB could be achieved.

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3.2. Airframe noise characteristics from flyover measurements and predictions

Aircraft noise impact around airports will increase corresponding to the predicted growth in air-traffic if no measures for aircraft source noise reduction are taken or noise abatement flight procedures are developed. The latter promise a medium-term reduction in aircraft noise impact around airports. Engine noise and airframe noise almost equally contribute to the approach noise signature, and therefore both sources must be considered in the development of low noise approach procedures. Based on the results of dedicated wind tunnel studies and flyover noise measurements, simplified airframe noise prediction schemes were developed to enable the calculation of noise contours in the surroundings of airports. Extensive flyover noise measurements were conducted on an Airbus A319 aircraft, and the measured noise spectra and directivities were compared to the results from noise predictions [9] (Fig. 5). The prediction accuracy is acceptable for landing gear noise and for high lift devices noise at small deflection angles. However, for the aircraft in configuration "full", a significant underestimation is observed for the high frequencies. This failure might be due to the noise contribution from flap side edges, which has not yet been accounted for in the noise prediction scheme, since not sufficient data are available for the development of a physically meaningful flap side edge source model.

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4. Fan and jet noise

4.1. Mode-matching method for non-axisymmetric lined ducts

A novel finite-element mode-matching approach has been developed for duct acoustics with flow and circumferentially varying liners [10]. The primary application of the method is the prediction of sound attenuation in turbofan inlets and bypass ducts including the effects of liner splices and hard patches. A fully numerical procedure has been developed to determine the acoustic modes in ducts of arbitrary cross-section and mean flow profile. By matching modal expansions at the interface between different uniform duct

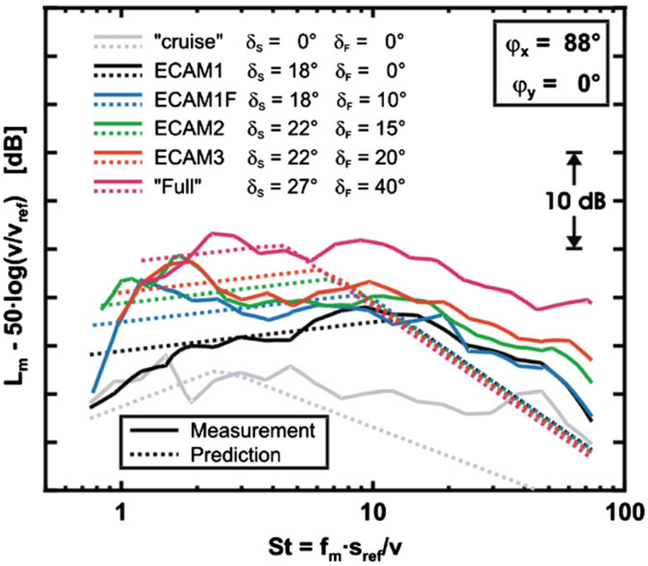

Fig. 5. Comparison of normalized noise spectra from measurement and prediction for different high lift wing configurations (gears retracted).

segments, the effect of axial variations of impedance can be modelled with far fewer parameters than would be required for a 3-D numerical transmission analysis. A numerical mode-matching method is proposed using a modified matching technique in order to deal more accurately with the liner discontinuity with flow. An analytic radiation model can also be integrated with the mode-matching procedure in order to obtain the far-field directivity for tones and broadband multi-mode noise. An application shown in Fig. 6 is the effect of a hard patch in a lined annular duct calculated in terms of modal scattering inside the duct, and in terms of noise radiated to the far field.

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4.2. Exact solution for sound radiated from a flow duct exit with lined afterbody

By means of a variant of the Wiener-Hopf method, known as weak factorization, an analytically exact solution has been found [11] of the problem of sound radiation from an annular duct, with piecewise uniform mean flow, with a centerbody which is lined downstream of the exit plane only (Fig. 7). This configuration is technically of interest for assessing the noise reducing capabilities of a lined afterbody applied to turbofan aircraft engines (Fig. 8). The work has been performed under EU project TURNEX.

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4.3. Hybrid approach for turbulent low mach number jets

The study is focused on sound generated by turbulent low Mach number jet flows. Under low Mach number conditions, the acoustic propagation does not influence the flow field: a hybrid approach can be used.

The CFD simulation results are compared with experimental PIV data obtained at the von Karman Institute on a $Re = 14,000$ jet flow. As the acoustic results are more sensitive to errors in the source term, comparisons on acoustic results will be performed later. The differences between simulated and measured fields are illustrated in Fig. 9 on a vortex pairing problem. For the numerical results, different curves are

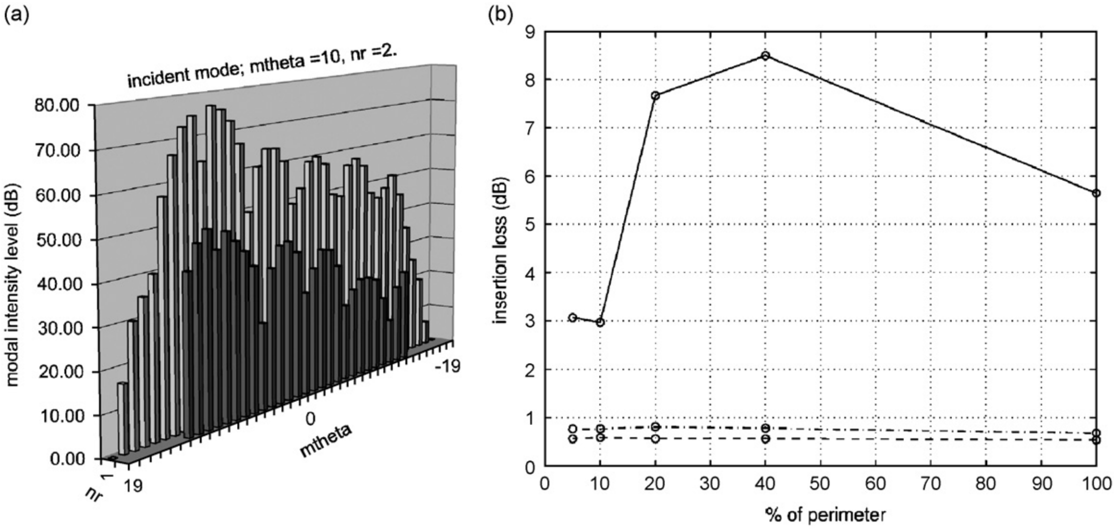

Fig. 6. (a) Modal intensity at the duct outlet; (b) insertion loss on the acoustic power radiated to the far field plotted against the width of the hard patch (solid line: single mode; dashed line: plane wave; dot–dashed line: broadband noise).

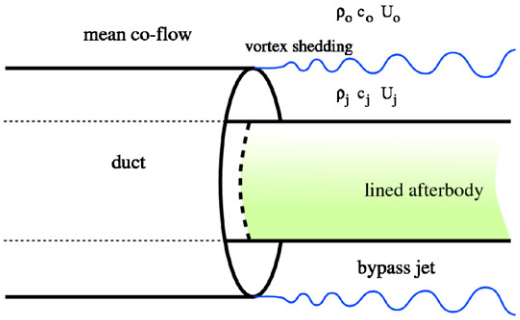

Fig. 7. Sketch of geometry of annular flow duct with lined afterbody.

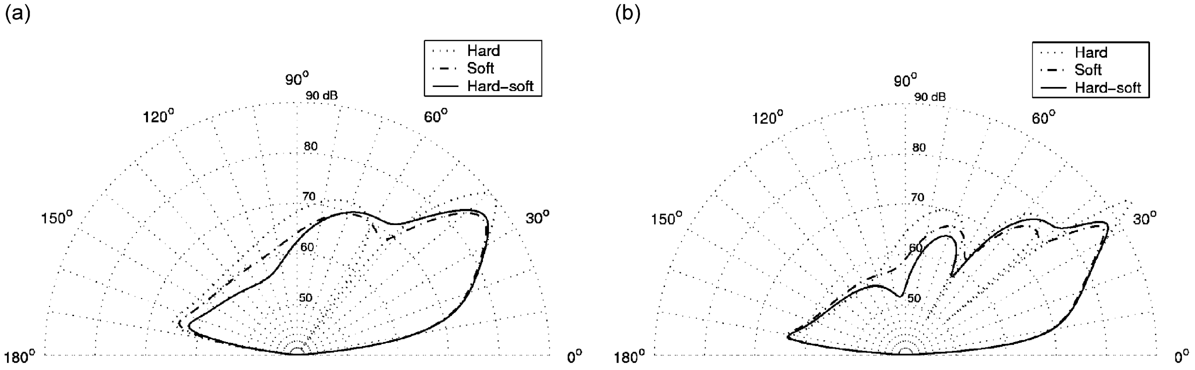

Fig. 8. Effect in far field of lined afterbody vs. lined centerbody vs. no lining for 1st radial mode with Helmholtz numbers $kR = 15$ (a) and $kR = 25$ (b), hub/tip = 0.67, and outer and jet Mach numbers 0.3 and 0.5.

presented which correspond to the same source terms with different conservation principles (kinetic energy, momentum balance, ...).

