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ABSTRACT From the in-flight measured circumferential modal spectra of the Rolls-Royce Tay 650 engine mounted on the Fokker 100, it was found that the sound field propagating upstream in the inlet is strongly modulated by intercostal hard-walled strips in the lined area, the non-cylindrical geometry of the duct, and the non-axisymmetric flow velocity distribution. To study the effect of the modulation of the acoustic field by the hard-walled strips separately, an experimental program in the NLR spinning mode synthesizer was carried out. In the first place, the effect of scattering of modes of low circumferential order in the absence of flow was studied using an array of loudspeakers as noise source. Sound was generated in the frequency range from 400 Hz to 3000 Hz. The target circumferential mode numbers ranged from 0 to 3. Modal scattering caused by simulated hard-walled strips was studied by measuring the incident and transmitted acoustic energy flux is not much influenced by the scattering of the incident modes, whereas the m-mode spectra of the transmitted field clearly show modulation effects caused by the hard-walled strips and the modulation increases with increasing mode number.			

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EXPERIMENTAL INVESTIGATION ON THE  
INFLUENCE OF LINER NON-UNIFORMITIES  
ON PREVAILING MODES

by

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## EXPERIMENTAL INVESTIGATION ON THE INFLUENCE OF LINER NON-UNIFORMITIES ON PREVAILING MODES

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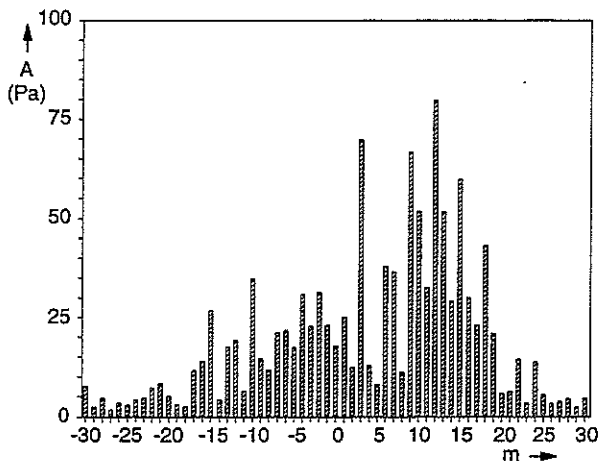
From the in-flight measured circumferential modal spectra of the Rolls-Royce Tay 650 engine mounted on the Fokker 100, it was found that the sound field propagating upstream in the inlet is strongly modulated by intercostal hard-walled strips in the lined area, the non-cylindrical geometry of the duct, and the non-axisymmetric flow velocity distribution. To study the effect of the modulation of the acoustic field by the hard-walled strips separately, an experimental program in the NLR spinning mode synthesizer was carried out. In the first phase, the effect of scattering of modes of low circumferential order in the absence of flow was studied using an array of loudspeakers as noise source. Sound was generated in the frequency range from 400 Hz to 3000 Hz. The target circumferential mode numbers ranged from 0 to 3. Modal scattering caused by simulated hard-walled strips was studied by measuring the incident and transmitted acoustic field in the duct. It was found that the total in-duct transmitted acoustic energy flux is not much influenced by the scattering of the incident modes, whereas the m-mode spectra of the transmitted field clearly show modulation effects caused by the hard-walled strips and the modulation increases with increasing mode number.

### Nomenclature

$R$	= duct radius
$\rho$	= air density
$c$	= speed of sound
$m_0$	= cir. mode number of first cut-off mode
$\mu_0$	= radial mode number of first cut-off mode
$\omega$	= dimensionless frequency ( $2\pi fR/c$ )
$M$	= Mach number
$\beta$	= $(1 - M^2)^{1/2}$
$\Omega_{m\mu}$	= $(\omega^2 - (\beta\gamma_{m\mu})^2)^{1/2}$
$\gamma_{m\mu}$	= mode eigenvalue in hard walled-duct
$A_{m\mu}$	= normalized incident modal amplitude
$B_{m\mu}$	= normalized reflected modal amplitude
$I$	= in-duct acoustic energy flux

