Development and validation of numerical methods for duct acoustics with DUCAT

Développement et validation de méthodes numériques pour l'acoustique dans les conduits : le projet DUCAT

The European aerospace industry is planning to introduce new nacelle noise reduction technologies such as adaptive and active liners (actuators) to further suppress fan noise. Optimisation of these reduction means requires a thorough understanding and accurate description of the sound propagation in ducts. Therefore, the EU-sponsored project DUCAT (Basic Research on Duct Acoustics and Radiation) was launched with main goals to develop, extend and validate computational methods for the propagation and radiation of fan, noise, including the effects of acoustic liners. The project started on the 1 st of January 1998 for a duration period of three years.

According to aerospace industrial needs, duct acoustics models should ideally be able to handle :

- realistic nacelle geometries and non-uniform flow (in intake and by-pass duct),
- non-uniform acoustic liners and duct wall mounted actuators,
- radiation into the far field,
- realistic frequencies and sound pressure levels (SPL).

Because it is not expected that all aspects can be addressed within a single model, a small number of numerical models wais developed in DUCAT, based on various methods as FEM, BEM, coupled FEM/BEM, non-linear propagation and ray-acoustics. Several experiments were carried out to validate these models. Finally within DUCAT, the range of applications of the models and the restrictions for the use as industrial design tools for nacelle acoustic optimisation were established.

L'industrie aéronautique européenne a décidé de mettre en place de nouvelles technologies pour réduire le bruit des nacelles. L'optimisation de ces techniques demande une compréhension minutieuse et une description précise de la propagation du son dans les conduits. C'est pourquoi, le projet DUCAT financé par la Communauté européenne a été lancé dans les buts principaux de développer, d'étendre et de valider des méthodes numériques pour calculer la propagation et le rayonnement du bruit des ventilateurs, y compris les effets des absorbants acoustiques. Le projet avait debuté le 1er janvier 1998 pour une période de 3 ans.

En accord avec les besoins des industriels, les programmes d'acoustique des conduits devaient être capable de fournir :

- des géométries réalistes des nacelles et un écoulement non-linéaire (à l'admission et dans la tuyère),
- des absorbants acoustiques non-uniformes et des actuateurs à monter sur les parois du conduit,
- un rayonnement en champ lointain,
- des fréquences et des niveaux de pression acoustique réalistes.

Parce qu'on ne peut pas concentrer tous ces aspects dans un seul modèle, un petit nombre de modèles numériques a été développé dans DUCAT, basés sur des méthodes différentes comme la FEM, la BEM, les FEM/BEM couplées, la propagation non-linéaire et l'acoustique des rayons. Plusieurs expériences sont menées pour valider ces modèles. Finalement des applications et des restrictions d'utilisation de ces modèles en tant qu'outils de conception à destination des industriels ont été établies.

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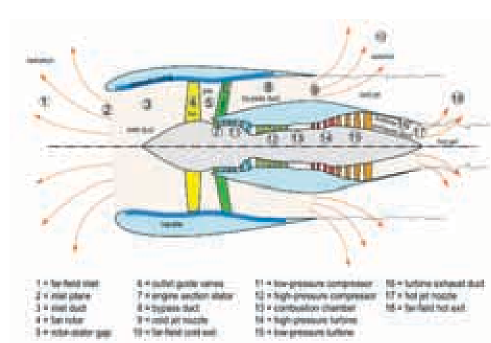
A modern turbofan engine generate noise at various locations. It may have a broadband or tonal character. Broadband noise can be generated by the interaction of the fan with in-flow turbulence, the unsteady combustion and the jet exhaust. Tonal noise may be excited by the interaction of blade rows with stator rows (low-pressure compressor fan noise or turbine noise). The generation of various noise sources within the engine, was not the subject of investigation in DUCAT, as it was for the RESOUND project. However, when the sound is generated, it starts to propagate in the intake and exhaust ducts and then it radiates into the environment.