Different formulations of the convection part of the Navier–Stokes equations may incorporate these conservation principles and in particular the conservation of kinetic energy at discrete level which looks to be

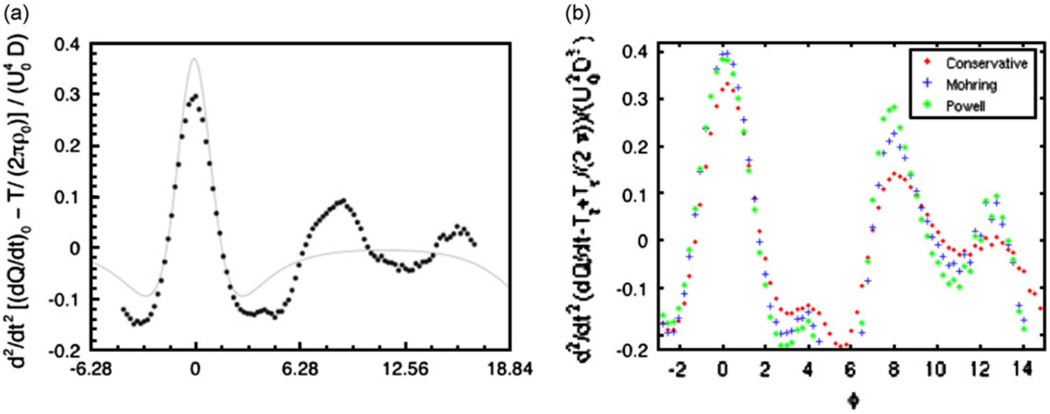

Fig. 9. Importance of the source term considered on a vortex pairing problem. Left: comparison between simulation and measurements. Right: influence of the source term used: conservative, Möhring and Powell source terms.

important for a correct turbulence modelling. The influence is currently tested and compared to experimental data to tune correctly the turbulence models.

In the present simulation, the hydrodynamic part is supplied by SFELES (www.sfeles.org) and the acoustic propagation is solved by Actran/LA (www.fft.be).

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4.4. Jet noise research activities at the LEA (Poitiers)

Jet noise research at the LEA involved numerical, experimental and analytical activities. On the experimental side, synchronous nearfield-pressure/velocity measurements in jets were used in order to better understand the subtleties of the underlying source mechanisms. In Ref. [12] nearfield measurements in a Mach 0.3, *Re* 300,000 jet were used to demonstrate how coherent structures generate noise via a wavy-wall type mechanism, and a strong correlation between this mechanism and the turbulent velocity field was demonstrated. Similar measurement strategies were implemented at the NTF, QinetiQ as part of the CoJeN European program (Fig. 10).

On the numerical front, the LEA develops approaches for the calculation of acoustic radiation from free shear flows. A hybrid method was recently developed which involves coupling a computation of the aerodynamic field using simulations based on compressible equations or low Mach number approximation, with an acoustic analogy [13] or propagators derived from the LEEs [14]. Furthermore, the fan noise problem was the focus of an analytical effort to understand the fundamental aspects of multimodal propagation in ducts [15].

In addition, Poitiers played host to a team of 16 researchers from 6 countries as part of the 2nd European Forum of Flow Control, where an activity was devoted to understanding source mechanisms in free shear-flows. Three numerical databases, from Poitiers (France), Urbana Champaign (USA) and Aachen (Germany), were mined over a three months period by this team. An overview of the preliminary results was given at the IUTAM flow control conference in London (September 2006). The authors thank the DLR for their participation to the measurements.

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4.5. Computation of the generation of screech tones in an underexpanded supersonic jet

The screech tones produced by a three-dimensional planar under-expanded jet have been computed directly by compressible large-eddy simulation (LES) to provide a better understanding of the phenomenon [16].

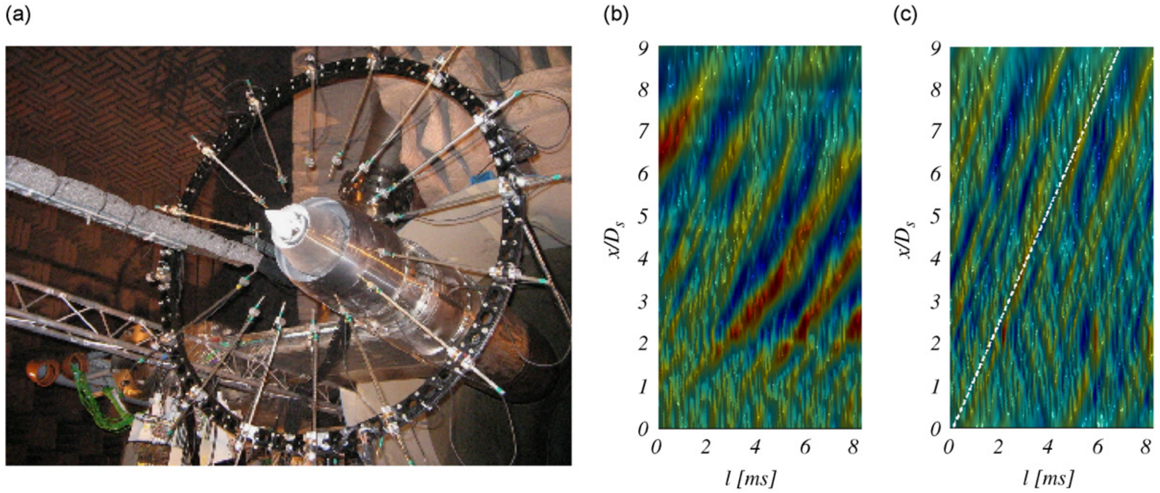

Fig. 10. Experimental set-up of DLR for the CoJen experiments at Qinetiq (a), nearfield hydrodynamic and acoustic (b and c) pressure signatures.

In shock-containing jets, screech tones are predominant in the sound field radiated in the forward direction. They are generated by an aeroacoustic self-sustained loop involving the quasi-periodic shock-cell system lying inside the jet plume, the turbulent shear layer and the receptivity process of the jet to acoustic disturbances.

The jet operates at fully expanded jet Mach number 1.55, with Reynolds number 60,000. The LES strategy is based on explicit selective filtering with spectral-like resolution [17], and low-dispersion and low-dissipation numerical algorithms are implemented to allow the direct computation of the noise. The investigation of the numerical results have showed in particular that the flow development, the shock cell structure and the upstream acoustic field are well reproduced by the computation. An instantaneous snapshot of the density modulus, of the spanwise vorticity and of the near-field pressure is represented in Fig. 11 in a plane perpendicular to the spanwise direction. Compression shocks corresponding to high-density gradients are observed inside the jet plume. Upstream-propagating wave-fronts associated with screech tones radiation are also clearly visible on either side of the jet. A further study of the simulation data have permitted to provide evidences of the connection between the shock-leakage process and the generation of screech tones. During the rotating motion of the compression shocks, the shock tip indeed produces an upstream acoustic wave-front when it hits shear-layer regions with low levels of vorticity. This process corresponds to the shock leakage phenomenon described by Suzuki and Lele [18].

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4.6. Measurement of acoustic quantity fields in duct flow by LDV

The traditional methods of acoustic measurements use microphones to determine the acoustic impedance of aeronautic liners in the presence of a grazing flow. Nevertheless, these methods are invasive and assume that the reaction of the liner is independent of the wave incidence (locally reacting liner). The approach suggested by ONERA [19,20] is radically different: laser Doppler velocimetry (LDV) is used to measure the acoustic perturbation of velocity, or acoustic velocity, thanks to signal processing. This technique allows to determine the acoustic displacement, which is the key parameter in the linear theory of Galbrun to access the perturbation of pressure and the field of active intensity. The wall impedance and the propagation paths of the acoustic energy in the presence of the liner may be known without any assumption and in a non-invasive way. This approach has been applied to characterize different liners (Helmholtz resonators, felt materials) in a test bench specially designed for aeroacoustic measurements with a 2D LDV system. The flow can be turbulent,

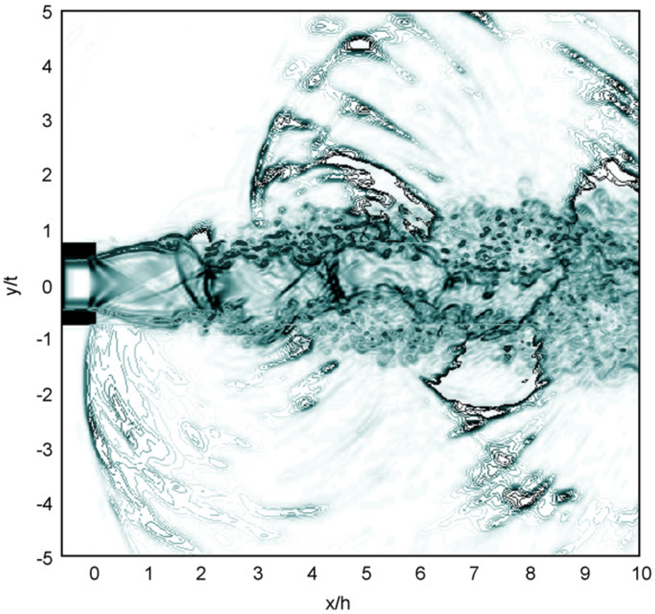

Fig. 11. Snapshot of the density modulus, of the spanwise vorticity and of the near-field pressure, in a plane perpendicular to the spanwise direction. The nozzle lips are represented in black.

