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MODE DETECTION WITH AN OPTIMISED ARRAY IN A MODEL TURBOFAN ENGINE INTAKE AT VARYING SHAFT SPEEDS

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Modal measurement techniques in engine intakes have been used previously to analyse the generated fan noise. A proven method is to use a wall-mounted array of Kulite transducers and operate the (model) turbofan under constant shaft speeds. A drawback of this method is the large number of (expensive) microphones and acquisition channels needed to obtain complete m-mode spectra at high engine orders. Furthermore, to get a full scan of the m-mode spectra as a function of shaft speed, many measurements are required. The issue of the large number of microphones was addressed by using a sparse array instead of an equidistant array. An array optimisation technique, similar to a technique used for the design of phased microphone arrays for sound source localisation, was used to define such a sparse intake array. This array consists of 100 Kulites and is able to determine without aliasing the modal spectrum from $m = -79$ to $m = +79$, which is appropriate to determine the modal content up to 3 BPF of a modern turbofan. This array was tested in a Rolls-Royce model fan rig at Ansty as a part of the RESOUND project. A new digital data-acquisition system made it possible to simultaneously and continuously record the Kulite pressure data as the engine speed was varied continuously from idle to maximum speed or vice versa, with each acceleration/deceleration lasting for a period of 9 minutes. Time histories of the Kulites were processed giving power spectra of the engine orders, which revealed the rotor locked tonal components. For each rotor revolution, a Discrete Fourier Transform was applied and, after averaging over a number of revolutions, the m-mode spectra were determined. In this way, a full modal scan with respect to shaft speed in a very limited testing time was obtained.

I. Introduction

The principal aircraft and engine manufacturers in Europe are facing increasing pressure to reduce aircraft noise levels. This arises both from the community expectations of improved quality of life and from the need to compensate for the expected growth in air traffic. Several research programmes are carried out, one of which is the RESOUND programme (Reduction of Engine Source Noise through Understanding and Novel Design led by Rolls-Royce), which addresses the challenge of reducing the turbomachinery noise at source. For the reduction of fan noise, the potential of several technologies such as reduced fan tip speed, swept and active stators was investigated.

Tests were carried out in the Rolls-Royce model fan rig at Ansty. In addition to acoustic measurements in the far field, modal measurements upstream of the intake liner with an optimised wall-mounted sparse array of 100 Kulites were performed to quantify the noise benefits. Due to the availability of a new, high-performance data acquisition system[1] at NLR, modal measurements could be continuously carried out during accelerations and decelerations of the fan. Within a data acquisition period of about ten minutes, a full scan of the modal content in the engine intake as a function of shaft speed could be obtained. The optimisation of the sparse array, the modal measurement technique and some preliminary results are described in this paper.

II. Theory

The optimisation technique of the sparse array and the spectral analysis technique for data acquired during engine acceleration and deceleration or ‘sweep’ are separately described hereafter.

Optimisation of the sparse array

The modal content in the intake at a certain frequency can be determined with a circumferential array of

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[±] Senior Research Scientist, Rolls-Royce plc, P.O. Box 31, e-mail: brian.tester@rolls-royce.com microphones. The circumferential pressure field is expressed by

$$p(\theta) = \sum_{m=-\infty}^{\infty} A_m e^{-im\theta} \ . \qquad (1)$$

Microphone locations are θ_k, $k = 1,..,N$. Modal amplitudes can be calculated according to

$$A_m = \frac{1}{N}\sum_{k=1}^{N} p(\theta_k) e^{im\theta_k} \ . \qquad (2)$$

If only a single mode is present, in other words, if $p(\theta) = e^{-i\mu\theta}$, then the array output is

$$A_m = \frac{1}{N}\sum_{k=1}^{N} e^{i(m-\mu)\theta_k} \ , \qquad (3)$$

which gives for $m = \mu$ the amplitude 1. For $m \neq \mu$ a residue will be found depending on the array.

The traditional, equidistant array $\theta_k = 2\pi k/N$ (for $k = 1,..,N$) yields

$$A_m = \frac{1}{N}\sum_{k=1}^{N} e^{2\pi i(m-\mu)k/N} \ , \qquad (4)$$

- $A_m = 1$ for $m = \mu + lN, l \in Z$ (aliasing),
- $A_m = 0$ for $m \neq \mu + lN, l \in Z$ (no side lobes).

A practical solution to avoid aliasing is to take the number of microphones at least equal to two times the mode number, for which the first radial mode is cut-off. However, at higher engine orders, when many circumferential modes are propagating, this would require a large number of microphones.

