NOISE RADIATION THROUGH AERO-ENGINE EXHAUSTS – LARGE SCALE MODEL EXPERIMENTS

F. Arnold[1], U. Tapken[2], R. Bauers[2], J. Zillmann[3]
[1]Rolls-Royce Deutschland, Dahlewitz
[2]DLR, Institute of Propulsion Technology - Engine Acoustics Department, Berlin
[3]EADS Innovation Works, Munich
Germany

OVERVIEW

The sound propagation through jet shear layers of aero engines is subject of the European FP6 programme TURNEX. This paper presents latest ~1:10 scale model tests following a sophisticated experimental concept in an engine representative configuration. The jet noise test facility NTF of QinetiQ, UK, accommodated the experiments led by Rolls-Royce Deutschland. EADS Innovation Works generated distinct acoustic modes in the bypass duct using loudspeakers and a control unit to simulate tonal fan noise sources at realistic frequencies and acoustic circumferential mode orders. DLR performed advanced acoustic measurements such as radial mode analysis in the bypass duct and azimuthal mode analysis in the downstream free field. A siren and an aerodynamic sound source were used to model turbine tones.

First results are reported. They will help to improve the physical understanding of sound propagation through the nozzle system and the jet shear layers and will be used to validate the numerical methods that are currently being adopted and applied in TURNEX. They will be used to extend the capabilities of fan rig facilities to measure fan rearward noise and will enable industry to assess merits of low noise technologies.

1. INTRODUCTION

Innovative concepts and enabling technologies to reduce aero-engine noise at source are essential to meet European noise reduction targets. In recent years, national and international research programmes have made already significant progress in reducing jet noise as well as both the generation of turbomachinery noise and the radiation of noise from the intake.

Turbomachinery noise radiating from the bypass and the core nozzle is now becoming a dominant noise source on modern aircraft. The current European FP6 programme TURNEX, coordinated by B Tester, ISVR, Southampton University, focuses on reducing the radiation of turbomachinery noise from exhaust nozzles, aiming for improved understanding and validated design methods, and by evaluating novel low-noise exhaust nozzle configurations. Twelve partner institutions from seven European countries including Turkey participate in the project. An overview of TURNEX can be found in [1].

The scope of TURNEX is depicted in FIG 1. Turbomachinery sound generated by the fan or the turbine propagates downstream through the bypass duct or the core duct, respectively. The attention of TURNEX is then following the sound waves through the nozzle system and through the jet shear layers into the far-field, ie. to the observer in the ambient. Sound generated by the jet is not subject of TURNEX, but well the (linear or non-linear) interaction of turbomachinery sound with the jet flow such as refraction or spectral broadening effects.

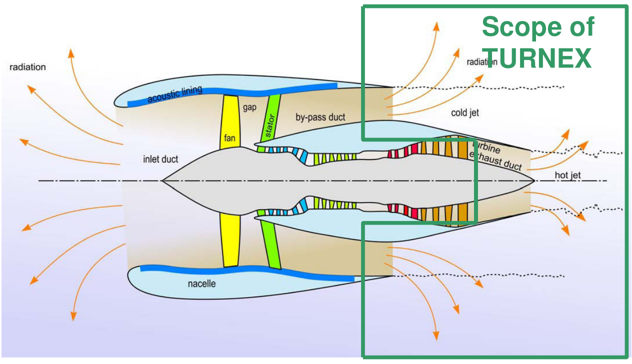

FIG 1. Scope of TURNEX.

TURNEX is structured in four Work Packages WP 0 - WP 3:

- WP 0 Co-ordination & Assessment, Management and Exploitation
- 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

WP 2 adapts and extends existing CFD / CAA (Computational Aero-Acoustics) codes to the needs of TURNEX. Specific issues are e.g. to model sound propagation through rotational jet shear layers, numerical or physical jet shear layer instabilities or interaction effects between flow and sound waves. The numerical codes are both verified using analytical solutions and validated against experiments, which are produced in WP 1 and which are the subject of this paper. WP 3, led by Airbus France, defined the industrial range of interest for the experimental work of WP 1.

The experimental strategy of TURNEX was to setup an in-duct turbomachinery sound simulator in a large scale jet noise test facility. The jet noise test facility NTF of QinetiQ, Farnborough, UK, offered realistic nozzle geometries and coaxial jet conditions such as flow temperatures and Mach numbers. The sound field in the bypass and the core duct were generated by specifically designed acoustic mode generators that allowed controlling a wide range of frequencies and acoustic mode orders.

Detail information of the in-duct sound field will be given from WP 1 as input to the numerical WP 2. Results of the numerically calculated radiated far-field can then be compared against extensive acoustic measurements in the downstream far field.