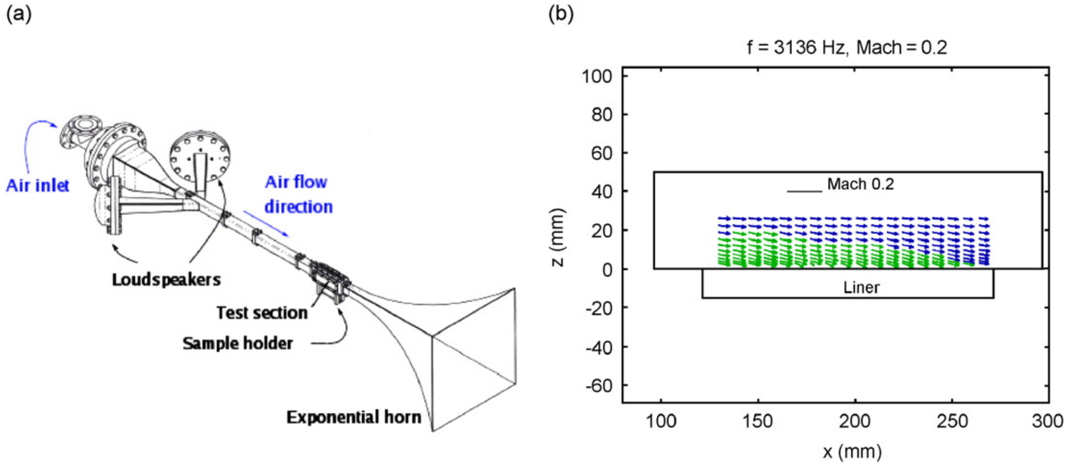

Fig. 12. Aero-thermo-acoustic bench (B2A) and example of active intensity at Mach 0.2 and 3136 Hz.

cold or hot, and the average Mach number can reach 0.3. Impedance and field of active intensity are obtained above the liner, in the shear layer (Fig. 12).

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4.7. Numerical simulation of fan tone noise

A computation procedure has been recently developed at ONERA in order to provide a full numerical simulation of fan tone noise, including source generation, acoustic propagation in the nacelle, and radiation by inlet or outlet [21]. Noise sources are given by a 3D Reynolds averaged Navier–Stokes (RANS) computation,

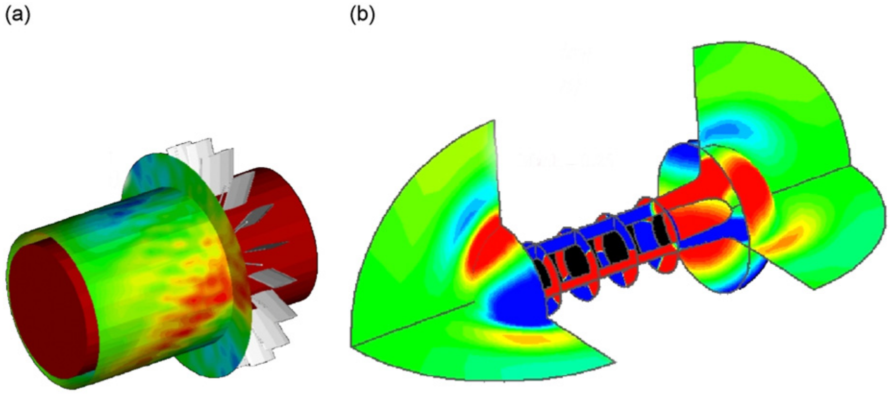

Fig. 13. Aeroacoustic simulations of a simplified turbofan model: 3D pressure disturbance generation and propagation.

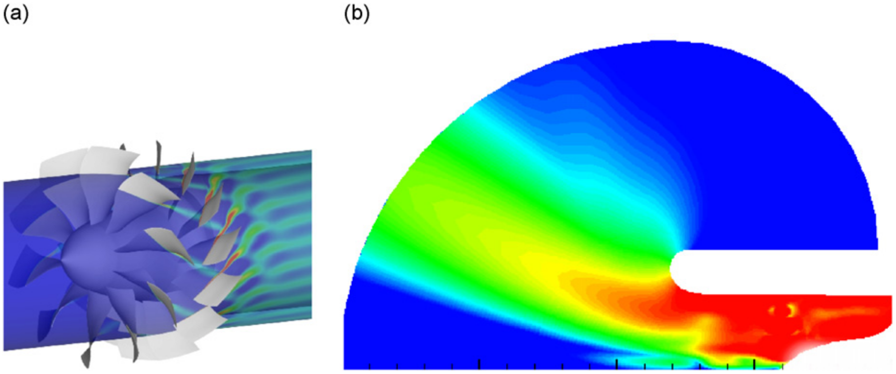

Fig. 14. Aeroacoustic simulations of a counter-rotating fan: 3D entropy snapshot and axi-section sound pressure levels.

using ONERA CFD platform elsA. By means of Matlab-based post-processing routines, CFD pressure disturbances are expanded over Fourier–Bessel modes, translated as equivalent source terms which are injected in a 3D (multi-block) high-order Euler solver, sAbrinA, also developed at ONERA. sAbrinA allows to simulate in-duct propagation and radiation in the vicinity of the inlet (and outlet). Acoustic pressure field is extrapolated up to the far field by using a Kirchhoff integral, written in the frequency domain. First validations of computation chain elsA-sAbrinA have been applied to a turbofan model tested in the DNW-LLF anechoic wind tunnel, in the framework of European DUCAT project, and also used as a reference case in TurboNoiseCFD project. Fig. 13 shows a simulation with elsA of the generation of interaction mode $(-2, 1)$, due to the interaction between the rotor wake (16 blades) and the stator (18 vanes), and the acoustic propagation of this mode using sAbrinA. As a first industrial application, the computation procedure has been recently used to perform an aeroacoustic analysis of a SNECMA counter-rotating turbofan, designed in the framework of VITAL Project, and to be tested in the Russian CIAM rig facility. Generation, propagation, and radiation by the inlet of all cut-on modes associated to the corresponding first five tones (simultaneously computed) is shown in Fig. 14.

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4.8. LES based analysis of jet noise

Hybrid methods, which separate the wave propagation part from the sound generation mechanisms, are an attractive alternative to lower the computational expense of a direct noise computation. Two different hybrid methods were investigated to decide which of the various hybrid methods is most appealing in terms of

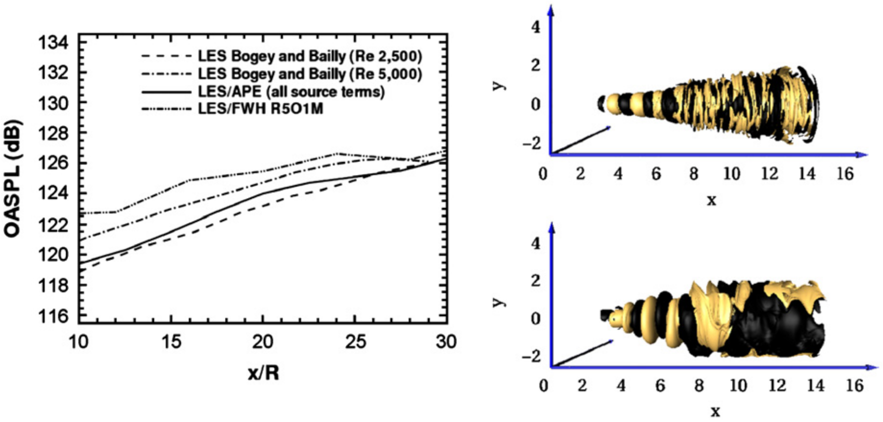

Fig. 15. Overall sound pressure level for $r = 15R$ (left) by LES/APE and LES/FWH approach. Fluctuations of the Lamb vector (upper, right) and the velocity field (lower, right) approximated by Galerkin expansions with 350 POD modes.

accuracy and reliability. The Ffowcs Williams–Hawkings (FWH) equation replaces the inhomogeneous flow regime in which the classical wave propagation holds and lumps all the remaining terms in the right-hand side. However, beside the acoustic source terms, the right-hand side contains also virtual acoustic sources describing convection and refraction effects, which intrinsically belong to the propagation effects. These effects are included in the left-hand side of the acoustic perturbation equations (APE) [22]. Based on the same LES solution of the compressible flow field of a $Ma = 0.9$ and Reynolds number 3600 jet, the acoustic near field solution generated by both hybrid methods were compared (Fig. 15). The LES/APE solution has been less susceptible to the size of the source region than the LES/FWH approach [23]. These findings indicate that the "true" acoustic sources are spatially more confined than the size of FWH source region might suggest. Consequently, the analysis of the APE source term seems to be more promising to identify the noise generation mechanisms. The dominant source term in the APE formulation for cold jets has been shown to be the Lamb vector. The flow field and its noise source, i.e., the Lamb vector, has been investigated by three different methods in Groeschel [24]: the statistical analysis, the azimuthal mode decomposition and the proper orthogonal decomposition (POD). It has been shown that the noise source efficiency per unit energy increases with higher azimuthal modes. The comparison of the compressible jet results with an incompressible LES at the same Reynolds number reveals a significantly smaller energy concentration in the first azimuthal modes, i.e., the incompressible flow is dynamically more distributed.