As a spin-off from the development of phased microphone arrays for sound source location^{2}, a different approach was taken. By the use of a non-equidistant array, one can increase the modal range from $-(M-1)/2 \leq m \leq (M-1)/2$ with $M > N$ and with the number of microphones *N* unchanged. This will be at the expense of the occurrence of side-lobes, which one can try to minimise. One could either minimise A_m, equation (3), for $\mu - M < m < \mu + M$ and $m \neq \mu$ or minimise the summation *J*, which is applied here.

$$J = \sum_{m=\mu-M, m\neq\mu}^{\mu+M} |A_m|^2 = \frac{2}{N^2}\sum_{m=1}^{M}\left|\sum_{k=1}^{N} e^{im\theta_k}\right|^2 \qquad (5)$$

This expression is independent of μ and can be minimised as a function of the parameters θ_k . Since the derivatives of *J* can be evaluated analytically, this minimisation could be done relatively quickly using the Conjugate Gradient Method.

The optimised array for $N = 100$ and $M = 159$ ($-79 \leq m \leq 79$) is given in figure 1. The residual response in dB shows the presence of side lobes (Fig. 2). Note that equation (2) is used to determine the modal spectra, which implies that no additional weighting functions are used (e.g. depending on the arc segment covered by the microphone). The maximum side lobe value, which is equal to the dynamic range, is 0.1229 (-18.2 dB). So, the modal range with 100 microphones has been increased at the expense of the occurrence of side lobes. The dynamic range may decrease somewhat further, when several dominant modes are present. With four dominant modes the value has decreased to 14.7 dB (Fig. 3).

In theory, it is possible to enlarge the signal/noise ratio by subtracting the side lobe spectrum of a dominant mode from the total spectrum. This will be investigated further. Note that a precise knowledge of the Kulite sensitivities is then required.

Spectral analysis on data acquired at sweep conditions

For the determination of fan noise, it is common practice to perform two types of acquisitions during engine sweeps:

- A data acquisition with the sampling process being coupled to rotation of the shaft (also denoted as external clock data).
- A data acquisition with a fixed sampling frequency governed by the internal clock of the acquisition system. (internal clock data).

In previous experiments, the so-called phase-locked time domain averaging technique was applied on the external clock data. The cross-power matrix was established for the internal clock data. The latter data suffer from the mismatch between the fixed time window of a FFT processing and the varying period of one revolution of the shaft leading to spectral leakage. The amount of leakage is strongly dependent on shaft speed. Modal spectra can be determined from both internal and external frequency spectra.

In the present experiment, data acquired with the internal clock are used to both obtain the auto-powers and the simulated phase-locked time domain averaged spectra (though also external clock data were acquired for backup and for benchmarking the new data acquisition system). The 1-p signal (one pulse per revolution of the shaft) is used to determine the varying number of samples acquired per revolution. The stepwise determination of the spectra is as follows:

Step 1

The trigger times t_j are determined (Fig. 4). These trigger times are defined as the moment during one period (revolution), when the (positive or negative) derivative of the 1-p signal reaches it maximum. The period lengths are updated using the found values for t_j.

Step 2
A Fourier transform for each channel and time interval is performed:

$$p^k_{j,n} = \frac{2}{t_j - t_{j-1}} \int_{t_{j-1}}^{t_j} s^k(t)\exp\left(-2\pi i n \frac{t - t_{j-1}}{t_j - t_{j-1}}\right) dt, \qquad (6)$$

where $s^k(t)$ is the time signal in channel nr. *k*. Since the number of samples in an interval $t_j - t_{j-1}$ is in general not a power of 2, an FFT is not possible. Therefor, the discrete Fourier transform is simply evaluated as:

$$p^k_{j,n} = \frac{2}{v_{\max}} \sum_{v=1}^{v_{\max}} s^k(\tau_v)\exp\left(-2\pi i n \frac{\tau_v - t_{j-1}}{t_j - t_{j-1}}\right), \qquad (7)$$

where $t_{j-1} \le \tau_1 < \tau_2 < .... < \tau_{v_{\max}} < t_j$.

Step 3:
The spectra are averaged in two different ways, with a specified number of averages *S* (50 for sweeps)

$$\text{"Complex average": } C^k_n = \frac{1}{S} \sum_{j=1}^{S} p^k_{j,n} \qquad (7)$$

$$\text{and "Auto-power average": } A^k_n = \frac{1}{S} \sum_{j=1}^{S} \tfrac{1}{2} \left| p^k_{j,n} \right|^2 . \qquad (8)$$

By complex averaging, the non-periodic noise (broadband noise) will be filtered out.