### Introduction

From the in-flight measured circumferential modal spectra of the Tay 650 engine mounted on the Fokker 100<sup>1</sup>, it was found that the sound field propagating upstream in the inlet is strongly modulated by intercostal hard-walled strips in the lined area, the non-cylindrical geometry of the duct, and the non-axisymmetric flow velocity distribution. A scattering by the three inlet splices is shown clearly in Figure 1 for approach case. It is further mentioned that a single splice inlet was flight tested on a Fokker 100 and was found to give significant noise reduction during approach and cut back. It seems that use of a spliceless inlet will give additional benefit and the present study is performed to quantify the effects of splices, i.e. number and width. Two experiments in the NLR Spinning Mode Synthesizer were defined. In the first phase, the effect of scattering of modes of low circumferential order in the absence of flow is studied using an array of loudspeakers as noise source. In the second phase, the scattering of modes of high circumferential order in the presence of flow will be studied using the NLR fan noise mode<sup>2</sup> as noise source. In this paper the results of the first phase are



**Fig. 1: Measured m-mode spectrum dominated by scattered modes in the inlet of the Tay 650 engine mounted on the Fokker 100, approach, 70% reduced engine speed**

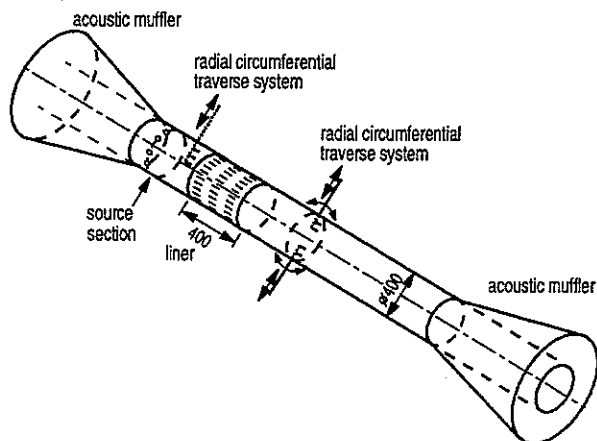
presented. For the experiments a spliceless cylindrical duct liner was provided having a liner length of 400 mm (one duct diameter), nominal DC-flow resistance of the facing sheet of 60 rayls and core depth of 17 mm.

The scattering of the sound field for several liner configurations was determined by measuring the acoustic power per m-mode transmitted through two cross-sectional surfaces (downstream and upstream of the lined section) in a hard-walled part of the duct. The damping attained by a liner is characterized by the insertion loss: the ratio of the transmitted in-duct acoustic energy fluxes at the duct end with and without a lined section.

### Experimental set-up

#### NLR Spinning mode Synthesizer (SMS)

The Spinning Mode Synthesizer (Fig. 2) is a cylindrical duct with an internal diameter of 400 mm and a length of



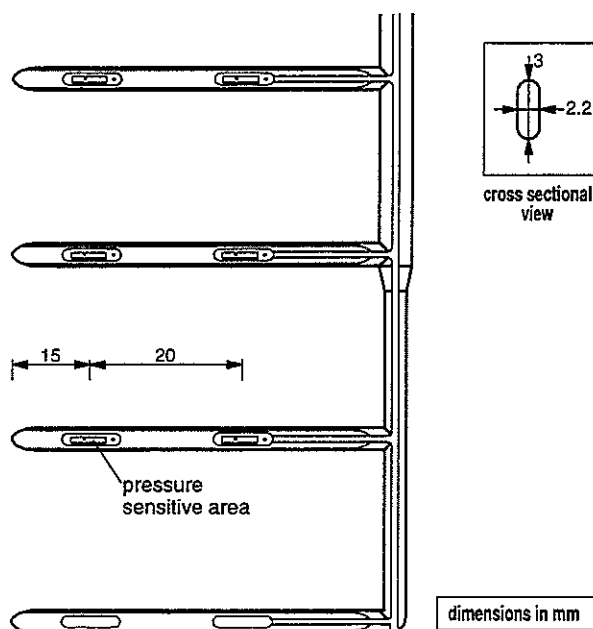
**Fig. 2: The NLR spinning mode synthesizer (SMS)**

4 m. At both ends acoustic mufflers are fitted to reduce sound reflections. The sound field in the duct is generated by an array of 9 loudspeakers type Isophone KM 11/150/8 equally distributed along the circumference. To control phase and amplitude of each loudspeaker, a small Electret microphone is mounted in front of each loudspeaker. When generating a spinning mode, each loudspeaker is set to the correct phase and amplitude with all other speakers switched off. When all speakers have been adjusted, they are switched on simultaneously. At that stage no further adjustments are made. In the present study the desired modes will be denoted by 'target modes' and the other (undesired and scattered) modes by 'parasitic modes'.

#### Radial and circumferential traverse system

Measurements for mode detection were carried out at both sides of the lined section with two microphone probes (Fig. 3). These probes cover a major part of the duct cross section by a traverse mechanism. The latter contains provisions for a circumferential traverse over 190 degrees and for a radial traverse over 37 mm. Position accuracy is 0.05 mm for the radial and 0.25 deg. for the circumferential position. The positioning was computer controlled.