Several aspects of an engine are important with respect to the duct acoustics modelling. A main aspect is the 3-D geometry. Many duct acoustic models at present are analytical models with simplified geometry. Furthermore the flow is non-uniform in engine ducts. The high flow Mach number near the engine intake lip will strongly modify the direction of radiation. Another important aspect is the presence of tonal fan noise at high frequencies. Modelling of sound propagation at high frequencies requires fine meshes with many field points, which is limited by the capacity of a computer. Sound pressure levels in an engine are rather high. Typical SPL's near the fan face are 175 dB, near the intake lip 155 dB. These high levels make that the sound will propagate non-linearly. To attenuate the sound, the duct walls are lined with acoustic treatment, which has to be included in the duct acoustics models. Finally the sound is reflected and radiated outwards.
To address all these aspects, a CEC-sponsored research project was launched under the supervision of the X-NOISE thematic network. The acronym of the project was DUCAT, which stands for Basic Research on Duct Acoustics and Radiation. It started in January 1998, and it was finished in December 2000. Main difference with the other industrial projects under X-NOISE was that within DUCAT emphasis was led upon the development of tools (i.e. duct acoustics models).

The objectives of DUCAT

The following main objectives were formulated in the technical work programme of the project (so-called Technical Annex) :
- Development, extension, and validation of various areas duct acoustic models,
- The reduction of the computation effort to obtain results up to dimensionless frequencies of 40,
- Constitution of firm experimental basis for present and future applications,
- The demonstration of the improved design capabilities to the European aerospace industry on a low noise nacelle of a generic turbofan and,
- the assessment of the applicability and the limitations of the models as industrial design tools.

The consortium

Eleven partners were co-operating within DUCAT :

- 2 research establishments : NLR in the Netherlands and ONERA in France,
- 4 aerospace industries : EADS Airbus and Turbomeca in France, Rolls-Royce England and Rolls-Royce Deutschland,
- 5 universities : the Technical University of Copenhagen, the Technical University in Compiégne in France, the University of Galway in Ireland, the Technical University of Stockholm in Sweden and the University of Southampton (Institute of Sound and Vibration Research) in UK.

The duct acoustics modelling work was

Duct acoustics models

In advance to the modelling, the industrial partners specified the industrial requirements on these models, which complied with the specifications in the Technical Annex. The models should able to handle 3-D geometry, non-uniform flow up to a Mach number of 0.8, non-uniform liners, realistic frequencies (dimensionless wave number kR is 40 typically) and realistic sound pressure levels (130 to 175 dB).

Within the scope of the project, it was not viable to model all these aspects simultaneously in a single model. Therefore a different approach was taken with the development of six models. In this way, the model could be compared and the best modelling solution could be found for a certain duct acoustics aspect.

Various methods

A ray-acoustics model has been developed for high frequencies (kR > 40). Several numerical codes for lined ducts were developed based on BEM (Boundary Element Method), FEM (Finite Element Method) and coupled FEM/BEM (FEM for the interior duct and BEM for the acoustic radiation). The propagation of rotor-attached shocks leading to buzz-saw noise was modelled with a non-linear propagation model.

Validation

Each model has to be validated before it, with confidence can be used as industrial design tool. So model validation was a crucial issue within the project. Predicted results were compared with analytical benchmarks and mutual comparisons were made. Finally comparisons were made between predicted and experimental results. Brief results of model developments and validations are shown in figures 2 to 5.

Ray-acoustics model ONERA

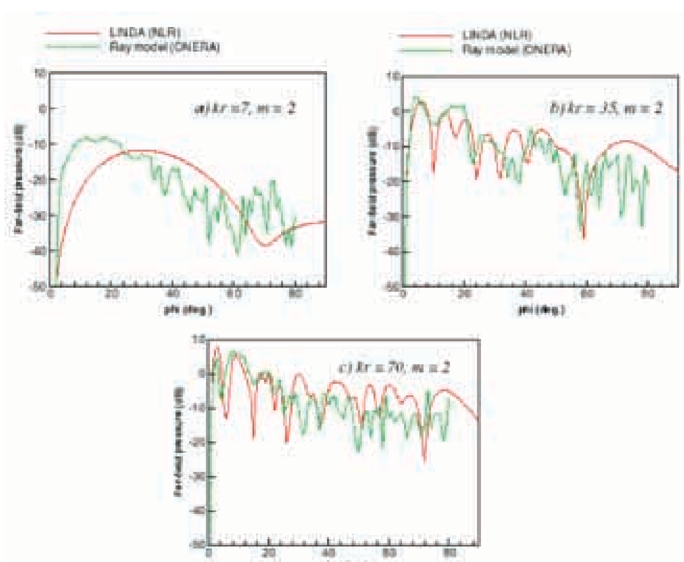


Figure 2 shows a result of calculated directivity patterns at high frequencies and comparisons with an analytical model of NLR (LINDA). A reasonably good agreement is found between both results.