Step 4:
The modal amplitudes are calculated from the complex averaged spectra of *N* Kulites:

$$B_{m,n} = \frac{1}{N} \sum_{k=1}^{N} C^k_n e^{im\theta_k} , \qquad (9)$$

where θ_k is the angular position of the *k*-th transducer.

III. Experimental Set-up

Test facility

Tests were carried out at the ANCTF (Ansty Noise and Compressor Test Facility, Fig. 5) of Rolls-Royce. The large anechoic room has dimensions of 46x37x12 m^3. A model turbofan of 0.86 m diameter in the present test is mounted in a wall of the anechoic room at a height of about 4 m. The model turbofan operated in intake configuration consists of a one stage compressor, with 26 wide chord fan blades, 58 ESS vanes (Engine Section Stator) in the core duct and 58 swept OGV vanes (Outlet Guide Vanes) in the by-pass duct (Fig. 6). A linear SDOF (Single Degree Of Freedom) segmented liner with 8 splices of 2 cm width is mounted upstream of the fan. Treatment L over D ratio is 0.35. The optimised array of 100 Kulites is located upstream of the liner. Air is drawn into the intake through an intake flare and a Turbulence Control Screen. The fan is driven by an electric motor of 10 MW. Fan rotational speed varies from 4000 rpm (idle) to 10,191 rpm (fan design speed = 100%).

Pressure transducers of the intake array

Modified Kulite XT-190 piezo resistive pressure transducers of differential type were used in the array, which are the same as previously used for flight tests on a Fokker 100[3]. Nominal range is 5 PSI. The dimensions of the transducers are a body length of 40 mm and a diameter of 3.86 mm. Temperature compensation is specified for a thermal sensitivity shift of less than 1% in the temperature range from –35 °C to 20 °C. The resonance frequency is above 80 kHz, ensuring a flat amplitude characteristics and negligible phase differences between the transducers in the 0 to 10 kHz frequency range. Combined non-linearity and hysteresis is within 1% of full-scale.

The differential transducers were used in “sealed gage mode”, the volume beneath the diaphragm was closed. The transducers were calibrated in an end plate of an impedance tube of 100 mm diameter using pure tone sound of 1000 Hz with a B&K 4135 ¼ inch microphone as reference.

Data acquisition system

The data are acquired with a new modular data acquisition system[1], so-called VIPER, made to the specifications of DNW-LLF and NLR by GBM mBH. Maximum number of channels per front-end is 48. The modular system can be extended to a complete system of 960 channels with a sampling rate 200 kHz per channel. DNW-LLF and NLR at present each have a system of 128 channels, consisting of two VIPER units of 48 channels and 1 unit of 32 channels. For the present test, a system with 176 (3x48 and 1x32) channels was used. In addition to the signals from the 100 Kulite array in the intake, OGV mounted Kulites were recorded. Total number of measurement channels was 165. General features of the system are:

- Simultaneous acquisition on all input channels.
- High speed over-sampling A/D converters.
- 16 bits resolution.
- Integrated transducers conditioning units and amplifiers.
- Maximum continuous sampling rate of 200 kHz per channel with two hard-disks installed in each front-end. Maximum acquisition time only limited by total hard-disk capacity.
- Signal to noise ratio better than 70 dB at a gain of 1000x.
- Capability to on-line resample and store the data on basis of a reference signal (tracking ratio tuner functionality included).

During engine sweep operations with a maximum elapsed time of 9 minutes, a number of 165 channels were recorded with an internal sampling frequency of 44 kHz. Additionally, for benchmarking the new system, phase-locked acquisitions were done (external sampling) with 256 samples per revolution. Note that the results presented in this paper are based on the internal clock data.

Test programme
Modal measurements in the intake were taken at constant and varying nominal shaft speeds according to table 1 (T_{ref} = 288.15 °C). The fan was operated at two aerodynamic conditions denoted by low and high working lines. Maximum shaft speed is determined by the maximum allowable bearing vibration levels and dependent on ambient temperature.

Table 1: Overview of the shaft speed, 2 working lines

Constant shaft speed	Idle, 50, 60, 70, 75, 80, 85, 90, 95 and 100%
Engine sweeps (660 rpm/minute)	Decels max. to 40% Accels 40% to 90%

IV. Results

The results shown here are to illustrate the mode detection technique under decelerations of the fan. Benefits from the new noise reduction technologies investigated in the RESOUND project are not discussed in this paper. Note that all results shown here are measured at “high working line” conditions with highly loaded wide chord fan blades and measured with the optimised circumferential Kulite array upstream of the liner.