A microphone probe contains 4 microphone holders each with two flush mounted microphones. The axial distance between the microphones is 20 mm. The radial distance of the microphone holders is 39 mm, so that a large part of the duct cross-section could be covered:  $0 \leq \theta \leq 360$  deg and  $0.25 \leq r/R \leq 0.99$ . In the duct centre region no measurements were performed because of strong gradients occurring in this region and which make the pressure field



**Fig. 3: Microphone rake.**



sensitive to small distortions (due to the presence of the probe). The microphones were piezo-resistive pressure transducers PPG Hellige (previously Honeywell) type MTC (Micro Transducer Catheter). These are differential transducers and in the present tests vented against the ambient atmospheric pressure. Front face dimensions of these transducers are 5 x 1.5 mm and the pressure sensitive area has a diameter of 0.7 mm. Maximum thickness is about 1 mm. The sensitivity of the transducer is about 1.8 mV/kPa at a supply voltage of 7 V. The thermal sensitivity shift of the transducers was compensated for in the data processing software.

#### Data acquisition and analysis

The 16 signals of the microphones were fed to the A/D converters of a 26 channel Fourier Analysis System based on a HP 9000/375 computer and LMS software. Also a signal of a B & K microphone placed at the duct wall and the 9 microphones placed in front of the loudspeakers were fed to the system (a total of 26 signals). The transducer signals were on-line ensemble averaged in the time domain with the sampling process phase locked to a reference signal of the source. All phase angles are related to this signal. The time frame was chosen to be 1 second and therefore the frequency resolution was 1 Hz. The blocksize was chosen to be 8192, which made the sampling frequency also 8192 Hz. Low pass filtering was applied at 40 % of the sampling frequency, which implies that possible aliasing components are reduced by at least 40 dB. The ensemble averaged time histories were stored on disc for further processing after the test. The number of averages was 20 for the incident and transmitted acoustic fields. The time domain averaged data of the transducers were Fourier transformed into the frequency domain. Per selected frequency and for one radial position, a complex Fourier Transform was performed on the circumferential distribution of the complex acoustic pressure to obtain the m-mode spectrum. Per selected m-mode, the radial distribution of the complex acoustic pressure at each axial station was decomposed in a set of radial  $\mu$ -modes using a least squares routine, involving routines for calculating the values of Bessel functions. These  $m, \mu$ -modes are modes of a hard-walled duct. The incident and reflected components of the sound field were calculated from the modal amplitudes at two axial stations. From these the in-duct acoustic energy flux was calculated according to:

$$I = \rho c^3 R^2 \pi \omega \beta^4 \sum_{\mu=1}^{m_i-1} \sum_{\mu=1}^{m_r-1} \Omega_{m\mu} \left[ \frac{|A_{m\mu}|^2}{(\omega - M\Omega_{m\mu})^2} - \frac{|B_{m\mu}|^2}{(\omega + M\Omega_{m\mu})^2} \right]$$

(see nomenclature for description of the parameters).

The contribution of the cut-off modes in the incident field to the total incident acoustic energy flux was in this experiment very small in comparison with the contribution of the cut-on modes, and was therefore neglected. The insertion loss and the transmission loss could be calculated from the acoustic energy fluxes.

#### Measurement accuracy

The measurement accuracy is mainly determined by the reproducibility of the acoustic incident field, which is estimated to be within about 1 dB in magnitude and 10 degrees in phase. This error is much more important than measurement inaccuracies like uncertainties in positions of the measurement probe and electric noise. The best reproducibility is obtained by applying a temperature correction on the adjusted frequency. Total inaccuracy in the measured insertion and transmission loss is estimated to be about 1 dB.

#### Test program

For spinning modes with circumferential mode number 0,1,2 and 3, acoustic mode measurements were carried out at four frequencies (Table 1). The frequencies are given at a nominal temperature of 15 °C. However, the actual frequencies will depend on the ambient temperature. The tested liner configurations with simulated "hard strips and splices" are given in Table 2 and corresponding Figure 4.