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5. Helicopter noise

5.1. Analysis of tail rotor noise reduction benefits using HeliNOVI aeroacoustic main/tail rotor test and post-test prediction results

The EU HeliNOVI project was designed to improve the understanding of tail rotor (TR) noise reduction and vibration reduction technology by means of a comprehensive investigation of main rotor (MR)/TR interaction noise and rotor induced vibrations through both theory and experiment. Several TR noise reduction techniques were investigated both through wind tunnel testing and through simulations. As regards the experimental part, a comprehensive wind tunnel test campaign was launched. The test model was a 40% scaled BO105 helicopter model with instrumented main/tail rotor and fuselage. The importance of TR and of MR/TR interference noise as well as of TR noise reduction potentials was investigated [25,26]. As regards the theoretical part of the HeliNOVI project, five codes of varying complexity from 6 organizations (CIRA, DLR, ECD, ECF, NTUA and QinetiQ) were used in producing the pre/post-test data base of numerical results plus flight mechanics codes for determining the control angles. The adaptation and validation of reliable prediction tools, with reference to the new experiment data set as well as numerical simulations on noise reduction techniques were conducted [27–29]. The flight conditions covered included level, climb, and descent flight at various flight speeds. The investigation of TR noise reduction included tip speed reduction, the sense of TR rotational direction and different TR rotor position. Both the test and simulation results indicated that TR noise is most important for climb and high-speed level flight. The analysis of the TR noise reduction benefits from test and simulation results show that besides a reduction of rotor tip speed, the most efficient tail rotor noise reduction concept consists in changing the tail rotor sense of rotation from ‘advancing side down—ASD’ to ‘advancing side up—ASU’. The reduction of the overall noise in ASU TR mode is the consequence of reducing the TR loading noise which in turn is beneficial for the avoidance of BVI on the advancing side. In addition, the noise reduction for the tested change in TR position is mainly due to increasing the advancing blade distance to the observers rather than changing TR aerodynamic behavior.

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5.2. Results of helicopter flyover tests in DLR-Project PAVE

Aeroacoustic flight tests have been performed in fall 2004 by DLR [30] on its two instrumented helicopters, the BO105 and the EC135-FHS, in order to generate a noise database covering the entire flight envelope, for noise abatement flight procedure design, and for aeroacoustic prediction tool validations. These tests are part of the project PAVE (2002–2007) whose goal is to develop an electronic copilot ensuring many tasks including low noise flight procedure performance. The instrumentation of the helicopters covered all the noise relevant flight parameters including 3-component velocity probes on nose booms and blade pressure measurements on the BO105. The noise was measured on the ground using 43 microphones distributed on an 800 m diameter disk (Fig. 16) thanks to a wireless measurement system composed of 30 2-channel remotely controlled acoustic units. Instantaneous noise directivities from maneuver flights could then be measured. The nominal flight height was 100 m above the central microphone. The data reduction performed up to 2006, provided for example following results for the EC135. For steady flights at 65 kts, the intense BVI noise can be avoided for descent slopes lower than 2° or larger than 13°. Starting from 18° slope the fenestron (then unloaded) noise

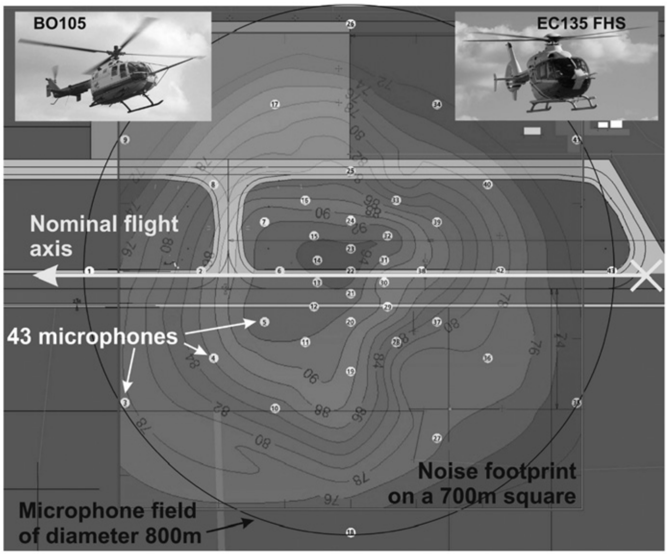

Fig. 16. Microphone layout on Cochstedt airport (Germany) for maneuver flight instantaneous noise footprint measurements.

makes the helicopter louder again. Horizontal steady flights are the noisiest below 40 kts and the quietest at 90 kts and above (8 dBSEL lower than at 40 kts on centerline). A series of maneuver flights was also measured: acceleration, deceleration, turns, begin and end of turn, begin and end of descent, autorotation, side-slip. For example compared to horizontal steady flights, deceleration can produce a noise increase of 10 dBA(max) at 40 kts, whereas acceleration and left turn (towards retreating blade side) can result in a 5 dBA noise reduction at 65 kts. 350 flyovers were measured in total.

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5.3. Acoustic localization into a generic helicopter cabin

Acoustic localization tools can be used to understand where and how the noise is radiated in the cabin by sidewalls, to improve internal acoustic comfort. But currently, the two main sources' localization techniques (holography and beamforming) are based on free field hypothesis. This implies that the presence of reflecting panels produces ‘‘parasite’’ sources which modify the response given by these techniques and introduce ‘‘image’’ sources. In order to evaluate and to try to correct this, ONERA has led experimentations to compare the performances of localization techniques in an anechoic chamber with reflecting panels, then in a generic helicopter cabin (VASCo) [31,32]. Solutions were proposed for improving beamforming, which is faster and more robust than holography: use of a reference microphone, a property of localization's function and an acoustic mask. These improvements make beamforming suited to a confined environment (Fig. 17).

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5.4. Active rotor control by flaps for vibration reduction—full scale demonstrator and first flight test results

An experimental BK117 was the first worldwide flying helicopter with an active rotor system based on Piezoelectric driven trailing edge flaps. This research project called ADASYS aims at the reduction of vibrations as well as blade in flight tracking adjustment, load reduction, performance improvement and stall delay. This joint effort from Eurocopter, EADS CRC, DaimlerChrysler Research Labs, and DLR in Germany is supported by the German Ministry of Economics [33]. The experimental test bed shows several features for active rotor control purposes. The blade design is based on the hingeless rotor of the EC145 and features modular units containing the actuation system and the flaps. The data exchange between airframe and rotor uses an optical device and the electric power is transferred via brushless technology. The controller is driven by

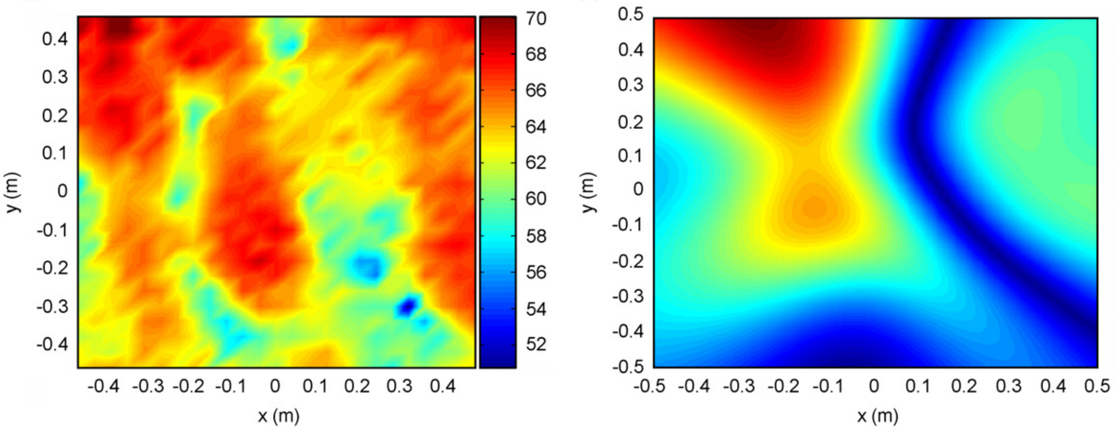

Fig. 17. Example of normal intensity field (left) and coherency function (right) by beamforming antenna (cross) in front of VASCo window (dots) excited by external acoustic pressure field (500 Hz).