FEM model NUIG

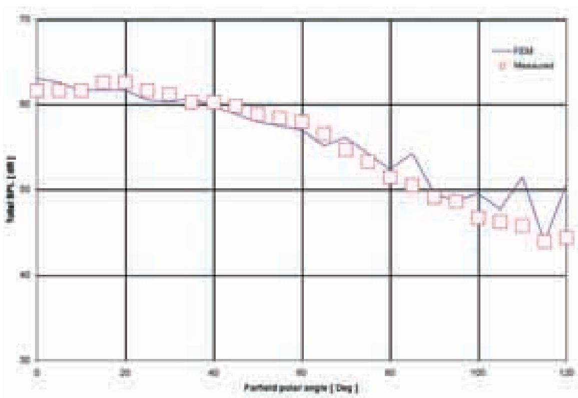


Fig. 3 : Calculated directivity patterns (FEM + analytical benchmark)

The figure 3 shows a comparison between calculated and measured directivity patterns. The experimental results were obtained from a duct acoustics experiment, which was carried out in a facility of ISVR in Southampton. A good agreement between both results is found.

Coupled FEM/BEM model UTC

A coupled FEM/BEM model has been developed at the University of Compiègne. FEM-modelling was used for the in-duct propagation and BEM for the radiation. The figure 4 shows comparisons of results obtained by this method (denoted by the Galbrun equation) with results from other methods. The agreement is very well. Note that the frequency is much lower than a typical frequency in a turbofan engine.

Non-linear propagation model ISVR

ISVR has a long tradition in modelling non-linear propagation (propagation of sound at high and very high SPL's ranging from 150 to 180 dB). Their model is not based on the linear wave equation, but on the non-linear Burgers equation. There are two approaches : a time-domain and frequency-domain based solution.

In DUCAT and RESOUND the latter method has been applied (so-called « Frequency Domain Numerical Solution» denoted by FDNS). The figure shows comparisons between predicted results (red line) and results obtained from a static engine test at the Roll-Royce test bed in Hucknall. The ISVR model reasonably predicts the spectrum near the intake lip, which causes noise to radiate.