Table 1: Test program in the NLR Spinning Mode Synthesizer: target modes and frequencies

$m_{\text{target}}$	$f_n$ in [Hz]	$f_n$ in [Hz]	$f_n$ in [Hz]	$f_n$ in [Hz]
m=0	400	1100	1300	2030
m=1	600	950	1550	1830
m=2	1000	1960	2100	2850
m=3	1220	1550	1960	2330

$f_n$ : nominal frequency at 15 °C

Note that the frequencies and mode numbers in the Rolls-Royce Tay 650 inlet are higher than those which can be achieved in the Spinning Mode Synthesizer. Scattering was enhanced for configurations 11 (two hard-walled strips with a width of 15 cm) and 12 (three strips with a width of 10 cm).

In Table 3 the percentage covered by the hard-walled strips of the lined surface is indicated. The insertion losses are not in any way corrected for these changes in the lined area. However, if it is assumed that the insertion loss in dB's is linearly dependent on the lined area, this correction is straightforward.





Table 2: Liner configurations tested in the NLR Spinning Mode Synthesizer

Test conf.	number of splices	width in [ mm ]	splice location [ deg ]
0*	-	-	-
1**	0	-	-
2	1	50	0
4	1	100	0
5	2	50	0/180
6	3	50	0/120/240
7	4	50	0/90/180/270
8	3	50	0/120/240
9	1	50	circumferential
11	2	150	0/180
12	3	100	0/120/240

\*configuration 0: incident field on the liner

\*\*configuration 1: transmitted field of uniform liner

Table 3: Percentage of covered liner area for each configuration

Conf.	Percentage covered by hard-walled strips [ % ]	Attenuation factor
1	0	1.0
2	4.0	.96
4	8.0	.92
5	8.0	.92
6	11.9	.88
7	15.9	.84
8	15.9	.84
9	12.5	.87
11	23.9	.76
12	23.9	.76

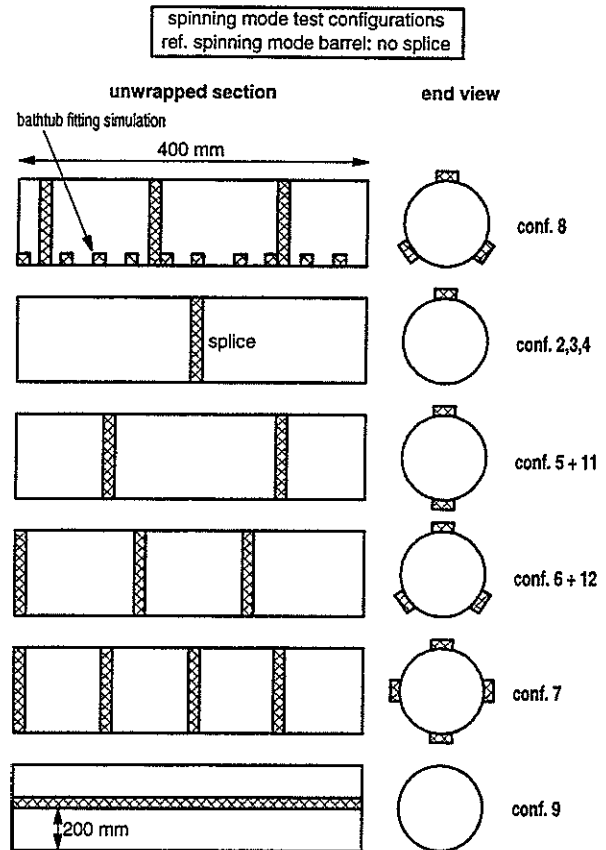


Fig. 4: Proposed liner configurations

### Experimental results

#### Reproducibility of the sound field

Because the incident and the transmitted acoustic field could not be determined simultaneously (the traverse system had to be exchanged with a hard-walled section of

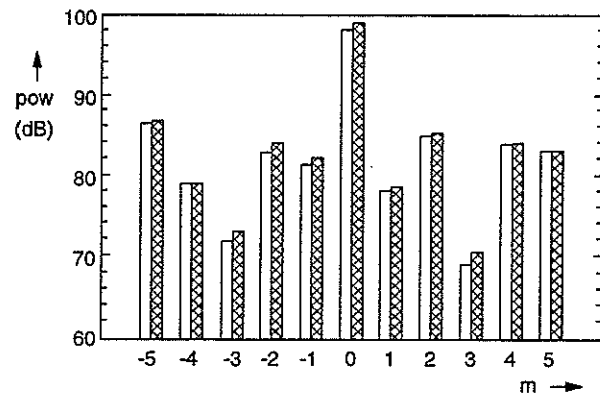
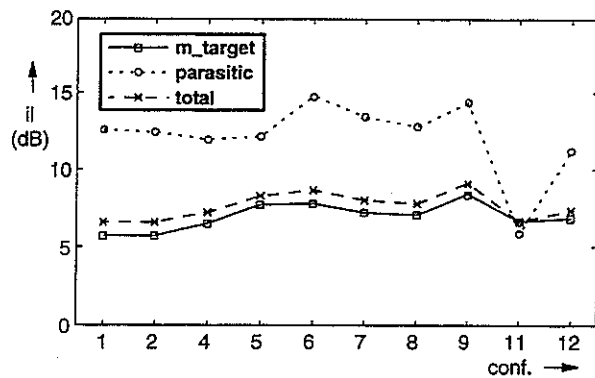


