ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

AFT FAN NOISE REDUCTION WITH A LINED AFTERBODY

L De Mercato, B J Tester and K Holland

Institute of Sound and Vibration Research, University of Southampton
Southampton, SO17 1BJ, United Kingdom

ldm@isvr.soton.ac.uk

Abstract

Aft fan noise is becoming a more dominant source as engine bypass ratio is increased and improved methods are required for its control. Bypass liners are especially effective in attenuating aft fan noise, but, in a recent paper [1] we introduced the idea of using acoustic linings on *external* parts of the aero-engine nacelle, such as the afterbody and plug nozzle. We conducted tests on a 'No-flow' rig with a broadband noise source, using scaled, linear SDOF acoustic linings to simulate the conventional, internal bypass liners and also the new external Afterbody Liner (AL). We showed that when the afterbody is acoustically lined, it reduces the far field sound power by up to 3 dB, a result which was confirmed with calculations using a commercially available CAA code. In this paper, we extend the previous broadband tests to include tone noise using an array of loudspeakers in the No-flow rig to excite specific modes. The measured tone reduction data are compared with calculations and the performance of AL is assessed relative to that achieved with the conventional bypass liners. The results confirm our expectations that the AL could also provide significant reductions in aft fan *tonal* fan noise levels. However, it should be emphasised that the results obtained so far are without mean flow and have to be confirmed by numerical simulations and tests with flow.

1. INTRODUCTION

Aero-engine fan noise radiating from the exhaust section of the bypass duct can now be considered as one of the dominant sources of noise for a conventional aircraft, this because the engine bypass ratio is increased for most engines. In order to tackle this problem in the most effective way, improved methods are required for the prediction and control of this type of noise. For over forty years acoustic linings have been used in aero-engines, as an effective means of reducing internally generated noise, mainly from the fan and turbine. In particular the bypass liners are especially effective in attenuating the aft fan noise.

Numerical analyses have shown that, as the fan noise emerges from the bypass exhaust nozzle, a significant part of the sound field radiates directly out through the shear layer but there is also another important propagation path, along which the sound field is first reflected from the hard extension of the internal surface of the bypass duct, *afterbody*, before it propagates out to the far field, see Figure 1, taken from Zhang et al [2].

As discussed in ref.[1], the observation of this mechanism suggests the installation of an acoustic liner on the afterbody surface. This would reduce the strength of that reflected field and that reduction might be sufficient to significantly reduce the far field sound pressure level. This application of the acoustic liners used for aero-engine nacelles is not usual, since this type of liners is are normally applied to internal engine ducting whereas here the afterbody surface is an external surface of the engine nacelle.

In this paper, we extend the previous broadband tests [1] to include tone noise using an array of loudspeakers in the No-flow rig to excite specific modes. As before, we use scaled, locally reacting, linear SDOF acoustic linings to simulate the conventional, internal bypass liners and also the new external Afterbody Liner (AL). The measured tone reduction data from this 'No-flow' rig is then compared with calculations performed with a commercially available code and the performance of AL is assessed relative to that achieved with the conventional bypass liners.

2. EXPERIMENTAL RIG AND TEST CONDITIONS

The rig used for the experiments is a 1/6th scale simplified model of a typical high bypass engine. A layout of the test rig is shown in Figure 2. These experiments have been run in no-flow condition. The source used to represent the fan tonal noise is a Mode Synthesizer (see Figure 3). This is a ring of 30 loudspeakers mounted on a cylindrical duct driven by a controller, and has been set-up by the EADS Company for the European research project TURNEX (Turbomachinery Noise Radiation through the Engine Exhaust) lead by the ISVR. A ring of 30 sensors is installed downstream and used to calibrate the loudspeakers and to monitor the quality of a single mode generation. On the opposite end of the duct a foam layer has been used to absorb all the sound propagating in that direction, simulating an anechoic termination. The sound radiation has been measured in an anechoic chamber with a polar array of fixed microphones at 5-degree intervals from 0 (on axis) to 120 degrees, at a distance of 3.95m from the highlight position on the duct axis (see Figure 3). The combination of frequencies and acoustic modes tested in this experiment is shown in Table 1, where *m* indicates the azimuthal order of the 'target' acoustic mode generated by the Mode Synthesiser, and ka is the Helmholtz number, the product of the wave number 'k' and the duct outer radius 'a'.