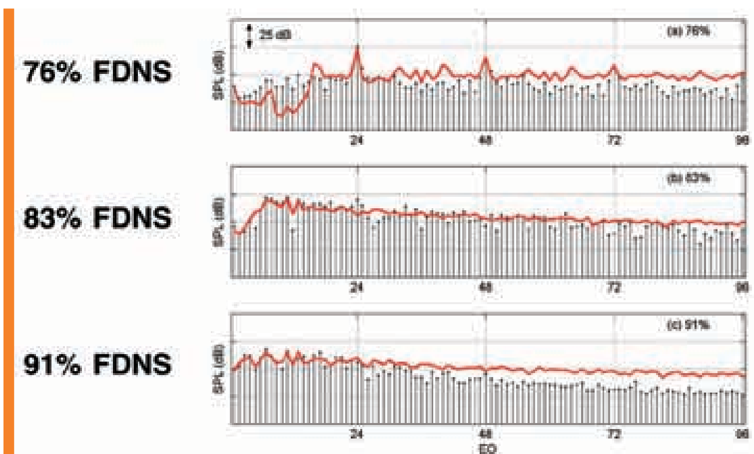


Fig. 5 : In-duct spectra at lip

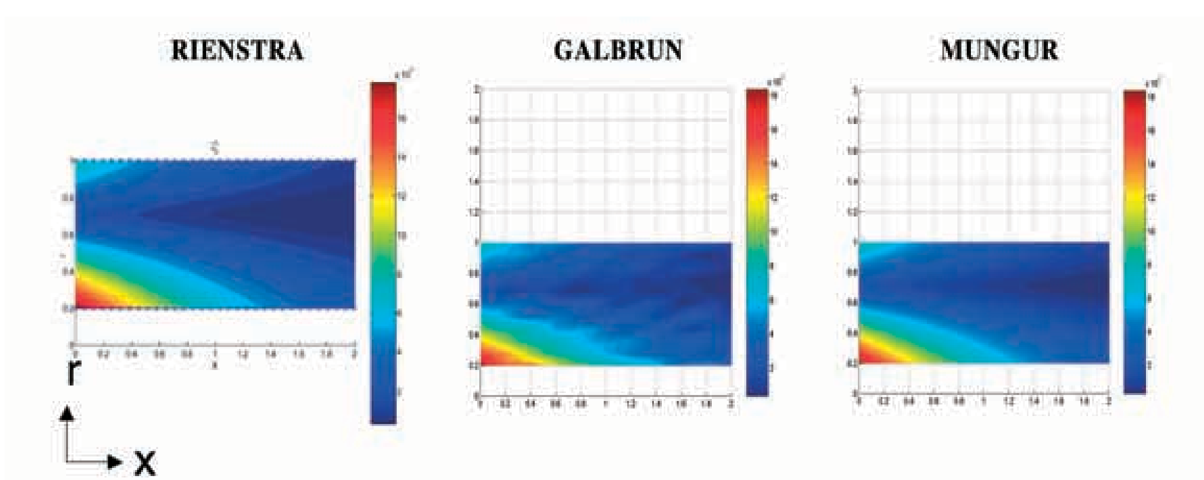


Fig. 4 : Comparisons between in-duct calculated pressure distributions (Galbrun axial

Validation experiments

Besides model development, three validation experiments have been carried out in DUCAT. The first experiment was with a model turbofan in the DNW-LFF in the Netherlands. The second experiment was a Rolls Royce experiment on complex duct geometries in an anechoic facility at ISVR. The third was a lined flow duct experiment at UTC. Furthermore, results from an engine test with a BRR-715 engine at Hucknall were available (test carried out in the RANNTAC Project).

NLR model turbofan in the DNW-LLF

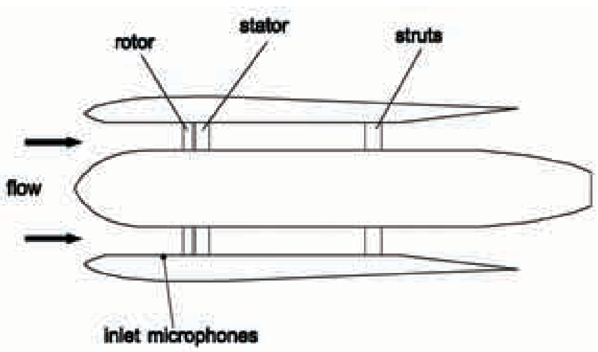


Fig. 6 : Schematic NLR model turbofan

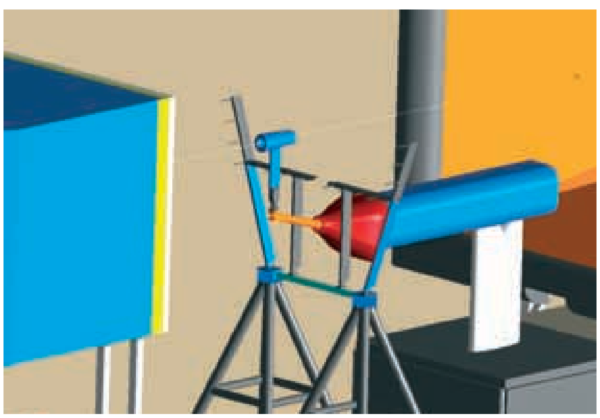


Fig. 7 : The expérimental set-up in the DNW-LLF

Figures 6 et 7 give a schematic view of the NLR model turbofan and an overview of the experimental set-up in the DNW-LLF. The model turbofan is a through-flow nacelle with a one-stage compressor (for the present test consisting of 16 rods and 18 stator vanes). Acoustic instrumentation (i.e. microphones and pressure transducers) for the determination of the acoustic source strength is mounted on the stator vanes, in the intake duct wall and in the by-pass duct downstream of the stator. The radiated acoustic field is determined with an axially traversing rig, on which 16 microphones were mounted.