Subsonic fan
Auto-power spectra of mikes 1, 2 and 3 at 60% reduced engine speed, acquired under steady and sweep conditions, are compared in figure 7. The sound field in the intake of a subsonically rotating fan is dominated by the blade passing frequency and harmonics. The differences in broadband levels between both acquisitions for individual microphones are within the range of ±1 dB. The differences in sound pressure levels at blade passing frequency and harmonics are larger, e.g. 3 dB for mike 1 at 1 BPF and 7 dB for mike 2 at 2 BPF. However, these differences are of the same order of magnitude as the differences between the microphones 1 to 3 at steady or sweep conditions. A comparison between the modal spectra at 1 BPF acquired from both acquisitions at 60% engine speed gives a more consistent result (Fig. 8). Note that only a range of 20 dB is taken, which corresponds to the dynamic range of the optimised array. The differences in levels between a number of dominant modes is less than 1 dB (m = -2, 2, 10 and 11). For other modes the differences are somewhat larger (4 dB for m=-14 and 2 dB for m = -6).

It is concluded that at subsonic conditions the measurements under sweep conditions reveal similar auto-power and modal spectra at 1 BPF as those acquired under steady conditions.

Supersonic fan
Auto-power spectra of Kulites 1, 2 and 3 at 80% reduced engine speed, acquired under steady and sweep conditions, are compared in figure 9. The presence of buzz saw noise is noted (for frequencies lower than engine order 10 and for frequencies near 2 and 3 BPF). The spectra of all microphones are very similar. The modal spectra at 1 BPF show a good agreement (Fig. 10). The differences between the dominant mode levels are less than 1 dB.

The new modal measurement technique under supersonic conditions even reveal better results than under subsonic conditions. This is due to the dominant rotor alone field, where at each frequency only a few modes prevail.

Modal spectra at 1 BPF
The advantages of a measurement technique under sweep conditions can be further exploited when modal spectra at fixed frequency are determined as a function of engine speed. This has been done for the dominant modes at blade passing frequency (Fig. 11). Note that besides dominant mode levels also the 100 microphones averaged SPL at 1 BPF (denoted by SPL in the legend) and the summation level of the dominant modes (denoted by Total) are given. For shaft speeds above 80%, the sound field at 1 BPF in the intake is fully dominated by the rotor alone mode (m = 26). However at transonic and subsonic conditions (i.e. for engine speeds between about 50% and 75%), the sound field is fully dominated by scattered modes, which are generated, essentially, by the interaction of the rotor-alone mode with the spliced liner. The mode spacing number is 8, which equals the number of splices. Strong modal scattering by splices and other intake inhomogenities was also previously found from flight tests[3]. In the cause of the RESOUND project, an improved liner has been used.

V. Conclusions

As a spin-off from the development of microphone arrays for source location, an array optimisation technique was used to define a sparse intake array of 100 Kulites capable to determine the modal content up to 3 BPF of a modern turbofan. This array mounted upstream of the intake liner was tested in a Rolls-Royce model fan rig at Ansty as a part of the

RESOUND project. The circumferential modal spectrum in the experiment ranges from mode –79 to +79 without aliasing. A new digital data-acquisition system made it possible to simultaneously and continuously record the Kulite pressure data as the engine speed was varied continuously from idle to maximum shaft speed or vice versa, with each acceleration/deceleration lasting for a period of 9 minutes.

Time histories of the Kulites were processed giving the standard power spectra at the engine orders, which revealed the rotor locked tonal components. Instead of re-sampling, the Digital Fourier Transform was used and m-mode spectra were determined. In this way, a full modal scan with respect to shaft speed in a very limited testing time was obtained, which gave valuable data for the assessment of fan noise reduction means.

Further work on the development of an optimised acoustic array is being considered. The modal measurement range can be enlarged by increasing the number of microphones and/or by selecting a different ratio between the modal range and the number of microphones (1.6 in the present experiment). Furthermore, the suppression of side lobes by improved post-processing software should be further investigated.