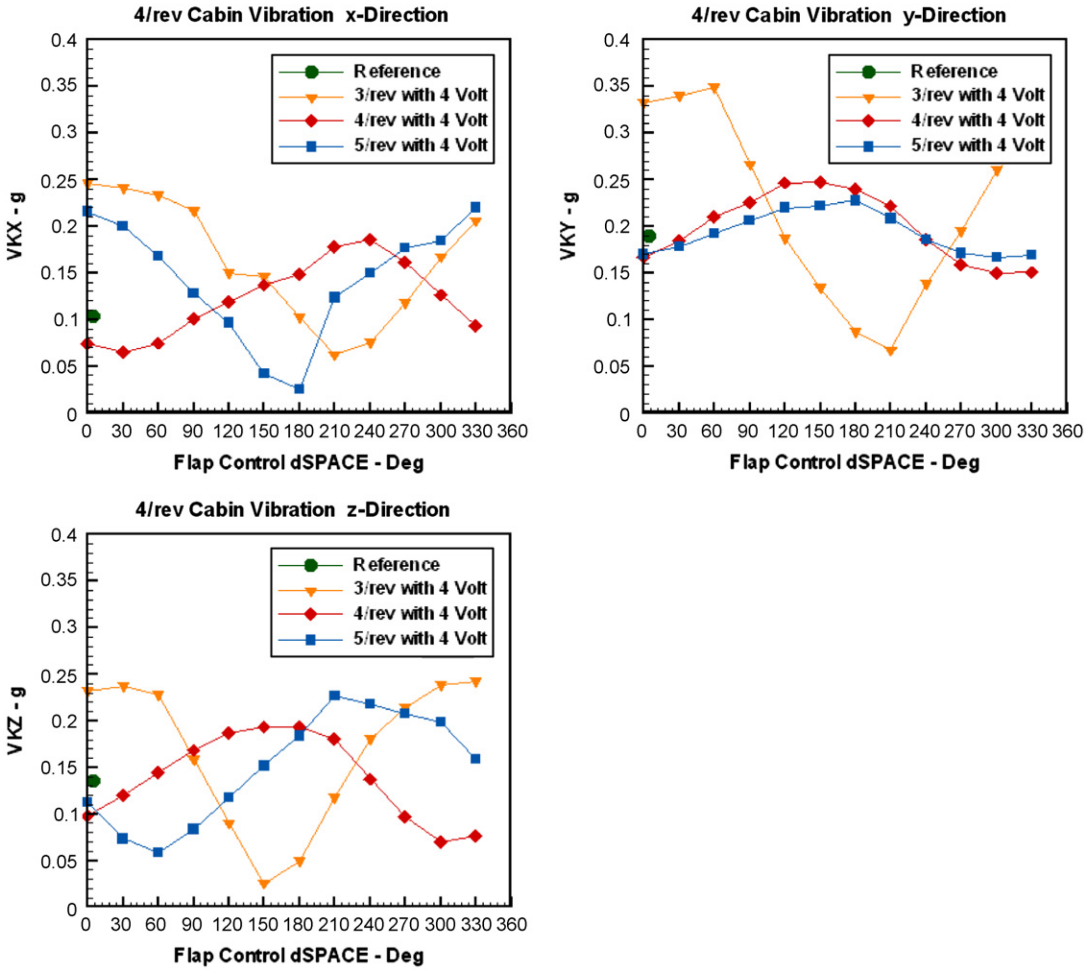

Fig. 18. 4/rev cabin vibrations with dynamic flap actuation at level flight (100 kts).

a rapid prototyping system using computer based tools. A lot of data pickups at the rotor blades, active units, and in the airframe are used to monitor the whole system. The flight test campaign started in the year 2005 with investigations on the passive and active characteristics of this advanced rotor system. After extensive ground tests the in-flight evaluation began with track and balance tests and checks on the dynamic behavior of the system. After confirming a save operation of the test helicopter in passive mode the flaps have been actuated steadily as well as with frequencies in the range between 2/rev and 5/rev. A remarkable performance of this system was demonstrated with respect to vibrations in open loop mode. These test results built the basis for the design parameters of advanced vibration controllers (Fig. 18).

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5.5. *Numerical analysis of noise scattering effects due to the airframe in tilt rotor systems*

Due to higher shaft speeds compared to helicopters, tilt rotors generate tonal noise peaks at relatively high frequencies. As a consequence, the presence of the wing may have a significant influence on the far-field acoustic signature. Therefore, the ability to evaluate the airframe noise scattering could play a crucial role in the optimization of shielding effects during the earlier design stages. A numerical campaign has been carried

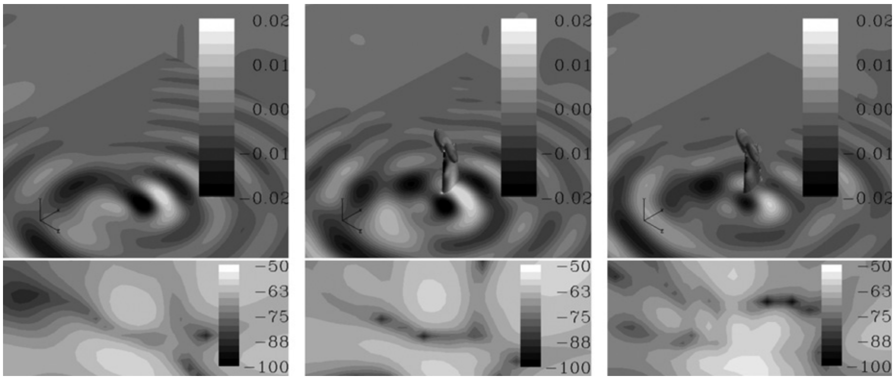

Fig. 19. 3rd BPF acoustic field: isolated rotor without flow (left), full system without flow (middle), full system with flow (right). In the top figures the non-dimensional real part of the acoustic pressure is plotted, whereas the far-field sound pressure level contours are plotted on the bottom figures.

out in the framework of CIRA Advanced Rotorcraft COncept (ARCO) project. The EC-funded TILTAERO project's configuration has been simulated by using a BEM code for the aerodynamic field, coupled with a GFD code for the acoustic propagation. The matching between the aerodynamic and acoustic fields has been carried out via a source synthesis method based on the acoustic analogy theory [34]. The results obtained have demonstrated that, as shown in Fig. 19, for the addressed operative conditions, in spite of the weak influence of the airframe reflection, a significant effect due to the flow on the far field noise radiation is present.

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6. Techniques and methods in aeroacoustics

6.1. An impedance model for time-domain numerical solutions

Sometimes it is numerically advantageous to solve a time-harmonic acoustic problem numerically in time-domain. If the problem includes lined walls of impedance type, it is necessary to convert the impedance relation from frequency-domain to time-domain. This requires a continuation of the impedance definition from its value at the design frequency to the whole complex frequency plane. Not any definition is physically possible. The impedance should remain causal, the variables real, and the wall passive. Based on first principles, an impedance function is proposed, which is derived from the Helmholtz resonator model, as follows:

$$Z(\omega) = R + \mathrm{i}\omega m - \mathrm{i}\beta \cot\left(\tfrac{1}{2}\omega v \Delta t - \mathrm{i}\tfrac{1}{2}\varepsilon\right).$$

It has the advantage that the inverse Fourier transform consists of a delta comb function. The virtual cell depth is chosen such that the time-domain impedance relation exactly synchronizes with the time step of a numerical solution of the full problem. Details can be found in Rienstra [35]. The work has been performed under EU project MESSIAEN.

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6.2. CFD-CAA matching methodology generalised to sheared and swirling mean flow

The triple-plane pressure matching methodology of Ovenden and Rienstra [36] aims to recover acoustic data for CAA from unsteady flow results obtained by CFD. This method has been extended to include sound propagation in sheared and swirling vortical flows in ducts of constant diameter with lined walls. The unsteady perturbations to the mean flow taken from the CFD data are expanded in acoustic/hydrodynamic modes in

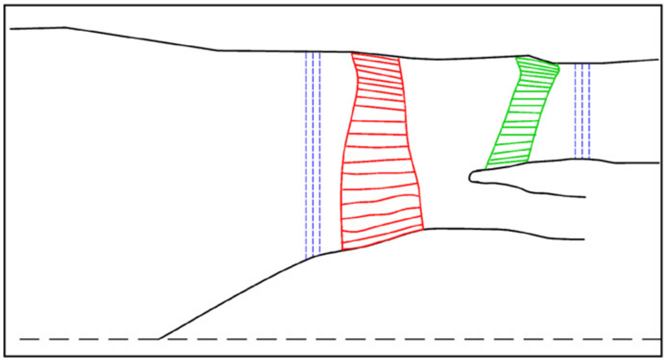

Fig. 20. Typical configuration of matching planes in engine geometry.

vortical mean flow, determined from the numerical solution of the related eigenvalue problem. The actual amplitudes are found after a careful least-squares procedure. Inclusion of the computationally expensive, wall-confined hydrodynamic modes allows for further improvement near the duct wall over a purely acoustic modal expansion. Otherwise, it appeared sufficient to use acoustic modes only. The accuracy of the method is checked against the test case based on the realistic engine geometry (Fig. 20) and the CFD data supplied by Rolls-Royce and originally considered in the paper by Ovenden and Rienstra [36]. Details can be found in Vilenski [37]. The work has been performed under EU project MESSIAEN.

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6.3. Aero-acoustic modelling of subsonic confined flows

In the framework of the CAPRICORN research project, the department of mechanical engineering at the K.U.Leuven is developing accurate numerical tools to investigate the aerodynamic noise generation and propagation in subsonic confined flows, which are present in a large number of engineering applications such as automotive mufflers and HVAC systems. For this purpose, a hybrid approach [38] is adopted were the source domain modelling is carried out using high-order finite volume LED [39]. The acoustic region is modelled with LEEs, based on both a finite difference and quadrature-free discontinuous Galerkin implementation, which allows studying convection and refraction effects in ducted flows with different mean flow assumptions.

It is shown [40] that for subsonic confined flows a coupling strategy based on acoustic analogies or acoustic boundary conditions between source region and propagation region can result in inaccurate results when the acoustic fluctuations become of the same order of magnitude as the aerodynamic fluctuations. For this reason an accurate filtering technique is needed. Mode matching strategies are only valid for a limited number of applications with slowly varying ducts in which the acoustic pressure fluctuations are of high amplitude and no strong vortical outflow occurs. The current research is focused on the development of a new aerodynamic/acoustic splitting technique [41]. This technique is more general than classical mode matching strategies since it only assumes an irrotational acoustic field and a totally incompressible aerodynamic field, resulting in the computation of a coupled system of Poisson equations on a small computational domain.