The results of TURNEX will improve the physical understanding of sound propagation and radiation through jet shear layers, will deliver numerical codes validated for industrial application, and will also deliver means to enhance capabilities of European fan noise test facilities such as of Anecom Aerotest in Wildau, Germany (FIG 2). The anechoic chamber of the Anecom facility already allows excellent measurements in the forward arc far field. Downstream of the bypass duct are currently acoustic in-duct but no free field measurements possible, because the airflow is directly led into the exhaust system of the facility. The results of TURNEX will allow to project from acoustic measurements in the bypass duct to the rearward far field, to predict accurate ambient noise levels and to assess merits of novel technologies to reduce fan rearward noise.

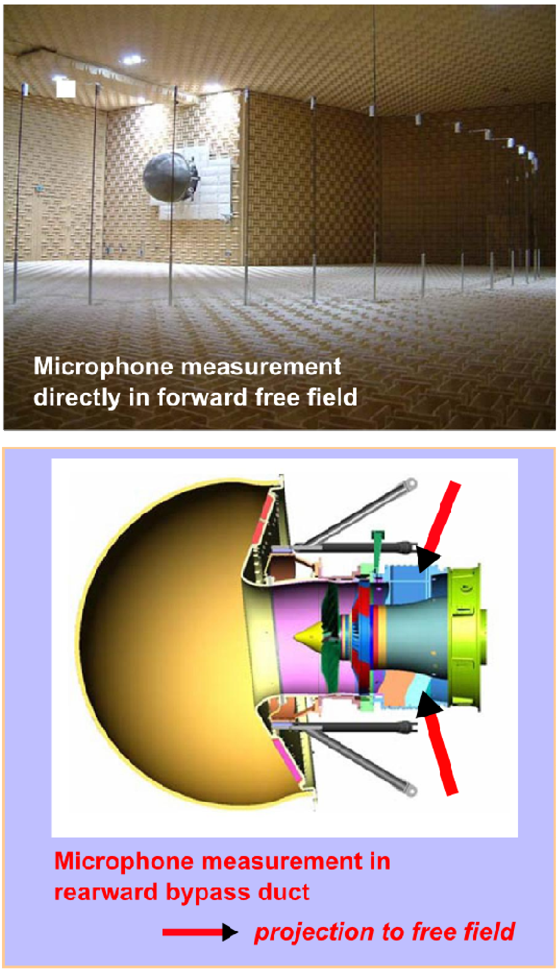

FIG 2. Fan noise test facility of Anecom Aerotest in Wildau, Germany. Top: Anechoic chamber with fan rig mounted at the wall and upstream far-field microphone arc. Bottom: Example of fan rig.

2. EXPERIMENTAL SETUP

2.1. Test rig in the jet noise test facility

A general view of the TURNEX test setup at the NTF is shown in FIG 3. The coaxial test rig carrying the acoustic mode generators and measurement instrumentation was installed in the large anechoic chamber; it is shown detail in FIG 4 and will be explained below. The coaxial jet entered the anechoic chamber (FIG 3) through the primary and secondary nozzles of the rig. It was discharged through the collector at the opposite facility wall. The anechoic chamber allowed acoustic measurements under free-field conditions down to ~80 Hz model scale. Measurements were taken with a polar arc microphone array arranged in the horizontal plane at rig height at a nominal distance of 12m to the nozzle exit, covering a range of polar angles in steps of 5° from 40° to 120° relative to the jet axis. Additional 80 microphone positions were provided by an azimuthal ring array of 9.63 m diameter that could be traversed along the jet axis. Thus, the 3D structure of the acoustic field could be scanned.

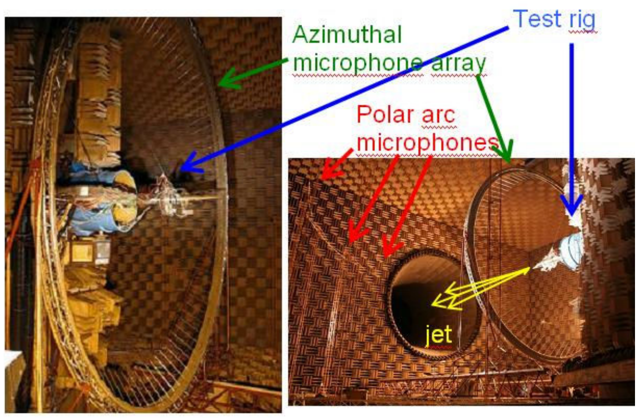

FIG 3. NTF anechoic chamber with test rig, circular far field and polar arc microphone arrays installed.