Fig. 5: m-mode spectrum showing the reproducibility of the incident acoustic field, target mode 0, 2030 Hz

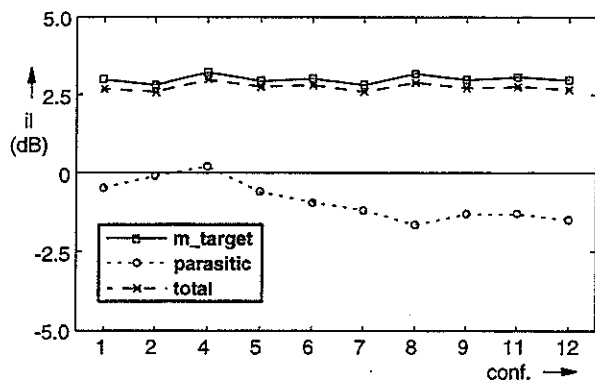
the SMS), it was important to determine how well the incident acoustic field could be reproduced. A typical example of the reproducibility of the incident acoustic field for target mode 0 at 2030 Hz is shown in Figure 5. On the basis of all results it was concluded that the reproducibility of the acoustic incident field is excellent.

**Attenuation based on the in-duct acoustic energy fluxes**

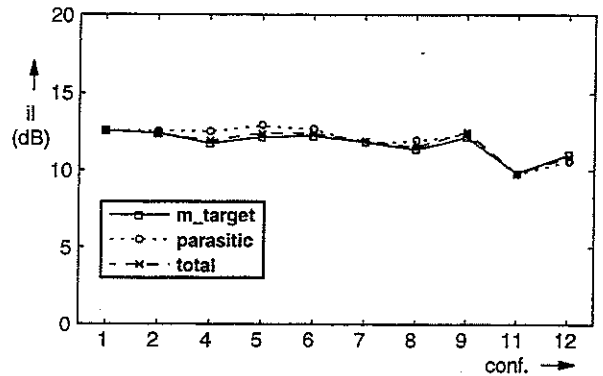
A typical example for the target mode number 0 at 2330 Hz is shown in Figure 6. Three radial modes are cut-on for this condition. The insertion loss of the target mode 0 is increasing with the number of non-uniformity of the liner even with a reduced lined area. This is probably caused by scattering to higher order circumferential modes, which are better attenuated by the liner. Only for some frequencies and mode numbers, configuration 9 with the hard-walled strip along the circumference of the duct, gave a maximum insertion loss. Possible reflections on the liner discontinuities result in additional insertion loss of about 2 dB. At configuration 11 with two hard-walled strips with a width of 15 cm, a very low insertion loss of



**Fig. 6:** The measured insertion losses of the target mode, total and the parasitic modes,  $m = 0$ ,  $f = 2030$  Hz



**Fig. 7:** The measured insertion losses of the target mode, total and the parasitic modes,  $m = 1$ ,  $f = 600$  Hz

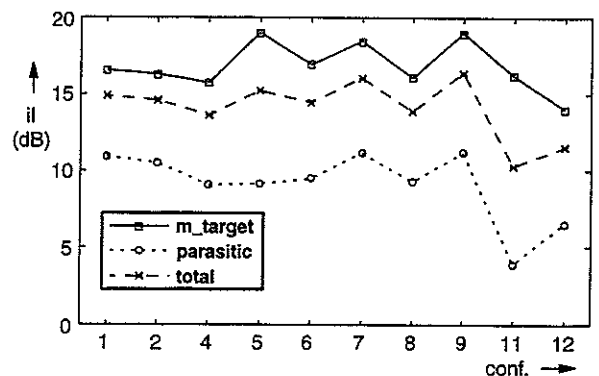


**Fig. 8:** The measured insertion losses of the target mode, total and the parasitic modes,  $m = 1$ ,  $f = 1830$  Hz

the parasitic modes is found indicating the combined effects of the presence of modal scattering and the decrease in lined area resulting in less attenuation.