Table 1 - Experiment test matrix

Frequency	***1.25k***	***1.25k***	***1.25k***	***1.25k***	***1.6k***	***1.6k***	***1.6k***	***2k***	***2k***	***2k***	***2k***	***2.5k***
m	0	1	2	3	0	2	4	0	3	5	6	0
ka	5	5	5	5	6	6	6	7	7	7	7	9
Frequency	***2.5k***	***2.5k***	***3.15k***	***3.15k***	***3.15k***	***3.15k***	***4k***	***4k***	***4k***	***4k***	***4k***	***5k***
m	4	7	0	5	7	9	0	6	10	11	12	0
ka	9	9	11	11	11	11	14	14	14	14	14	18
Frequency	***5k***	***5k***	***5k***	***6.3k***	***6.3k***	***6.3k***	***8k***	***8k***	***8k***	***10k***	***10k***	***10k***
m	8	13	14	0	10	14	0	8	14	0	4	14
ka	18	18	18	23	23	23	29	29	29	36	36	36

The design specification for the inner and outer bypass liners (BL) and the afterbody liner (AL) are essentially the same. These are Helmholtz type single degree of freedom locally reacting liners, with the same cavity depth, 6mm thick honeycomb, and approximately the same surface sheet properties. A metallic wire mesh, provided by Airbus-France, has been bonded directly on the honeycomb layer, with no support sheet in between. This induces a linear behaviour on the liner resistance and reduces the mass reactance to a negligible value. The BL and AL impedances, used to model these liners in the computational analyses described below, are plotted versus frequency in Figure 4. These are non-dimensional values of the liner resistance and reactance, i.e. scaled on the local values of the static density and speed of sound ($\rho_{s,}$ c_s), which in this case are respectively 1.1921 Kg/m^3 and 344.95 m/s. A snapshot of the AL is shown in Figure 5.

The configurations in which the bypass duct and the afterbody are lined have been compared with those in which those surfaces are left impervious (Hard) to the acoustic waves. In particular Table 2 lists the configurations that have been object of the current investigation. These three configurations are also shown in Figure 6.

Table 2 – List of the studied configurations

Build number	***Bypass Outer Surface***	***Bypass Inner Surface***	***Afterbody***	***Name of the Configuration***
1	Hard	Hard	Hard	Datum
3	Lined	Lined	Hard	Conventional
5	Lined	Lined	Lined	Conventional + AL

3. NUMERICAL MODEL AND ANALYSIS

The CAA code used to perform the numerical predictions is ACTRAN. This is based on the finite/infinite element method and has been developed by Free Field Technologies (FFT) SA of Mont-Saint-Guilbert, Belgium, and is generally used by the ISVR for application to this class of problems. This solves the convected wave equation for the linear sound propagation in the frequency domain. Astley et al [3] have benchmarked the ACTRAN code against the axisymmetric analytic solution for radiation from a semi-infinite unflanged duct with uniform flow.

For this study an axisymmetric numerical analysis has been performed on the same configurations and the same frequencies tested for the experiments. An axisymmetric model has been considered appropriate, as the effect of the 6mm diameter radial bolts, which connect the centre-body with the outer duct (see Figure 6), has been initially considered negligible for the studied frequencies. The mesh used for this model is shown in Figure 7. On the left end of the duct is the sound source plane ('Modal Basis'). On this plane the source has been decomposed into a set of cut-on acoustic modes, which have been analysed individually. The acoustic liners have been modelled as admittance boundary condition on the edge of the mesh, as shown in Figure 7. The Helmholtz number (ka) shown in Table 1 is a good index of the size of the finite element model, in fact it contains the information on the acoustic wave length, which drives the refinement of the finite element mesh, and an indication of the size of the finite element domain, which is directly proportional to the duct outer radius.. The FE domain is then closed by a layer of infinite elements which have the double role of avoiding any reflection in the FE domain and of the extraction of the solution to the far-field. The far-field SPL directivities are computed on an array of 121 field-points, one per each angle from 0 to 120 degrees, which simulate the exact position of the microphones in the experiment.