30 loudspeakers and error sensors were installed at the bypass duct of the test rig (FIG 4), in order to control the azimuthal acoustic modes. It was not intended to control radial modes due to the restrictions of the maximum number of controllable channels and of just one single plane being available to mount the loudspeakers. Instead, a rotatable duct section equipped with two linear arrays of thirty microphones each and additional reference microphones in the fixed duct section allowed to break the generated sound field down into its radial modes and to obtain full information about its 3D structure.

Generation of modes in the core duct with the help of controlled loudspeakers was not feasible due to hot temperatures and spatial limitations. Therefore, alternatives had been sought. One option was a radial strut as an aerodynamic noise generator installed in the core duct, which could be pneumatically retracted. Another installed option was a siren at the upstream end of the core duct (not shown in FIG 4). Two probe microphones were installed in the core duct to measure sound pressure levels in the hot flow.

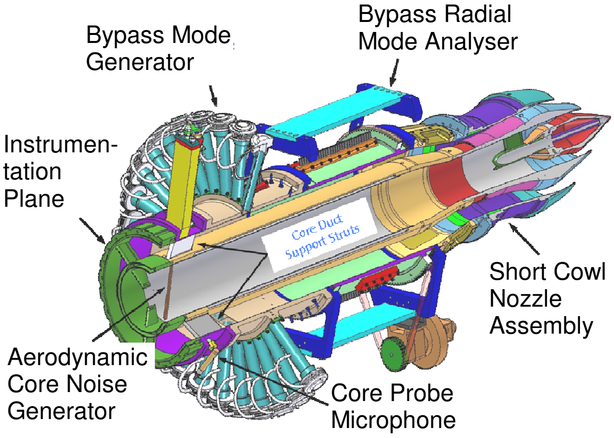

FIG 4. Test rig with short cowl bypass nozzle installed.

Aerodynamic rakes installed in an instrumentation plane were used to set the operating conditions of the rig.

It was a design requirement not to have any struts in the bypass duct downstream of the mode generator that could disturb the flow or cause mode scattering. Therefore, extra design effort was necessary to integrate the additional rig length of the mode generator and the radial mode analysis sections. Also, the different thermal expansion rates in the bypass and the hotter core duct had to be compensated. Rig design was contracted to QinetiQ, who achieved the defined targets. The core and the bypass nozzle were recorded on a video system during the tests. The horizontal and the vertical displacement relative to each other were observed to be less than 1mm.

2.2. Nozzle installations

The first test configuration was a short cowl nozzle with separated jets as shown in FIG 4. The core nozzle was supported just by the core structure, as described in the previous section. It was not connected to the bypass nozzle downstream of the bypass duct mode generator. The core nozzle itself, on the other hand, supported the exhaust cone model via three struts, one of which is shown in green in FIG 4. This was a compromise between an ideal but technically not feasible configuration without any struts avoiding any mode scattering, and an engine realistic setup with a typically much higher number of turbine outlet guide vanes. It was assessed that the possible effect of mode scattering at the three struts could be included in the validation work of the numerical codes.

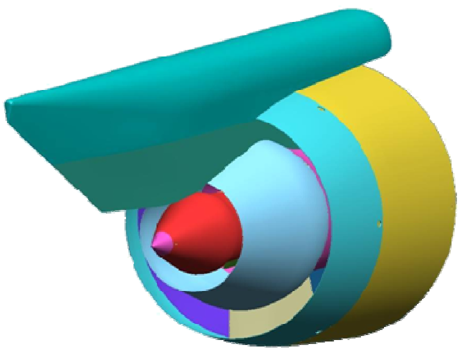

FIG 5. Short cowl nozzle with pylon.

The next test configuration was the described short cowl nozzle but with a pylon for a typical under wing installation, FIG 5. Thus, the flow as well as the acoustic field was strongly three-dimensional.

Installation effects were further investigated using a flat plate modelling the effects of sound reflection at a wing, FIG 6. Further systematic tests to model reflection effects were made with external loudspeakers used as image sound sources instead of the wing.

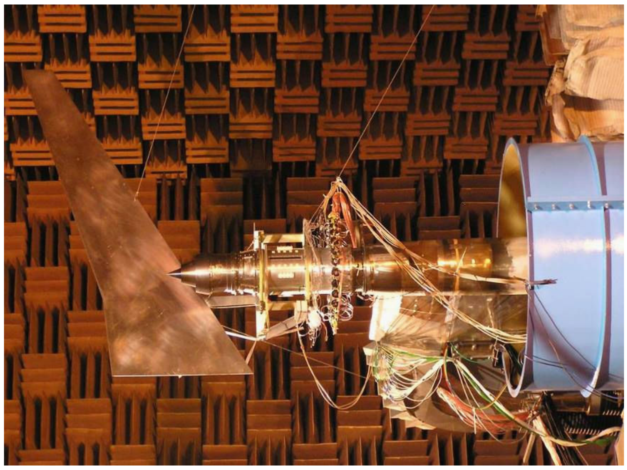

FIG 6. Installation of wing plate model.