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6.4. Time-domain impedance modelling based on recursive convolution

A new impedance boundary condition, suited for single frequency as well as for broadband simulations in the time-domain, was developed [42]. First, a continuous frequency model is generated through curve fitting of a set

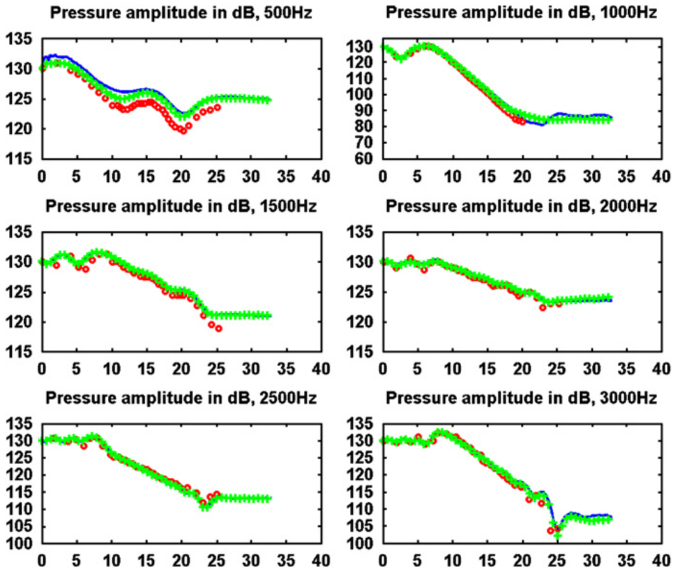

Fig. 21. Sound Pressure Level on wall opposite to lined wall for Mach number 0.1 (–: multifrequency simulation, +: single frequency simulation, o: measurements).

of impedance values using predefined frequency templates having a priori known time-domain counterparts. Secondly, the time-domain formulation is obtained by recursive convolution, performed in a novel way using complex-valued accumulators. The impedance formulation is suited for general broadband simulations because it embeds sufficient freedom to make a good fit to a set of impedance values. The recursive convolutions makes the formulation very efficient as it requires only a few additions and multiplications. It does not require solution data from previous time steps to be stored or high order time derivatives as did some previous formulations. The formulation is implemented within the framework of a quadrature-free discontinuous Galerkin method for the LEEs [43]. Validation was done by comparing numerical results with measurement data for the NASA Langley flow impedance tube (TP-2679), a well documented benchmark. For both single frequency and broadband simulations, with and without mean flow, some good agreement with experimental data is obtained (Fig. 21).

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6.5. Acoustic propagation in non-uniform lined intake by a multi-modal approach

An efficient method is proposed for modelling time-harmonic acoustic propagation in a non-uniform lined duct without flow [44]. The lining impedance is axially uniformly segmented, but varies circumferentially. The sound pressure is expanded on the basis of the rigid duct modes and an additional group of modes that carries the information about the impedance boundary. The rigid duct modes and the additional group of modes are known a priori so that calculations of the true liner modes, which are difficult, are avoided. By matching the pressure and axial velocity at the interface between different uniform segments, scattering matrix is obtained for individual segments and then combined to construct a global scattering matrix for multi-segments. It is numerically shown (Fig. 22) that using the present method, acoustic propagation in non-uniform lined intake of aero-engine can be calculated by a personal computer for dimensionless frequency K up to 80, approaching the third blade passing frequency (BPF) of turbofan noise.

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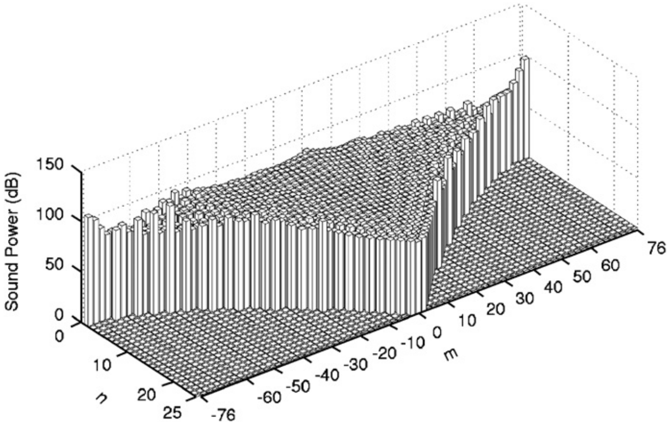

Fig. 22. Output sound power of rigid modes at the exit section with $K = 80$, normalised impedance $= 2 + 1j$, mode (76,0) is incident, 2 splices with angle 0.06 rad.

6.6. Numerical simulations of the installation effects onto the Aft fan noise of a Turbofan engine

For a long time, manufacturers investigated the single prediction/reduction of the fan noise's upstream component, a component which is emitted by the engine's air intake. Since a few years, they are also working on the more complex problem of predicting/reducing its downstream component, which is emitted through the exhaust and its highly inhomogeneous jet flow. In particular, several current national and European projects aim at highlighting how an aft fan noise attenuation could be obtained through the installation effects (or acoustic shielding) potentially offered by structural elements (wing, empennage, fuselage) of non-conventional airplanes. Taking place in this framework, the ''Low Noise Aircraft—LNA2'' project consists in both an experimental and a numerical study of the shielding effect provided by an empennage wing onto the downstream fan noise of a coaxial engine. The numerical part of this study was recently achieved at ONERA, with the help of the sAbrinA platform [57,58]; resulting from the merging of two CFD solvers and one CAA code (all developed at ONERA), sAbrinA allows to perform both aerodynamics (CFD) and aeroacoustics (CAA) calculations. The sAbrinA solver simulates taking into account the possible diffraction effects by solid obstacles, and also the refraction effects due to the (inhomogeneous) mean flows. The LNA2's CAA task consisted in simulating both the 2D and 3D acoustic propagation of the downstream fan noise emitted by a coaxial engine which was considered under both its ''isolated'' and ''installed'' (over an airfoil profile) configurations, and computed with realistic flight conditions (in terms of jet mean flows and fan noise modal contents). As an illustration of the 2D calculations conducted over the ''installed engine'', Fig. 23 presents the near and far-field results related to the downstream propagation of a mode (0, 3) continuously emitted (at the blade passing frequency) in the upstream region of the secondary exhaust [59]. This calculation was computed over the medium at rest case in order to allow the validation (against a boundary element method—Sysnoise code) which is provided on the same figure.

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6.7. CAA prediction of slat cove filler effect on broadband slat noise sound generation and radiation

In an ongoing effort as part of the German project FREQUENZ to study the broadband noise reduction due to design modifications on slat/main-wing airfoil configurations numerically and experimentally, a hybrid RANS/CAA method has been applied successfully. The hybrid RANS/CAA approach combines CAA techniques to compute sound propagation in inhomogeneous mean-flows with stochastic sound sources in the time domain all integrated into DLR's CAA-code PIANO. The mean-flow is determined from steady RANS

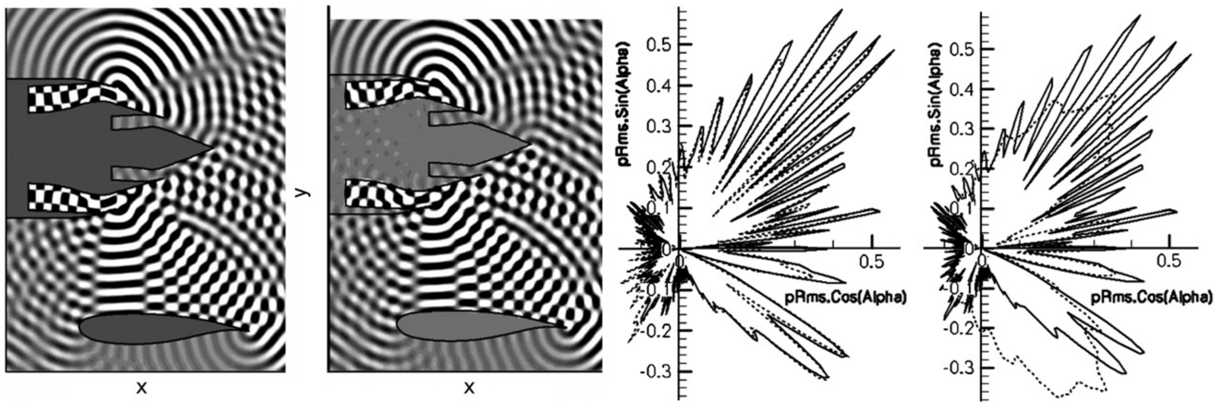

Fig. 23. Aft fan noise propagation over an installed engine (medium at rest case): First three items: acoustic computation and validation with, successively, sAbrinA (first item) against Sysnoise (second item) near-field (instantaneous) pressure, and sAbrinA + Kirch2D (third item, solid line) against Sysnoise (third item, dashed line) far-field (root mean square) pressure. Fourth item; installation effects, with sAbrinA + Kirch2D far-field results over both the installed (solid) and isolated (dashed) configurations.

simulations using DLR's RANS solver TAU. The fluctuating right-hand side source term is modelled by a new highly efficient stochastic particle method (termed the fast random particle-mesh (RPM) method), which reconstructs the spatially varying turbulent kinetic energy and length scale of the related steady two-equation RANS mean-flow simulation [45]. For the considered slat-noise problem, the overall benefit in computational time reaches roughly three orders of magnitude compared to high fidelity methods such as LES or DNS. Hence, the application of the stochastic method to high Reynolds number problems in a design environment becomes feasible. The considered slat geometry and the main-element up to 40% main chord length correspond to the geometry of a representative three-element high-lift configuration. Based on the simulation of three different flow Mach numbers ($M = 0.088$, 0.12, 0.16) and corrected for 3D the sound intensity was found to scale with $M^{4.24}$, in close accordance with an exponent of 4.3 found in experiments. The effect of an add-on device termed slat cove filler was studied numerically. Acoustic spectra were computed for 12° angle of attack. Fig. 24 presents two spectra from the hybrid RANS/CAA method for the receiving point 1.5 chord lengths below the slat. Up to frequencies of 8 kHz (0.4 m chord length) a reduction of sound pressure levels around 5 dB is predicted.