The projection of the point P.P. (Projected Point) on one edge of the FE/IE interface to the far field generates a virtual hard baffle. The Infinite Element formulation, in fact, is based on a multiple expansion of the acoustic field at the FE/IE interface along the straight lines that connect the nodes on this surface; the hard wall point P.P. in this case, with the acoustic centre (A.C). The acoustic centre is a conventional point where all the sources and the reflecting surfaces can be seen as concentrated if observed from the far field. The hard baffle produces some reflections that result in an oscillating pattern in the far field sound directivity.

A preliminary test on this model demonstrated that the range of angles form 0 (on axis) to 90 degrees is not affected by these reflections, and consequently chosen for the comparison with the measurements.

3.1 Source Modelling and Scaling

As mentioned above, the sound source plane is defined in terms of a modal basis. Each radial cut-on mode for the azimuthal orders (m) listed in Table 1 has been individually analysed as having a unit modal intensity (1W/m^2). The SPL far-field directivity of each of these modes has then been scaled on the relative modal amplitude as generated by the Green functions, as described in [4], which models as point sources the loudspeakers of the Mode Synthesizer used in the experiment. In particular the SPL directivities, predicted using a unit intensity mode as a source, have been first scaled on the correspondent source having unit modal amplitude (1 Pa). The resulting values have been then scaled according to the Green function shown below, in order to have the correct relative distribution of amplitudes over the set of radial modes for a give azimuthal order:

$$G(x,r,\vartheta;x_0,r_0,\vartheta_0)=\sum_{m=-\infty}^{\infty}e^{-im(\vartheta-\vartheta_0)}G_m(r,x) \tag{1}$$

where:

$$G_m(r,m)=\frac{1}{2\pi i}\sum_{\mu=1}^{\infty}\frac{J_m(\alpha_{m\mu}r)\cdot J_m(\alpha_{m\mu}r_0)}{Q_{m\mu}\cdot J_m(\alpha_{m\mu})^2}\cdot e^{-i\kappa_{m\mu}(x-x_0)} \tag{2}$$

$$Q_{m\mu}^{\pm}=\pm\left[(\kappa_{m\mu}+\Omega_{m\mu}M)\cdot\left(1-\frac{m^2}{\alpha_{m\mu}^2}-\frac{\Omega_{m\mu}^4}{(\omega\alpha_{m\mu}Z_1)^2}\right)-\frac{2iM\Omega_{m\mu}}{\omega Z_1}\right] \tag{3}$$

$$\Omega=\omega-\kappa M \tag{4}$$

In these non-dimensional equations x, r and ϑ are respectively the axial, radial and azimuthal coordinates, the subscript 0 indicates the point source, μ is the radial modal order, J_m is the is the Bessel function of order m, α is the radial wave number, κ is the axial wave number, ω is the Helmholtz number, Z_1 is the impedance of the outer wall at the Mode Synthesizer section and M is the Mach number. In the specific case studied here r_0 = 1 since the point sources (loudspeakers) are placed on the wall, $Z_1=\infty$ since the duct section where the Mode Synthesizer is installed is acoustically hard and M = 0 (no-flow condition) and equation (3) reduces to:

$$Q_{m\mu}^{\pm}=\pm\left[\kappa_{m\mu}\cdot\left(1-\frac{m^2}{\alpha_{m\mu}^2}\right)\right] \tag{5}$$

The SPL far-field directivities of each individual radial mode have then been summed coherently for each azimuthal order.

4. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

In order to compare the numerical predictions with the experiments, the calculated SPL far-field directivities radiated by each individual radial mode (n) excited by the Mode Synthesiser for a given azimuthal order are presented together with their coherent sum and the measured directivities for the same azimuthal mode. Figure 8 and Figure 9 show in particular the SPL directivities for the azimuthal orders modes 0 and 10, respectively for the conventional and conventional+AL configurations. The general trend of the predicted directivities appears to be similar to the measured one, although for a number of modes the measurements showed significant incoherent oscillations, whereas the numerical prediction always showed a smooth variation. In the angle range between 0 and 20 degrees for m=0 the agreement is reasonably good but for m=10 the measurement and the predictions have a completely different behaviour over these small angles. This always appears to be the case for target *m* numbers close to cut-off, and suggests that when one of these modes is generated, other azimuthal order modes are present, with low order, well cut-on modes being most evident in directions close to the duct axis. This may be due to scattering of the target mode by the radial bolts indicated in Figure 6, which are not present in the FE model. Another reason might be the excitation of azimuthal modes other than the target mode by the Mode Synthesiser.

The attenuation benefit of the AL can be assessed by taking the difference between the SPL directivities of the conventional and the conventional+AL configurations. Both measurements and predictions showed a maximum attenuation of the AL at 6300Hz. Figure 10 shows in particular the ΔSPL directivities for the azimuthal orders modes 0 and 10 at 6300Hz. The m=0 results show pronounced attenuation at and near the duct axis, which is consistent with the previous broadband results, but with even larger attenuations of up to 10 dB. These decrease with increasing angle, with most of the data points falling close to zero, apart from some localised peaks and troughs at 35-40 degrees and at 65-70 degrees, the latter possibly being related to the trough in the predicted attenuation at just over 70 degrees.

For m=10, the discrepancies between the prediction and the measurements up to 20 degrees may be caused by the contamination of other extraneous modes in the experiment, as described above. However, a significant benefit seems to be obtained for angles higher than 50 degrees, with a predicted peak attenuation of 8 dB at 63° angle and a measured peak of 15.4dB at 75° angle. This suggest that modes with the higher *m* values, which have a higher peak radiation angle, may be more attenuated, as Figure 10 seems to confirm.

5. CONCLUSIONS

The aim of this investigation has been to extend the previous broadband noise assessment of the effectiveness of the acoustic lining on the afterbody surface (AL), for a typical high bypass engine, to the attenuation of the aft radiating *tonal* noise. The performance of the AL has been studied both numerically and experimentally. Both the predictions and the experiments seem to confirm that the peak attenuation is concentrated around a specific frequency for which the liner is tuned (6300 Hz). The numerical predictions show a broadly similar trend to the measurements, except for small radiation angles when extraneous modes are present. Well cut-on target modes radiating close to the duct axis appear to be well attenuated, like the previous broadband results. At larger angles, for target *m* orders close to cut-off, there is a reasonable correspondence between predictions and measurements. Future tests and numerical modelling with flow will help to confirm and improve our understanding of the afterbody tone noise attenuation mechanisms.

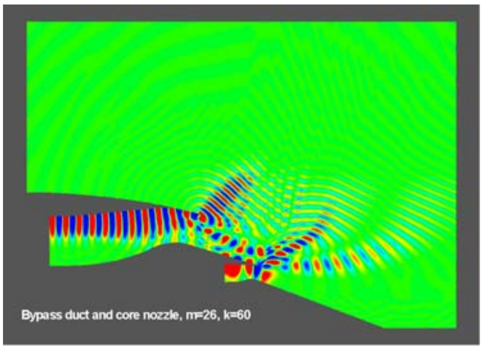

Figure 1 - Radiation of fan tone mode from typical high bypass exhaust.