Also a model of a long cowl nozzle representing a typical rear installation was tested, the core nozzle being buried within the bypass nozzle (FIG 7). It was decided to install an annular core nozzle rather than a forced mixer (compare eg [2]), in order to focus on sound propagation effects in a not too complicated geometry.

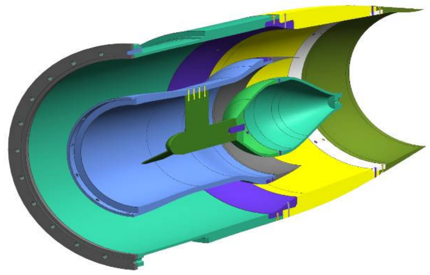

FIG 7. Long cowl nozzle.

2.3. Mode generators

2.3.1. Bypass duct mode generator

EADS was responsible for the mode generation in the bypass duct. For the excitation, a ring with 30 loudspeakers was mounted to the outer duct wall with radial adaptation pipes to fit the space requirements. 30 error sensors were mounted flush to the duct wall downstream of the loudspeakers. A controller hardware was utilised to measure the error sensor signals and to generate proper speaker signals

The mode generator had to deal with this high number of loudspeakers to avoid the simultaneous excitation of spill over modes. Furthermore, due to the scaling factor of the model scale experiments, the frequencies of interest were fairly high. All these facts led to very high requirements on the controller hardware for this real time application. Therefore, pre-tests at the Small Anechoic Windtunnel KAT of NLR had been carried out within the experimental work package of TURNEX before, which were been reported in [3]. TURNEX tests of lined afterbodies in the no-flow facility at ISVR, Southampton University, had offered another opportunity to successfully check the bypass duct mode generator [4].

Several aspects had to be considered for the choice of an appropriate control algorithm. For such cost intensive tests with a large number of tests points it was prohibitive to use adaptive optimisation tools to find the best speaker signals subsequently for each single test point. The convergence would have taken too much time. The final result of adaptive tools as well as matrix inversion methods would be uncertain, hard to be reproduced and documented.

Instead, an alternative method was chosen that reflected the characteristic of the individual loudspeakers. Under ideal conditions, the speaker signals were predefined by the frequency and mode number. For the application under realistic conditions, an optimised method was developed to account for magnitude and phase mismatch of the loudspeakers.

It was required that the optimisation had to be done only once for each frequency of interest. One modification of the control parameters should not only optimise a certain mode but it had to improve the performance of all modes.

A reasonable approach was to introduce calibration factors for the loudspeakers. For that purpose the controller was used to measure the transfer functions between all loudspeakers and all error sensors for all frequencies of interest. The controller automatically searched for calibration factors that alter the transfer functions in accordance with the requirement of the axi-symmetric duct properties.

Once the calibration factors were found, they were applied throughout the tests. Afterwards the error signals were used for monitoring purposes only.

This procedure was quick, extremely robust and reliable. It allowed to slightly modifying the test matrix during the test, to avoid modes that were difficult to generate in the real geometry and to select modes and frequencies instead, which could be properly excited.

2.3.2. Core duct sound generators

An aerodynamic sound source was installed in the core duct, shown in FIG 4. No loudspeakers could be used in the hot environment, and also limited space and accessibility had to be taken into account. Pre-tests had been carried out by Rolls-Royce Deutschland at DLR Berlin in their duct flow facility, and various flow obstacles had been tested, see [5]. A U-shaped sting had been chosen and installed diametrically through the core duct. It could be automatically retracted through the bypass duct, ie. through one of the three struts that supported the core structure in the bypass duct. The device did not interfere with the aerodynamic and acoustic fields in the bypass duct.

The objective of the device was not to get full control over the azimuthal modes, but at least to generate just single modes at individual frequencies. It could be shown in [5] that mode orders were preferably generated at frequencies that were just higher than their so called cut-on frequency, i.e. the frequency below which acoustic pressure modes decay exponentially and above which they propagate through the duct. The width of the strut was chosen based on the expected flow velocities, so that the frequencies of the flow vortices shedding from the strut would coincide with the cut-on frequencies of distinct acoustic modes. Energy of the flow would be used to generate acoustic modes. The physical mechanism worked in [5], however, considerable risk was identified in the higher turbulence level in the main experiment and in the high jet noise background level.

Therefore, the risk was mitigated by a siren driven by compressed air. The siren was located on the duct axis, in order to generate mainly axisymmetric modes. It was designed to generate a large number of harmonics at high frequencies. Most of the core noise tests were performed with the siren.

2.4. Acoustic mode analysis

A sophisticated arrangement of sensor arrays was developed and used in combination with different advanced analysis techniques, in order to satisfy the manifold requirements of the TURNEX project.