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6.8. Myers boundary condition in the time domain

Aero-engine designs without passive acoustic treatments, which allow very large levels of noise reduction, are out of question today. At the same time numerical methods have gained popularity in aeroacoustics over the last two decades. These methods are formulated in the time domain and therefore necessitate time domain impedance models. Two recently developed models have been examined and tested numerically [46]. Both have the capability to model the effect of a parallel flow on the lined surface by the Myers boundary condition, without the requirement to resolve the boundary layer. One model (EFI) is based on the three parameter model of Tam and Auriault augmented by a method to evaluate the effective impedance under flow conditions for a harmonic source [47]. The other (EHR) is based on Rienstra's extended Helmholtz resonator model and its time-domain representation obtained by a z-transformation [46]. A filtering of the auxiliary liner variable is required for the stability of this boundary condition. The validation and verification, performed for the latest NASA GIT experiment (comp. Fig. 25) and a lined generic aeroengine inlet with spinner [46], show that the results from both models in general agree quite well with the benchmark data. The benchmark configurations

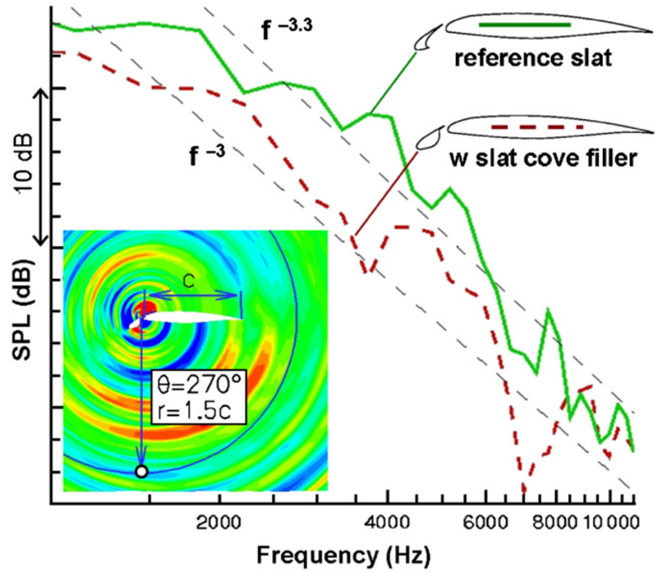

Fig. 24. CAA/fast RPM slat-noise simulation—reference slat spectrum (solid line) vs. slat cove filler spectrum (dashed line).

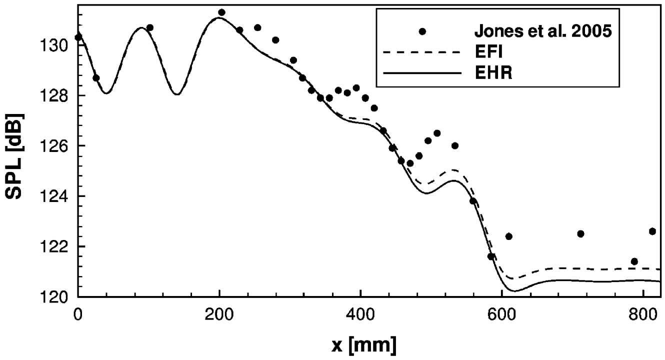

Fig. 25. Comparison of the two time domain impedance models for the NASA-GIT Experiment ($Ma_{\mathrm{avg}} = 0.335, f = 1500\,\mathrm{Hz}$).

cover two-dimensional and axisymmetric problems, the latter with higher azimuthal modes at high Helmholtz numbers respectively. The extended Helmholtz resonator is used to model the measured open end impedance for the NASA-GIT experiment within a broadband impedance deduction. It could be successfully carried out, resulting in a physically reasonable extended Helmholtz resonator representation for the ceramic tubular liner (comp. Fig. 26).

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6.9. Acoustic measurements inside an aero-engine test cell

Under the framework of the German research project LEXMOS, DLR is developing together with Rolls-Royce methods for acoustic indoor measurements. These methods will allow acoustic tests to be performed in semi-reverberant aero-engine test cells. Currently, static noise tests are performed on open-air test beds in order to ensure free-field condition. However, open-air tests are prone to delays due to unfavorable weather

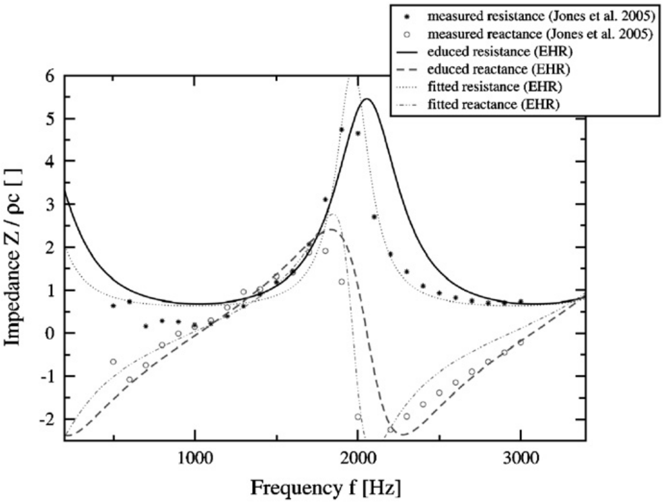

Fig. 26. Deduced impedance function together with the impedances educed in the frequency domain by Jones et al.

conditions. For measurements in a closed test-cell, a linear microphone array is positioned in the corner between floor and sidewall and the data is analyzed using a beamforming method. The position of the microphones in the corner minimizes the effect of reflections. In the standard development and production pass off test beds at Rolls-Royce Deutschland in Dahlewitz, measurements with loudspeakers as sound sources were taken in order to analyze the room acoustic properties. The first results are very promising: Fig. 27 compares beamforming results from data simulated under free-field conditions with experimental results for a loudspeaker in the test-cell. The method will be verified by comparing measurements of a Rolls-Royce BR700 series engine on an open air test-bed under free field conditions with measurements of the indoor test bed at Rolls-Royce Deutschland that were made in September 2006.

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6.10. Heterogeneous domain decomposition for computational aeroacoustics

For CAA, an accurate and feasible direct simulation that considers both the generation of sound and its propagation into the far field is hard to realize with one numerical method in a single computational domain. However, a direct approach contains automatically the interaction of the acoustic perturbations with the flow-field, a property which lacks the acoustic analogy models. The method considered by Utzmann et al. [48] is basically a direct simulation, but it simplifies the simulation for individual regions in the computational domain. The idea is to use a non-overlapping domain decomposition where the equations, methods, grids and time steps are adapted to meet the local requirements. High-order methods such as the ADER finite volume method (ADER-FV, Schwartzkopff [49]), the ADER discontinuous Galerkin (ADER-DG, Dumbser [50]) schemes and high-order finite difference methods (e.g. Taylor-DRP finite difference (FD) method and the Lax-Wendroff like finite difference method, Lörcher [51]) are combined on structured and unstructured grids, ensuring excellent wave propagation capabilities. In the domains, the Euler equations and the LEEs are solved. The data between the domains are exchanged by interpolating the values from the neighbor-grid onto the Gauss integration points of the ghost elements. Domains with completely different time steps are allowed in order to use the largest time step possible in each domain. The multiple cylinder scattering example proposed by Sherer [52] has been treated using this technique. The unstructured DG domain (4th order) covers only the areas in the direct vicinity of the cylinders. The source region is

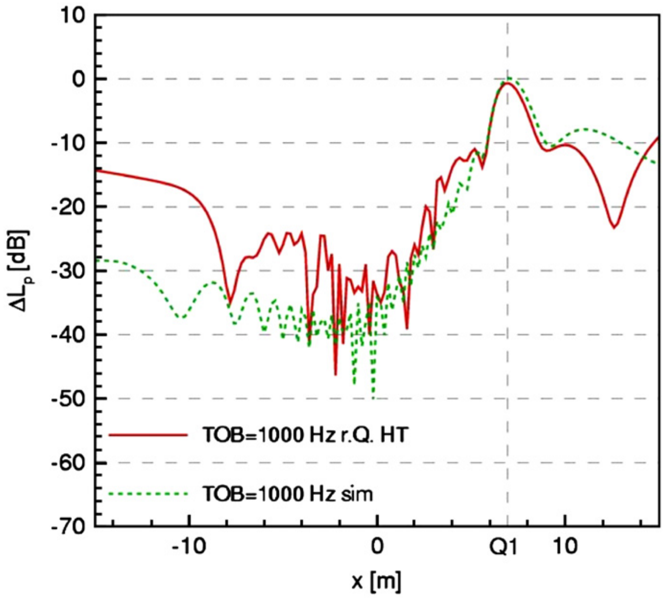

Fig. 27. Beamforming results for a 1 kHz loudspeaker signal (solid line) with a simulated source (dotted line) under free-field conditions.

modelled with a Taylor-DRP FD domain (8th order) and the rest of the domain consists of very high order (12th order) ADER-FV areas.