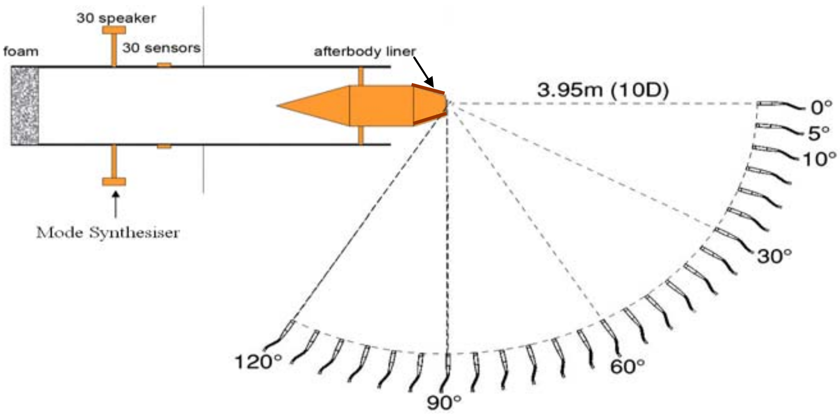

Figure 2 - Layout of the Test Rig

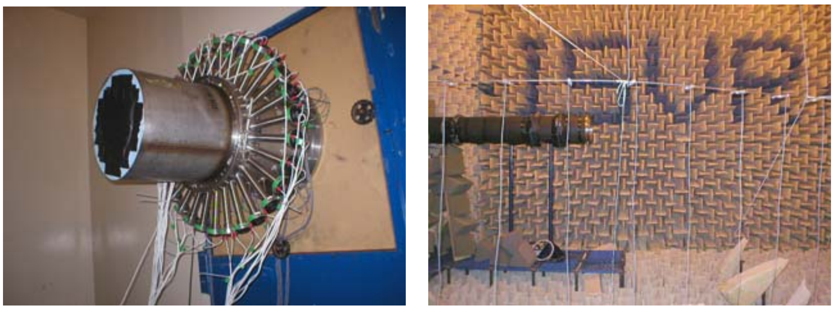

Figure 3 - Mode Synthesizer (left) and microphones array (right)