For the compilation of a detailed experimental data base, which constituted the fundament for the validation of the various models and prediction methods of the project, DLR performed Radial Mode Analysis (RMA) of the sound field in the bypass duct. A rotating in-duct sensor array downstream of the mode synthesizer – which is referred to as 'Bypass Radial Mode Analyser' in FIG 1 – was used to detect thoroughly the complex modal structure of the sound field that was afterwards radiated from the nozzle into the far-field.

The effects of real geometry and flow on the radiated far-field were assessed by DLR with sound pressure measurements in three dimensions and subsequent azimuthal mode analysis. For this task the large circular sensor array in the anechoic chamber was applied. The analysis of the azimuthal mode structure of the radiated far-field enables – e.g. in comparison with the measured in-duct modal structure - deeper insight into the physical processes, which modify the sound waves on their propagation path from the nozzle through the shear layers into the far-field. Further, with this technique, the impact of e.g. the pylon on the radiated sound field could be investigated in detail.

In total DLR recorded the time series of all acoustic sensors except the sensors of the polar arc array, i.e. 177 sensors plus three output signals of the mode synthesizer. For the measurements, a data acquisition system providing 128 input channels with A/D converter of 24 bit resolution and a maximum sampling frequency of 192 kHz was used. To manage the acquisition of all sensors, a 2 x

64 channel hardware switch was interposed between the front-end of the data acquisition system and a sub-set of the sensors. Hence, the whole measurement was subdivided into two separate sequences. For most test points up to 10 axial positions of the circular far-field array and up to 80 azimuthal positions of the rotating microphone array were measured. In order to minimize the overall testing time DLR implemented a global control of all processes, cp. FIG 8. By synchronizing the data acquisition, the hardware channel switch, the axial traverse of the circular far-field array and the traverse of the rotating in-duct microphone array, the measurement sequences and could be interleaved effectively.

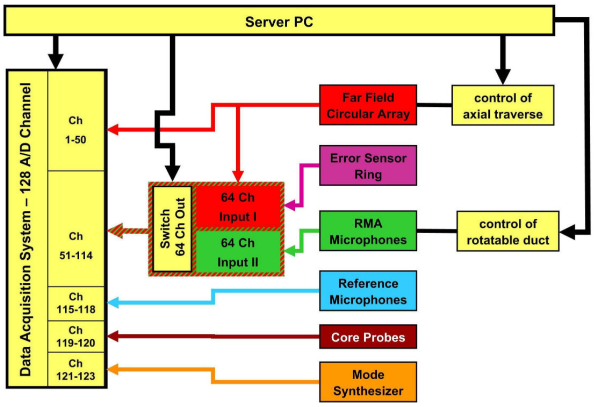

FIG 8. Global control of the data acquisition of the sensor arrays, the rotation of the bypass radial mode analyser and the axial traverse of the circular far field array by a single server PC.

2.4.1. In-duct radial mode analysis

Radial mode analysis (RMA) is an experimental technique that delivers the complex amplitudes of higher order acoustic modes propagating up- and downstream in flow ducts of e.g. aero engines [6] [7]. Theoretically, the determination of the radial mode spectrum can be regarded as an inverse problem, i.e. the solution is deduced by means of inverting the matrix that relates the measured complex sound pressure values to the radial mode amplitudes, considering an analytical description of the in-duct sound propagation. In most applications, this system has more parameters than unknowns, therefore implying a linear least squares fitting problem.

The requirements for the radial mode analysis are set by the maximum azimuthal mode order and the maximum radial mode orders that are propagating in the flow duct. In the TURNEX tests mode measurements were targeted in the bypass duct for the range of dimensionless frequencies $5.8 \le kR \le 43.5$. At the upper frequency approximately 672 modes were propagating in the mode analysis duct section, whereby the maximum azimuthal mode order is $m = \pm 40$ and the maximum radial mode order was $n = 6$.

In principle, for a given frequency range and set of flow parameters, the quality of radial mode analysis depends sensitively on the chosen measurement coordinates [8]. In the present case a sensor arrangement mounted flush with the outer duct wall was chosen, which avoided disturbances of the flow and sound field due to the measurement process but had the drawback of requiring a large number of axial measurement positions. Thus, in order to achieve optimum results with reasonable experimental effort, the sensor configuration was optimized with the help of a numerical condition analysis. For the determination of the radial mode analysis accuracy that was associated with the optimized sensor arrangement, computer simulations assuming synthetic sound pressure data with realistic superposed noise amplitudes were carried out in a subsequent step.