Figure 8 shows a photograph of the actual test, which was carried out in September 1999. Test results form a firm

Fig. 8 : Photograph of the actual test

propagation and radiation. Some time histories of the unsteady pressures measured near the leading edge of the instrumented stator vane are given, (Fig. 9) which are responsible for fan noise generation.

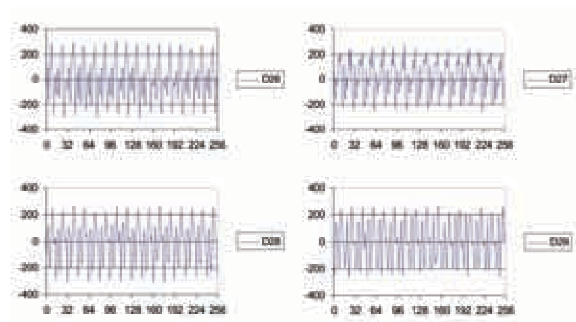


Fig. 9 : Time histories of unsteady pressures as measured near the leading edge of the instrumented stator vane

Figures 10 et 11 show measured acoustic results in the intake of the model turbofan and of the radiated acoustic field at the blade passing frequency. A dominant acoustic mode in the intake is found, which is generated by the viscous-wake interaction of the rotor with the stator.

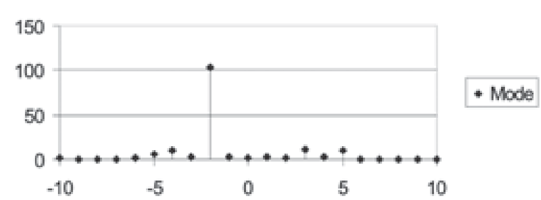


Fig. 10 : Fan noise in the intake, 6 650 rpm, 1 BPF, circumferential mode 2

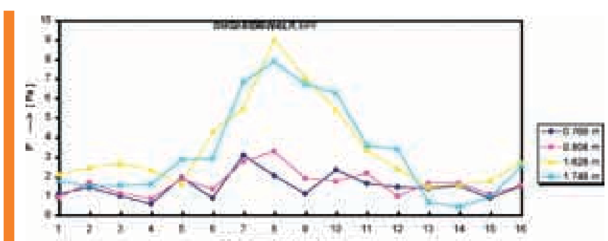


Fig. 11 : Radiated acoustic field, 6 650 rpm, 1 BPF, model

Lined flow duct experiment UTC

A lined flow duct experiment was carried out at UTC. The flow duct consists of a source section with loudspeakers and a test section, in which a liner can be installed. The duct is placed in an anechoic room. The incident sound field on the liner, the transmitted and the radiated sound fields can be determined.

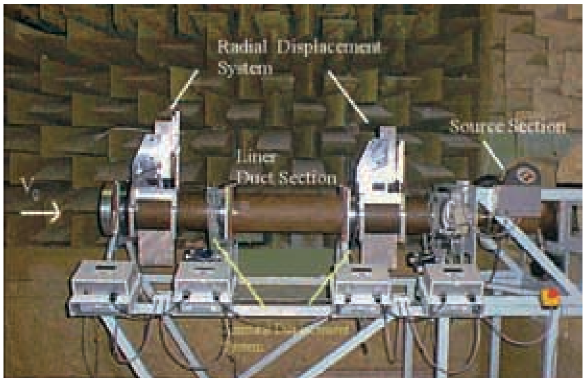


Fig. 12 : Photograph on a test set-up at UTC

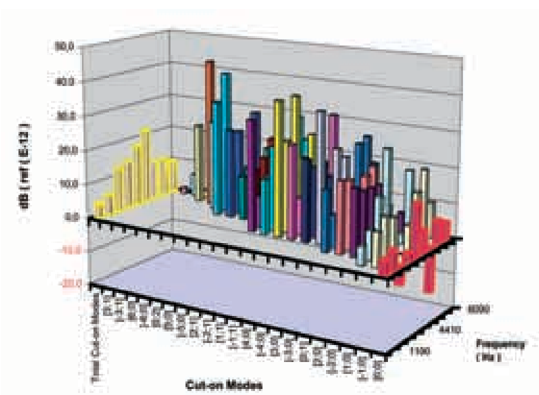


Fig. 13 : Configurations : hard wall, locally reacting liner, non-locally reactiong liner