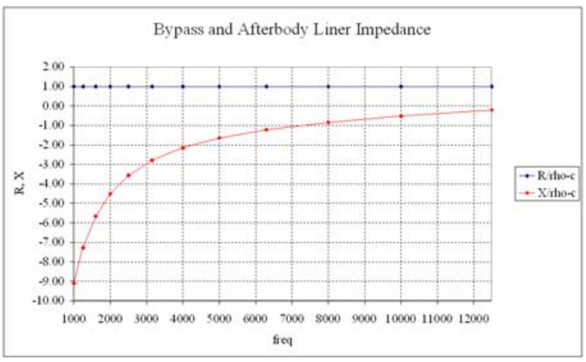

Figure 4 - Bypass Liners (BL) and Afterbody Liners (AL) Impedances

Figure 5 - Duct Exhaust Section with the Afterbody Liner

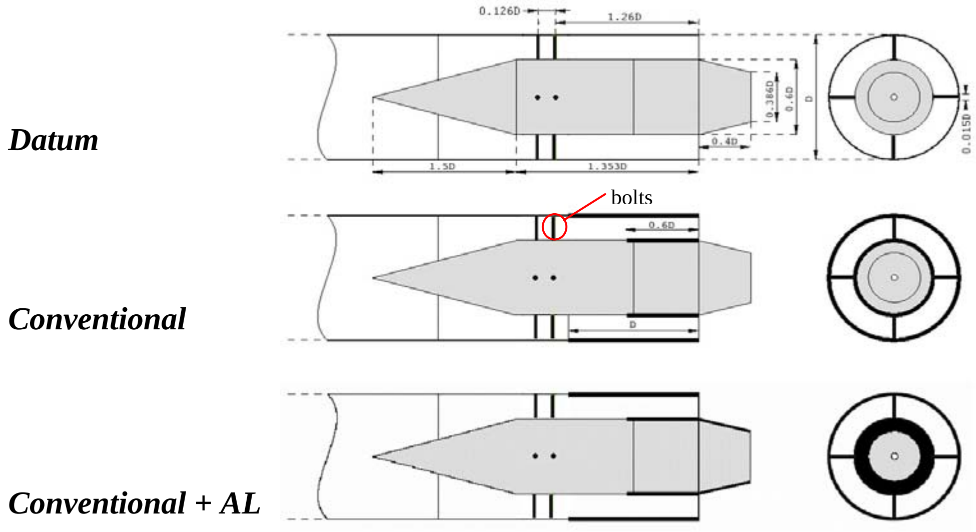

Figure 6 - Sketch of the studied configurations (D = 397mm)

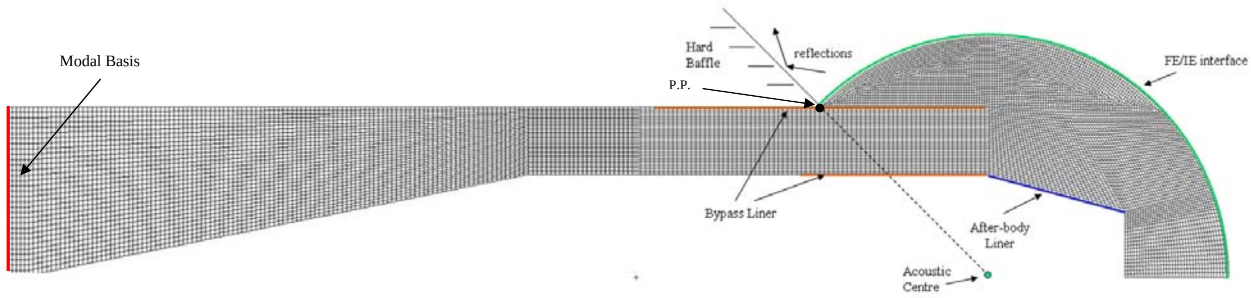

Figure 7 - Finite/Infinite Element Model

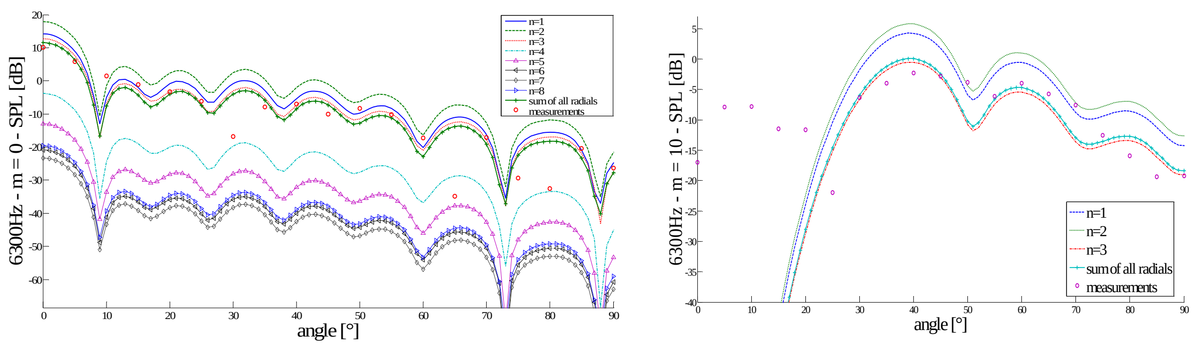

Figure 8 – SPL directivities for m=0 and m=10 at 6.3 KHz, Conventional configuration