For target mode number 1 at 600 Hz the insertion loss for all configurations is nearly constant (Fig. 7,  $IL \approx 2.6$  dB). Note that the insertion loss of the parasitic modes becomes negative, indicating that energy is transferred from the target mode to the parasitic modes. The insertion loss at higher frequency and target mode number 1 (Fig. 8,  $f = 1830$  Hz) is slightly decreasing by the increase of the non-uniformity of the lined section. For configuration 11 with enhanced strip width, the decrease in insertion loss is about 3.0 dB.

For target mode number 2 at 1960 Hz, except for configurations 11 and 12 (circumferential strip), the insertion loss is nearly constant. The insertion loss of the configurations with enhanced strip width is strongly decreased: 6.8 and 4.4 dB respectively. For target mode number 3 at 2330 Hz similar results are found, though the values for decreases in insertion loss for configurations 11 and 12 are less (Fig. 10).



**Fig. 9:** The measured insertion losses of the target mode, total and the parasitic modes,  $m = 2$ ,  $f = 1960$  Hz

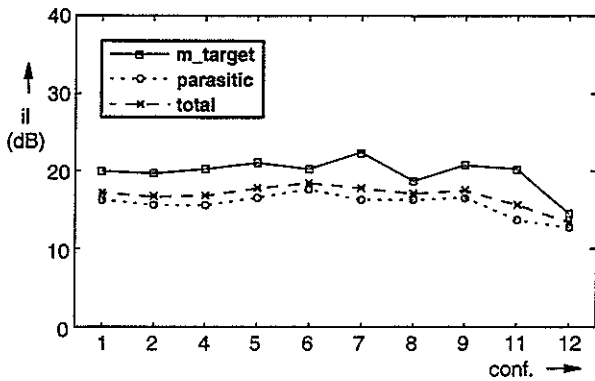


Fig. 10: The measured insertion losses of the target mode, total and the parasitic modes,  $m = 3$ ,  $f = 2330$  Hz

On basis of all experimental results, it is concluded that the scattering of modes for low target mode numbers, ranging from 0 to 3, has a small effect on the total transmitted acoustic energy flux. Generally, for cases with target mode number 0, the insertion loss increases somewhat with the level on non-uniformity of the lined section. Maximum differences of about 1 dB are found. Contrary to the results for target mode number 0, the insertion loss of higher order modes is somewhat decreasing with the level of non-uniformity of the lined section. At some conditions, the insertion loss of the parasitic modes is found to be negative indicating the effect of scattering. Further it is found that scattering, if an equal percentage of the lined section is covered, is stronger for a configuration with a few wide strips than with a larger number of smaller strips.

The experimental results of configuration 9, for which a hard-walled strip was placed in circumferential direction show for a few cases a high insertion loss. Sound reflections on the liner discontinuities are probably important in these cases.

#### Scattered m-mode spectra

In the previous section the effect of mode scattering on the total energy flux was analyzed. In this section a comparison is made between the m-mode spectra of the transmitted field with and without the hard-walled strips installed. The m-mode spectra of configuration 1 (the uniform liner) are therefore used as reference.

In Figure 11 for the  $m = 0$  mode at 2030 Hz a comparison is made between the m-mode spectra of the transmitted acoustic field with the homogeneously lined section (configuration 1, black bars) and the lined section of configuration 11 (two hard-walled strips, white bars). The modulation due to the presence of the hard-walled strips is clearly indicated by the increased amplitudes of modes with mode numbers -2, 2 and 4.

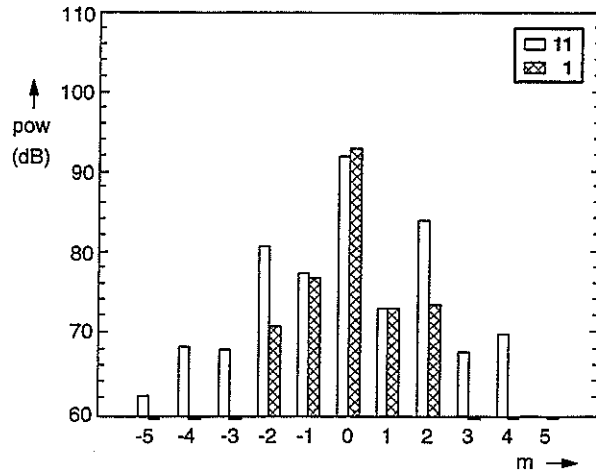


Fig. 11: Comparison between the m-mode spectra of the transmitted acoustic fields of configurations 1 and 11,  $m = 0$ ,  $f = 2030$  Hz

The transmitted acoustic fields of configuration 11 for target mode number 1 at frequencies 600 and 1830 Hz are clearly modulated by the presence of two hard-walled strips (Figs. 12 and 13). The modal amplitude for mode number -1 at 600 Hz is clearly present but does not have a strong influence on the transmitted acoustic energy flux.