Outcome of the optimization procedure was the use of 60 sensors, which were placed in two axial rows with an axial sensor separation of 8.5 mm at the outer duct wall, so that by traversing the duct section over 180° the complete sound field could be acquired. FIG 9 gives an overview of the relative accuracy that could be achieved in the analysis of each individual azimuthal mode order at sideline condition. The graphics demonstrates that the amplification of measurement perturbations keeps weak in the whole targeted frequency range. In comparison to the high mode order range the accuracy of low azimuthal mode order is inferior, which can be explained by the larger radial mode content.

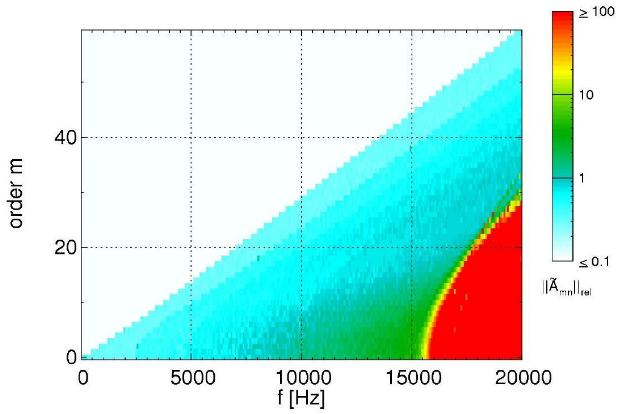

FIG 9. Relative accuracy of the radial mode analysis in the bypass duct, for all cut-on mode orders using 30 axial sensor positions with optimized sensor spacing. For the simulation, synthetic sound pressure data and realistic superposed noise amplitudes were assumed.

2.4.2. Far-field azimuthal mode analysis

Azimuthal mode analysis was applied to the sound pressure data that was detected in the far-field with help of the large circular sensor array at up to 10 different polar angles. For the given arrangement with 80 sensors equidistantly spaced in the ring, the analysis simply can be performed by a discrete Fourier transform in the azimuthal coordinate. However, in the tests a number of microphones failed so that finally azimuthal mode analysis was realized as a least square fit.

The quality of the analysis was additionally influenced by the fact that the radial distance of the sensors to the nozzle turned out to be not identical for all microphones and varied systematically with the axial position of the array traverse. This observation was an outcome of a calibration measurement and could be ascribed to the substantial size of the circular microphone array. Nevertheless, by application of appropriate corrections the quality of the circular array measurements could be improved in such a way that azimuthal mode analysis could be performed successfully.

In general, the quality of the azimuthal mode measurements substantially depended on the excitation level, modal dominance and peak directivity of the tested sound field as well as on the background noise that was caused by the ducted flow and the jet, respectively.

3. EXPERIMENTAL RESULTS

Examples of first experimental results are shown in this section.

3.1. Modal sound field in the bypass duct

In FIG 10 the capability of the Bypass Mode Generator to excite distinctive modal in-duct sound fields is demonstrated. The sound pressure pattern measured at the duct wall with the Bypass Radial Mode Analyser for the Short Nacelle configuration under no-flow operating condition is shown. Target was the generation of azimuthal mode order m = 7 at the frequency f = 4538 Hz. The graphics displays the sound pressure amplitude detected in a grid of 2400 measurement positions, which were interpolated for an enhanced view. Obviously, the modal structure could be generated with high emergence. FIG 11 shows the corresponding result of the radial mode analysis. The radial mode analysis yielded the mode amplitudes of all up- and downstream propagating mode orders with high accuracy.

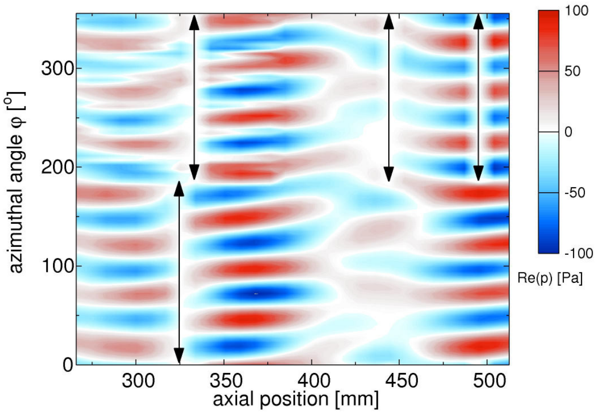

FIG 10. Sound pressure pattern at the duct wall generated by the Bypass Mode Generator for target azimuthal mode order m = 7 at frequency 4538 Hz. Measurement positions at which microphones did fail are marked by arrows.