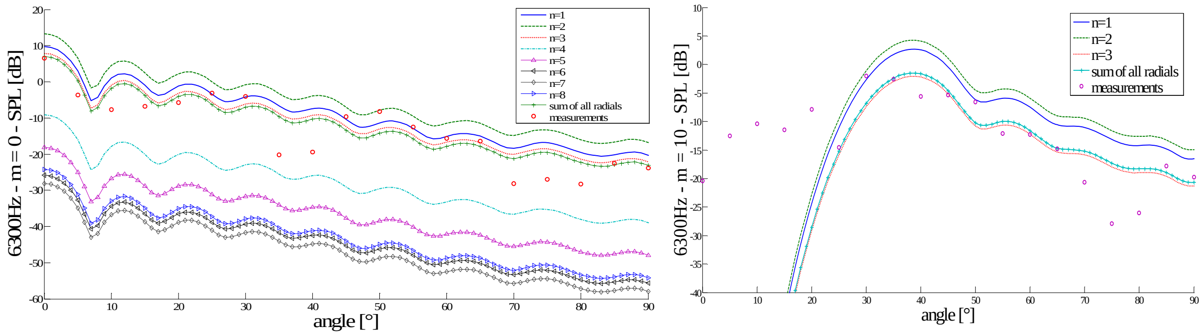

Figure 9 - SPL directivities for m=0 and m=10 at 6.3 KHz, Conventional + AL configuration

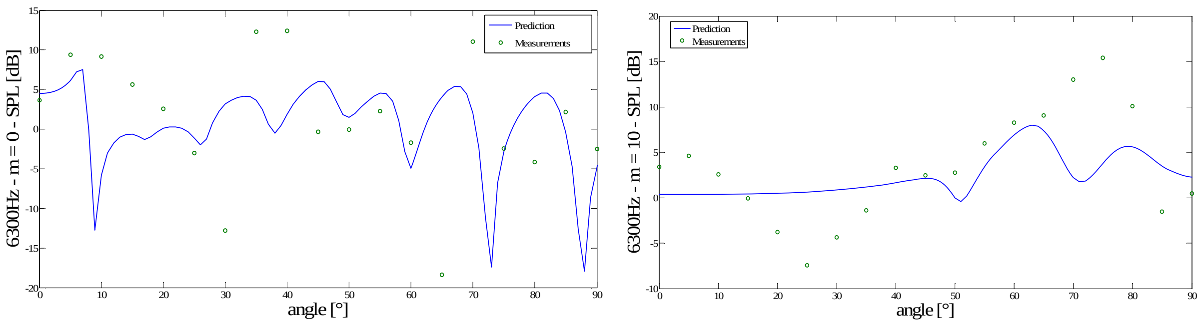

Figure 10 - ΔSPL directivities, conventional – (conventional + AL), for m=0 and m=10 at 6.3 KHz

ACKNOWLEDGEMENTS

The authors are grateful to Prof Jeremy Astley for helpful discussions, to Jörgen Zillmann from EADS for providing the Mode Synthesizer necessary for the experiments and to the European Commission for financial support through the TURNEX project, Tech. Officer Daniel Chiron.

REFERENCES

[1] B. J. Tester, L. De Mercato and K. Holland, “Aft fan noise reduction with an lined afterbody”, 2007 AIAA 2007-3527, *13th AIAA/CEAS Aeroacoustics Conference 21-23 May 2007, Rome, Italy.*

[2] X. Zhang, X. X. Chen, C. L. Morfey and B. J. Tester, “Computation of fan noise radiation through a realistic engine exhaust geometry with flow”, 2003 AIAA 2003-3267, *9th AIAA/CEAS Aeroacoustics Conference 12-14 May 2003 Hilton Head, South Carolina, USA.*

[3] R. J. Astley, J. A. Hamilton, N. Baker and E. H. Kitchen, “Modelling tone propagation from turbofan inlets – the effect of extended lip liners”, 2002 AIAA 2002-2449, *Proceedings of the 8th AIAA/CEAS Aeroacoustics Conference, Breckenridge, Colorado, USA.* .

[4] S. W. Rienstra, B. J. Tester, “An Analytic Green’s Function for a Lined Circular Duct Containing Uniform Mean Flow”, 2005 AIAA 2005-3020, *11th AIAA/CEAS Aeroacoustic Conference, Monterey, USA.*