For configuration 11 and target mode number 2 at 1960 Hz a strong decrease in insertion loss was found. The related m-mode spectrum for this condition is shown in Figure 14. A high modal amplitude at scattered mode number 0 is found, besides a number of additional modes with absolute mode number higher than 2.

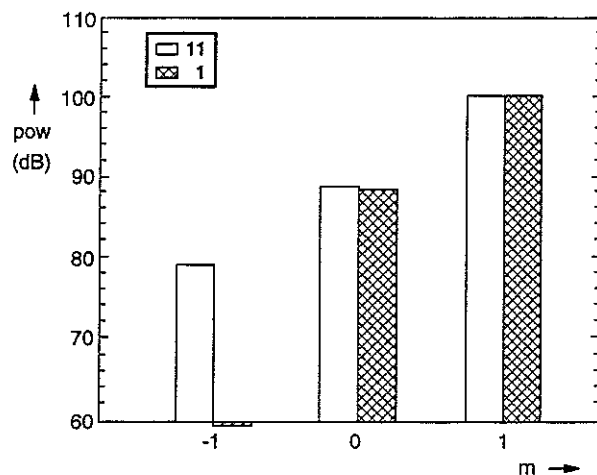


Fig. 12: Comparison between the m-mode spectra of the transmitted acoustic fields of configurations 1 and 11,  $m = 1$ ,  $f = 600$  Hz

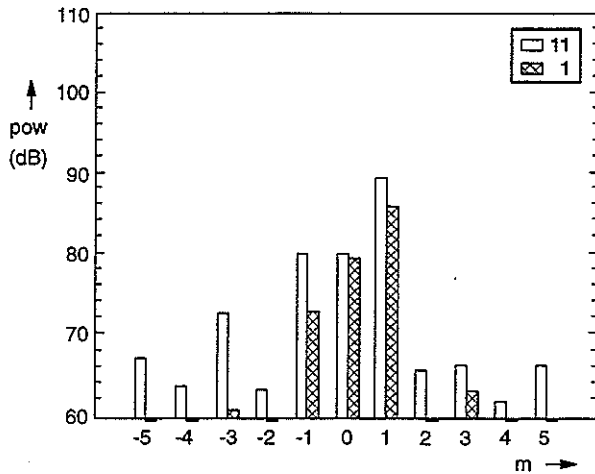


Fig. 13: Comparison between the m-mode spectra of the transmitted acoustic fields of configurations 1 and 11,  $m = 1$ ,  $f = 1830$  Hz

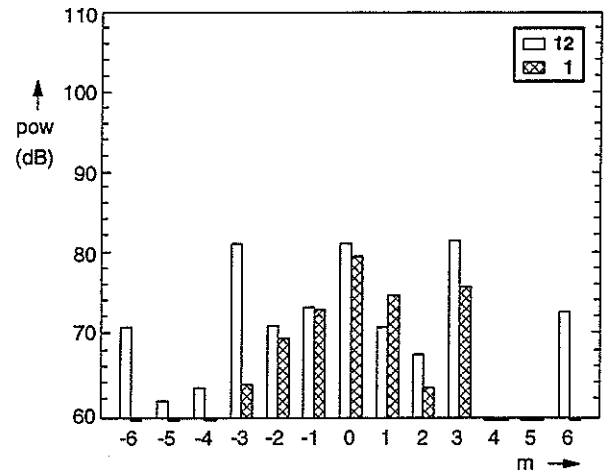


Fig. 15: Comparison between the m-mode spectra of the transmitted acoustic fields of configurations 1 and 12,  $m = 3$ ,  $f = 2330$  Hz

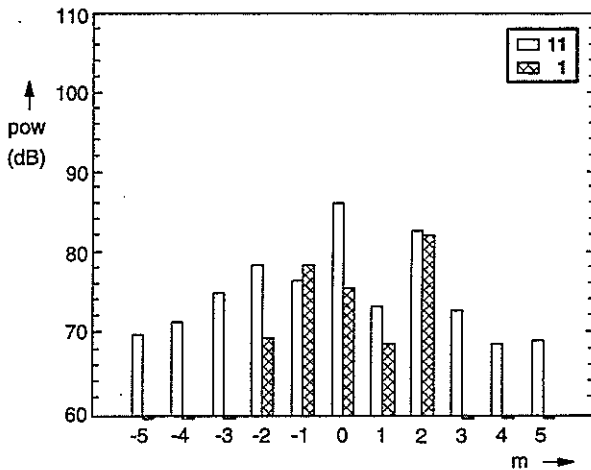


Fig. 14: Comparison between the m-mode spectra of the transmitted acoustic fields of configurations 1 and 11,  $m = 2$ ,  $f = 1960$  Hz