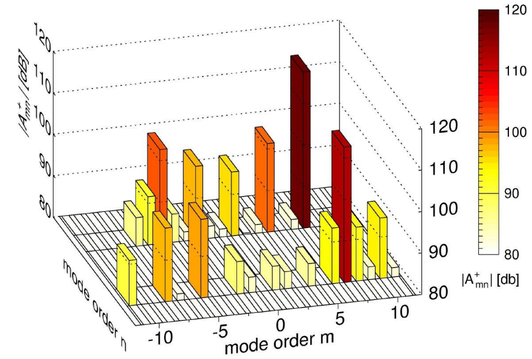

FIG 11. Mode amplitudes of azimuthal and radial order m and n, respectively, travelling downstream to the nozzle exit, resulting out of the radial mode analysis of the sound pressure pattern shown in FIG 10.

3.2. Polar directivity of radiated sound field

FIG 12 illustrates the effect of the flow velocity on the radiated far field peak directivity for mode order m=14. The directivity pattern with flow settings typical for an Approach operating condition is compared against the no flow case. Polar arc angles are given relative to the jet axis. The chosen frequency at Approach simulated the blade passing frequency BPF of a virtual engine. It was adjusted in the no flow case to keep the ratio of the measured frequencies and the mode cut-on frequencies for both curves constant, which was influenced by the flow velocity. The shift of the peak frequency can be clearly identified, indicated by a blue arrow.

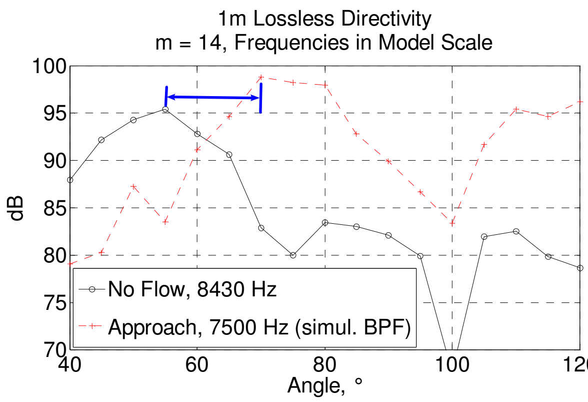

FIG 12. Influence of flow velocity on polar directivity.

FIG 13 demonstrates the effect of the azimuthal mode order m on the radiation angle for a given flow condition at take-off (Flyover with Cutback) and a frequency that corresponds to approximately ½ BPF. Again, there is a pronounced shift of the peak radiation angle.

The directivity pattern of the aero engine as a sound source is an important parameter that has a strong effect on the distance to the observer, on the atmospheric attenuation and thus on the perceived community noise level.

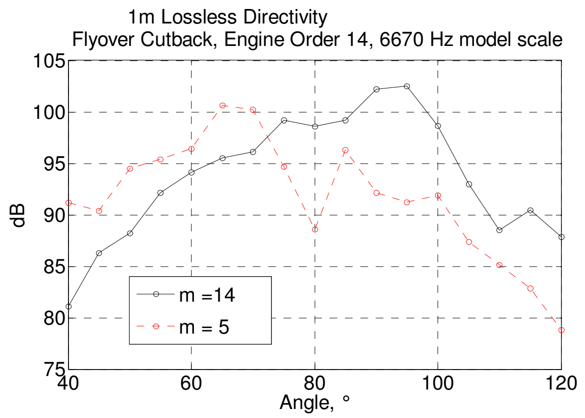

FIG 13. Influence of azimuthal mode order m on polar directivity.

3.3. Azimuthal structure of the radiated sound field

In FIG 14 the 3D far-field sound pressure pattern corresponding to the in-duct sound field of the Short Nacelle configuration under no-flow operating condition – cp. FIG 10 – is depicted for ten polar radiation angles. The directivity measurement shows a clear modal structure in the peak radiation sector. The comparison of FIG 11 and FIG 15 reveals that the dominant azimuthal mode structure of the in-duct sound field is sustained in the far-field radiated from the nozzle exit.

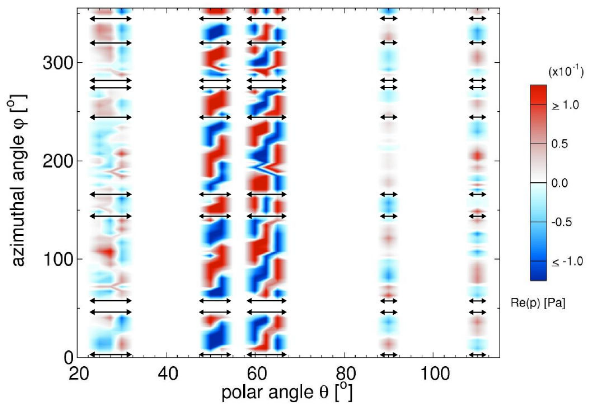

FIG 14. Sound pressure pattern measured with the large circular sensor array in the anechoic chamber at ten different polar radiation angles. The result is related to the in-duct sound field depicted in FIG 10 and FIG 11. Positions at which microphones did fail are marked by arrows.