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6.11. Quantitative evaluation of the lattice boltzmann method for use in aeroacoustics

The Lattice Boltzmann method (LBM) is studied regarding applications in aeroacoustics. The dispersion errors for the propagation of sound waves in the linear regime are computed for two widely used models (namely D2Q9 in two dimensions and D3Q19 in three dimensions), for each of which a single relaxation time model (LBGK) as well as a multiple relaxation time (MRT) model was considered. The most important results are, that the LBM-models introduce an error in phase speed of the sound waves of 1% (0.1%) for are resolution of 10 (30) grid spacings per wavelength, respectively. It was found that the numerical dissipation of sound waves in the LBM-model is much smaller than the dissipation introduced by viscosity, thus the method is well suited to compute sound wave propagation. The MRT model has the advantage of higher numerical stability only as long as the second (bulk) viscosity, which is responsible for sound wave dissipation, is chosen to be much larger than the first (shear) viscosity. In a second part two aeroacoustic problems were studied applying the LBM and the results were compared to analytical predictions or data taken from literature. The problem of a single vortex generating sound by interaction with the leading edge of a semi-infinite thin plate was simulated in two dimensions. The sound pressures of the generated sound waves were compared to predictions based on Howés formula as well as calculations based on an acoustic analogy. The results show good agreement between the acoustic analogy and the direct computation, where the absolute sound pressures as well as the scaling with mean flow velocity and vortex circumferential velocity was well matched. As a second example the sound generation of a cavity in a plate under grazing flow was simulated. The results show good agreement with measurements from a wind tunnel experiment.

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6.12. Green's function discretization of linearized Lilley's equation

A third-order convective wave equation for the pressure perturbation obtained by linearization of Lilley's acoustic analogy equation has been discretized in the frequency domain by using the GFD method [53]. Verification tests have been performed by computing the sound refraction through a two-dimensional shear jet, for which an analytical solution is available [54], and by computing the sound scattering by a two-dimensional compressible vortex, for which a numerical Navier–Stokes solution is available [55]. Fig. 28(a) shows the acoustic pressure contours for the shear jet case, whereas a comparison between the GFD solution and the analytical solution for the same case is shown in Fig. 28(b). The same numerical approach has been also used to simulate the sound radiated by an aero-engine by-pass duct model, for which an analytical solution is available [56]. Fig. 29(a) shows the acoustic pressure contours for the spinning mode (17,2) transmitted through a by-pass duct and refracted by a zero-thickness shear layer. A comparison between the GFD and the analytical solution is shown in Fig. 29(b).

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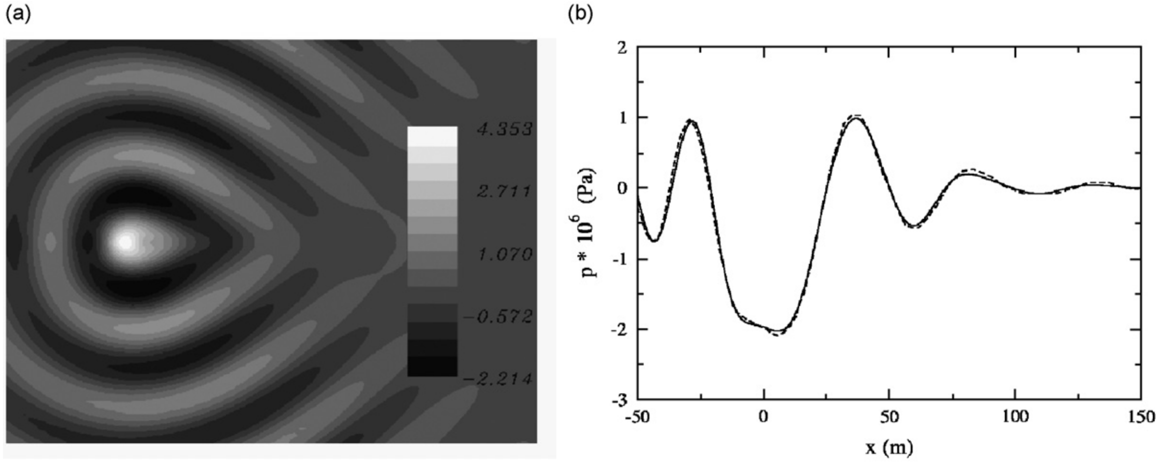

Fig. 28. Prediction of the sound refraction through a two-dimensional shear jet. Contour levels of the real part of the acoustic on the left, comparison between the analytical (broken line) and the GFD solution (line) on the right.

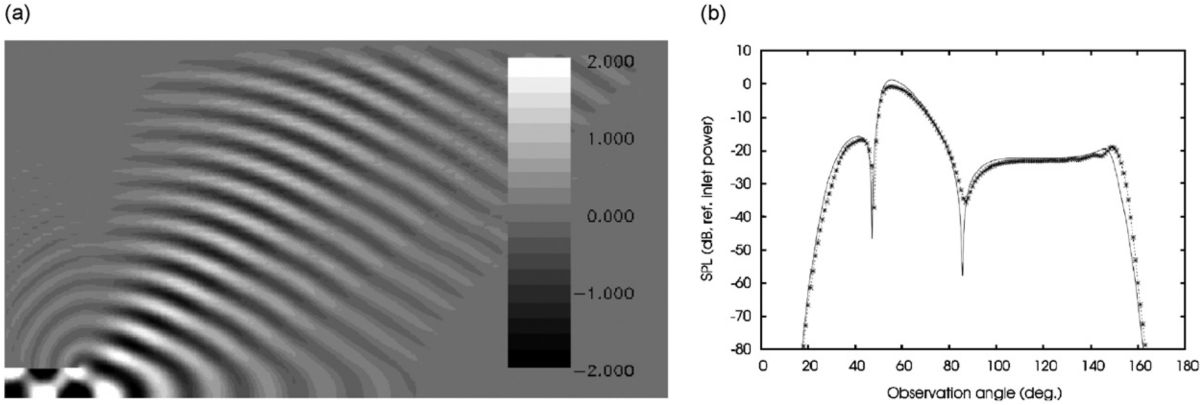

Fig. 29. Prediction of the sound radiation from an annular jet pipe. External Mach number 0.25, by-pass Mach number 0.45, inner-to-outer radius ratio 0.75, Helmholtz number 30, mode (17,2). Contour levels of the real part of the acoustic pressure on the left, comparison between the analytical (line) and the GFD solution (symbols) on the right.

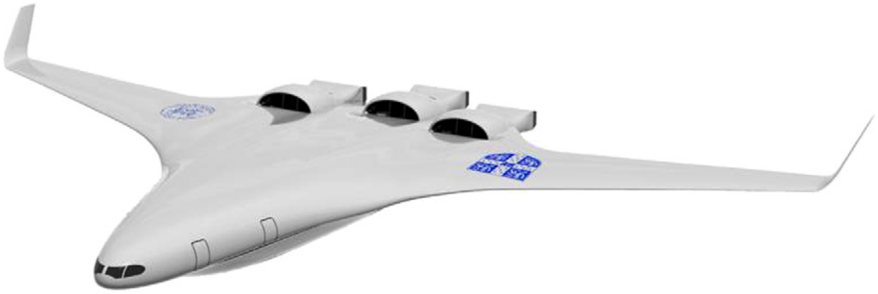

Fig. 30. The SAX 40.

7. Miscellaneous topics

7.1. The Silent Aircraft Initiative

In November 2006, the Silent Aircraft Initiative presented the conceptual design of a low-noise and fuel-efficient aircraft, SAX40, designed to carry 215 passengers for journeys up to 5000 nm. The noise is estimated to be below 63 dBA outside the perimeter of a typical airfield, with a fuel-burn of 149 passenger-miles per (UK) gallon—some 25% better than current aircraft. The project has been carried out through collaboration between about 40 researchers at the University of Cambridge and MIT, and a community of many different stakeholders in aerospace, including industry, government and academia. Theoretical and experimental research focussed on an aerodynamic design of an efficient airframe that could fly a quiet, low-speed approach; the design and integration of an embedded low-noise propulsion system; operational procedures; and economic implications.

Low noise is not achieved by a single feature but rather from many disciplines integrated into the design and operation of a noise-minimizing aircraft. Embedding the engines into the fuselage, with engine inlets above the wings, enables significant opportunity for sound absorption and shielding of forward propagating fan noise. The novel ultra-high bypass engines have variable-area exit nozzles, which means that they can be configured for low noise at take-off and for minimum fuel burn in cruise. After take-off, the engine settings and climb rate are chosen to minimize noise. The low noise on approach is partly due to a design with no slats or flaps, to flying the final approach more slowly, and landing further down the runway. The design also includes a deployable drooped leading edge on the wings; vectored thrust; low-noise fairings on the undercarriage; and an advanced airfoil trailing edge treatment. Technical design reviews by the industrial partners of emerging and final designs informed the design (Fig. 30).

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