A clear example of modal scattering with three hard-walled strips (configuration 12) for target mode number 3 at 2330 Hz is shown in Figure 15. The m-mode spectrum is fully dominated by modes with modes numbers which are a multiple of 3.

The m-mode spectra for the investigated configurations clearly show the effect of modal scattering. However, it is emphasized that for most configurations scattering of low order circumferential modes has a minor effect on the transmitted acoustic energy flux through the duct and therefore a small effect on the attenuation.

## Conclusions

From in-flight acoustic mode measurements in the inlet of the Tay 650 engine, it was found that scattered modes dominated the acoustic field near the intake lip. The modal scattering in the inlet is caused by the fact that the duct, the flow and the liner, the latter due to the presence of hard-walled intercostal strips, are not axi-symmetric. To study the effect of modal scattering by liner inhomogeneities such as hard-walled strips, under more controlled conditions, an experiment was carried out in the NLR spinning mode synthesizer.

In the spinning mode synthesizer spinning modes were generated at frequencies varying from 400 to 3000 Hz. The target mode numbers were ranging from 0 to 3. These numbers are much lower than the mode numbers found in the inlet of the Tay 650 engine, which powers the Fokker 100. The modes are generated by an array of 9 loudspeakers along the circumference of the duct. Consequently at higher frequencies, also some aliased modes are generated (for mode numbers  $m = 2$  and  $3$ ,  $-7$  and  $-6$  respectively). Due to imperfections in the duct geometry and differences in the loudspeakers, always parasitic modes in the incident acoustic fields are generated. By installing hard-walled strips in axial direction, by means of high speed tape with a width of 5, 10 and 15 cm, the effect of modal scattering could be examined by measuring the incident and the transmitted acoustic field. Measurements for mode determination were carried out in the duct at both sides of the lined section at four frequencies for each target mode. From these, the damping attained by the liners, the insertion loss and transmission loss could be determined. From the experimental results, the following conclusions are drawn.



1. The total in-duct transmitted acoustic energy flux is not much influenced by scattering of target modes, which have a low circumferential mode number ( $m < 4$ ). For target modes with a mode number 0, the transmitted acoustic energy has been decreased somewhat possibly caused by energy transfer to modes with a higher circumferential mode number ( $\Delta IL_{\max} \approx 1$  dB). These modes are better attenuated by the liner. For target modes with a mode number larger than 0, the transmitted acoustic energy flux has been increased somewhat ( $\Delta IL_{\max} \approx 2$  dB).

2. The m-mode spectra of the transmitted field clearly show modulation effects caused by the hard-walled strips. The modulation increases with increasing mode number, except for the target mode number 3. For this mode number a more broadband incident m-mode spectrum was found, which makes it more difficult to establish scattering effects. If an equal part of the surface of the liner is covered by hard-walled strips, scattering is stronger if the width of the strips is larger (2 strips with a width of 15 cm cause more scattering than 3 strips with a width of 10 cm).

3. At some test conditions the highest insertion loss occurred with one strip placed in circumferential direction. This might be caused by sound reflections in axial direction. The transmitted acoustic field of configuration 9 with one circumferential strip installed was characterized by the absence of modes with modes numbers higher than 3. These modes are well attenuated by the liner.

### Recommendations

Further investigation is recommended on the following issues:

1. the effect of scattering of cut-on modes of high circumferential mode order which are typical for turbofan engine intake configurations (mode numbers in the range between 20 and 40). This will be investigated during the 2nd phase of the study with the NLR fan noise model as the noise source.
2. the effect of scattering of cut-off modes on the total radiated acoustic energy in the inlet. For high by-pass ratio turbofans with a subsonically rotating fan, a scattered rotor-alone field (which is initially cut-off) may become cut-on. A non-uniform liner therefore may change the radiation impedance of the source by scattering modes of high order which are initially cut-off to modes of lower order which may be cut-on.

### Acknowledgement

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- <sup>2</sup>Zandbergen, T., *Stator Vane Response due to the Impingement of the Wake of an Unloaded Rotor*, AIAA-paper 89-1125