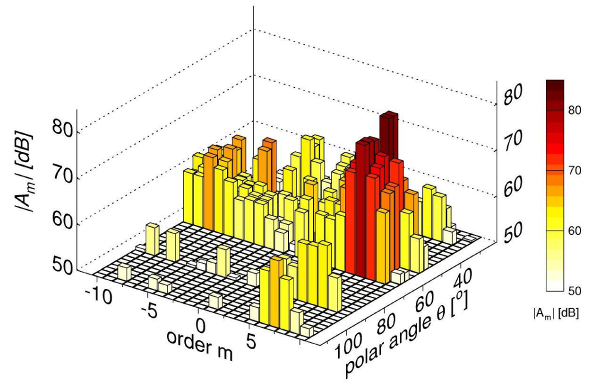

FIG 15. Azimuthal mode spectra measured with the large circular array in the anechoic chamber at ten different polar radiation angles. The diagram corresponds to the sound pressure pattern depicted in FIG 14.

4. CONCLUSIONS

Model scale test to investigate sound propagation through jet shear layers were done in the European FP6 project TURNEX. The test setup and first results were reported.

The tests took place in the jet Noise Test Facility NTF of QinetiQ, UK, which provided aero-engine representative operating conditions. An acoustic mode generator in the bypass duct synthesized in-duct sound fields being typical for fan tones and also allowed the investigation of broadband noise effects. Specifically designed noise sources were installed in the hot core duct.

Radial mode analysis in the bypass duct delivered full 3D information of the generated sound field.

Acoustic measurements in the downstream far field were taken in the anechoic chamber. Microphone positions on a polar arc array and on an axially traversable large azimuthal array were used to plot polar directivities and to perform azimuthal mode analysis.

The first results showed that the tests were executed successfully.

Test data being further evaluated will help to improve the physical understanding of sound propagation through the nozzle system and the jet shear layers and will be used to validate the numerical methods that are adopted and applied in TURNEX. They will be used to extend the capabilities of fan rig facilities to measure fan rearward noise and will enable industry to assess merits of low noise technologies.

5. ACKNOWLEDGEMENT

The authors acknowledge to the EC for financial support of the TURNEX project, Technical Officer Daniel Chiron. TURNEX Industrial Partners Airbus France, AVIO, Dassault Aviation, Rolls-Royce and Rolls-Royce Deutschland contributed financially to the tests.

REFERENCES

[1] Tester, B.: Turbomachinery Noise Radiation through the Engine Exhaust (TURNEX). 14th International Congress on Sound and Vibration ICAS, 9-12 July 2007, Cairns, Australia.

[2] Lieser, J., Deinert, B., Möller, C., Müller, F.: Numerical Simulation of Mixed Jet Exhaust System and its Verification, Deutscher Luft- und Raumfahrtkongress 2007; First CEAS European Air and Space Conference, 10-13 September 2007, Berlin, Germany, Paper CEAS2007.

[3] Sijtsma, P., Zillmann, J.: In-Duct and Far-Field Mode Detection Techniques. 13th AIAA/CEAS Aeroacoustic Conf., May 21-23, 2007, Rome, Italy, Paper AIAA-2007-3439.

[4] Tester, B., de Mercato, L., Holland, K.: Aft fan nise reduction with a lined afterbody. 13th AIAA/CEAS Aeroacoustic Conf., May 21-23, 2007, Rome, Italy, Paper AIAA-2007-3527.

[5] Böhning, P., Arnold, F., Holste, F., Rose, M.: Aerodynamic Duct Mode Generator. 13th AIAA/CEAS Aeroacoustic Conf., May 21-23, 2007, Rome, Italy, Paper AIAA-2007-3433.

[6] Enghardt, L.; Tapken, U.; Neise, W.; Kennepohl, F.; Heinig, K.: Turbine Blade/Vane Interaction Noise: Acoustic Mode Analysis using In-Duct Sensor Rakes. 7th AIAA/CEAS Aeroacoustic Conf. Maastricht, Netherlands, May 28-30, 2001, Paper AIAA 2001-2153.

[7] Enghardt, L.; Tapken, U.; Kornow, O., Kennepohl, F.: Acoustic Mode Decomposition of Compressor Noise under Consideration of Radial Flow Profiles. 11th AIAA/CEAS Aeroacoustic Conf., May 23-25, 2005, Monterey, USA, Paper AIAA-2005-2833.

[8] Tapken, U., Enghardt, L.: Optimisation of sensor arrays for radial mode analysis in flow ducts. 12th AIAA/CEAS Aeroacoustics Conf. Cambridge, MA, May 8-10, 2006, Paper AIAA 2006-2638.