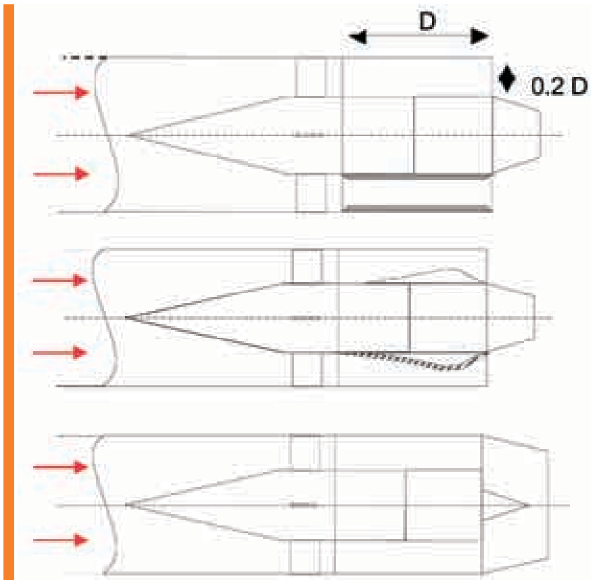


Fig. 14 : Rolls-Royce and ISVR exhaust configurations (3/4 and full cowl)

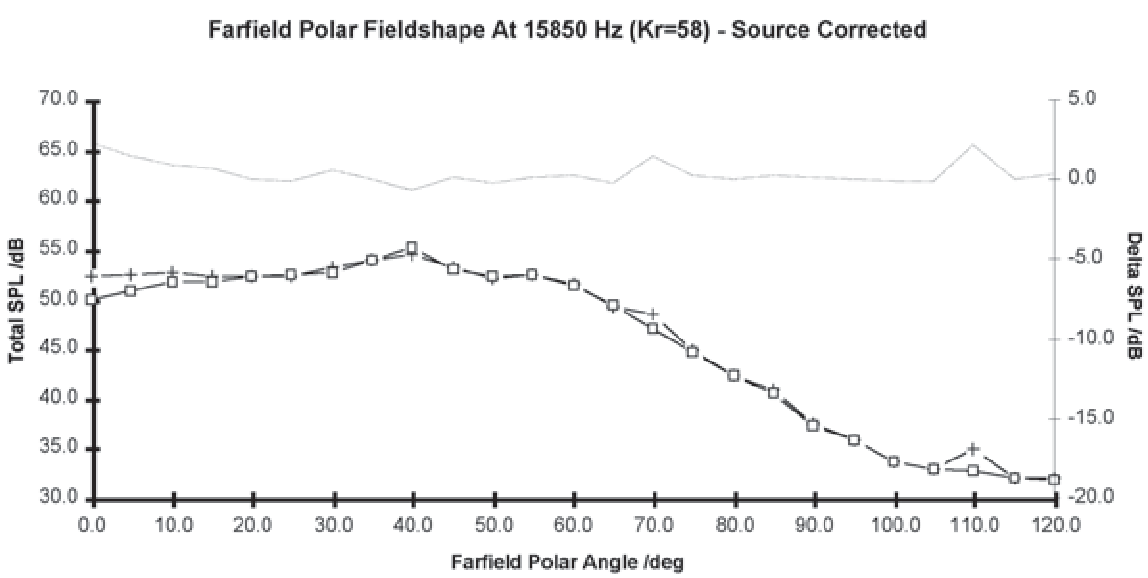
Figures 12 et 13 show a photograph of the test set-up and a measured modal spectrum in the duct. Results from this experiment have been used to validate the coupled FEM/BEM model developed at UTC.

Experiment on complex duct geometries

An experiment with complex exhaust configurations defined by Rolls-Royce (figure 14) was carried out at ISVR. The influence of turbine humps and buried cones was experimentally studied. Measured results were used by model developers for validation (Figure 15).

BRR-715 turbofan engine test at Hucknall

Model developers in DUCAT had limited access to the results of a RANNTAC test on a BRR-715 engine, which was run at the Rolls-Royce test bed in Hucknall.



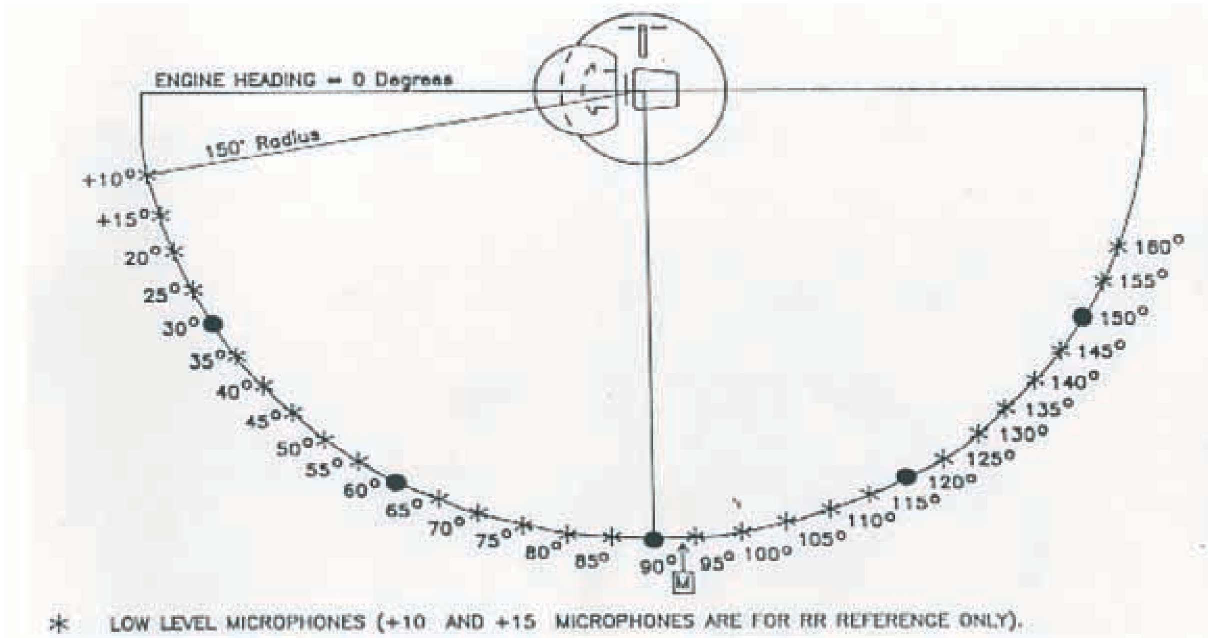


Fig. 16 : Overview of the test set-up

Fig. 17 : The expérimental set-up in the DNW-LLF

Figures 16 and 17 show an overview of the test set-up and a photograph of engine with turbulence control screen. Besides microphones in the radiated far field, a few microphones (Kulites) were placed downstream and upstream of the intake liner to determine the incident and transmitted acoustic fields. ISVR used test results for comparisons with predicted results (Fig. 4, non-linear propagation model).

Conclusions

The DUCAT project has been finished after a running period of three years. The achievements are summarised hereafter.

- A thorough description of the industrial design needs has

- Various acoustic models have been developed and validated.

- Comparisons between the advantages and disadvantages of various methods have been reported. Furthermore, the missing aspects of the duct acoustics model have been addressed (an example is the rotational flow between the rotor and the stator which strongly modifies the propagation of sound in this region).

- Several firm databases for future validations of duct acoustics models have been constituted.

Finally there are some remarks and recommendations. In the cause of the DUCAT Project, priority was shifted to model validation at the expense of a liner design exercise for a nacelle of a generic turbofan. This modelling work was much more laborious than anticipated at the start of the Project. Therefore the initial goal to calculate the 3-D lined duct acoustics propagation in the nacelle of a real engine at sufficiently high frequencies was not fully met. Probably, this can be achieved in a follow-up project with a limited number of duct acoustics models.

Furthermore, it seemed that mutual comparisons between predicted results were hampered by model assumptions and boundary conditions. This aspect should be taken into account at the definition phase of a future project.

As final remark it is stated that the models need further development to cover industrial requirements (as 3-D geometry, realistic frequencies) and further validations at relevant conditions, after which the capability of the models as major industrial design tools can be demonstrated.