Acknowledgement

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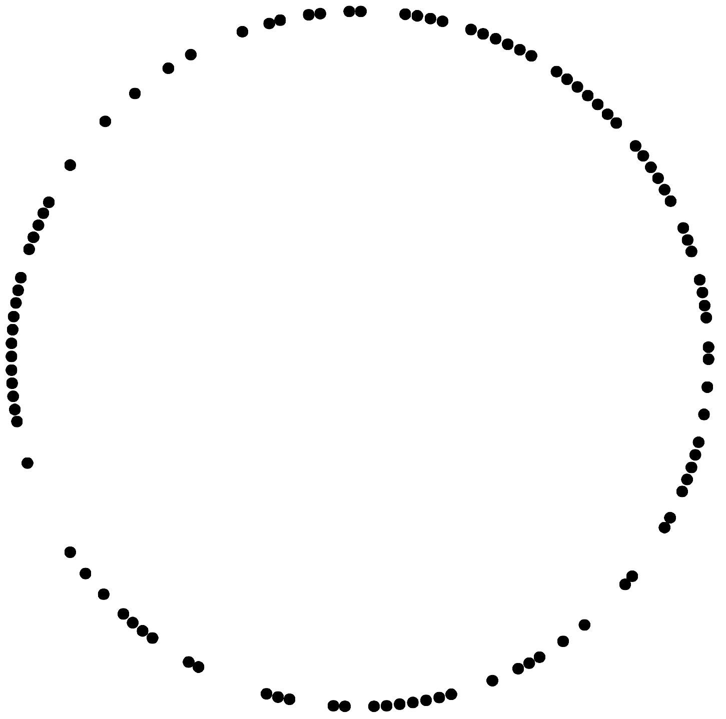

Fig. 1 **The optimised circumferential array, 100 microphones, modal range –79 ≤ *m* ≤ +79**

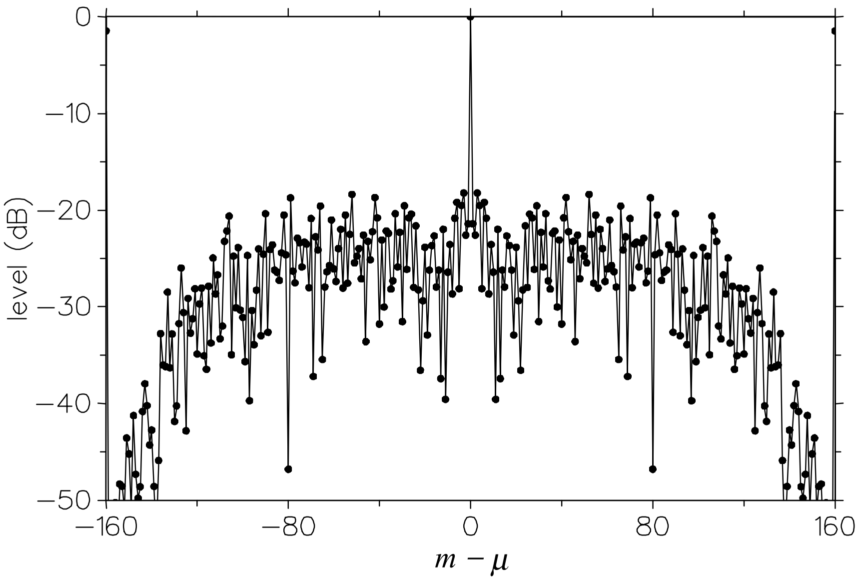

Fig. 2 Residual modal response function of the sparse array, dynamic range is 18.2 dB

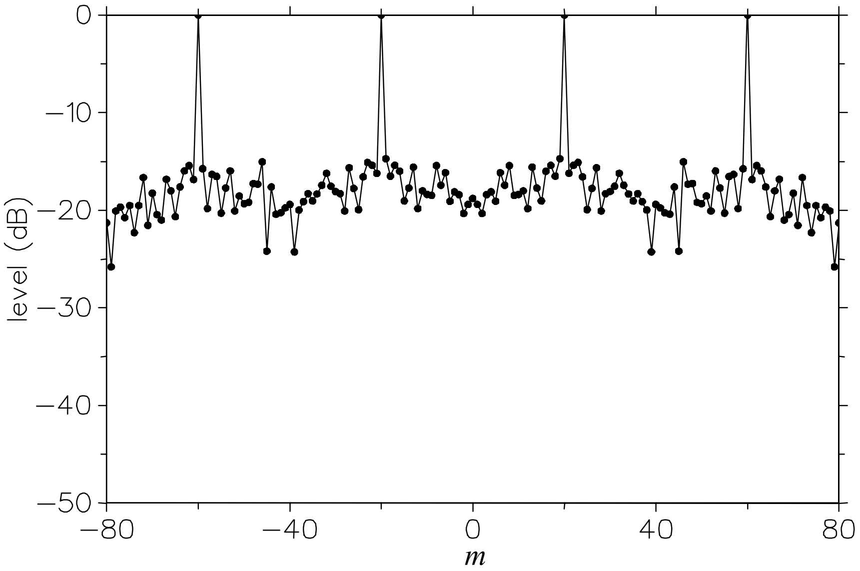

Fig. 3 Modal response function with four dominant modes, dynamic range is 14.7 dB

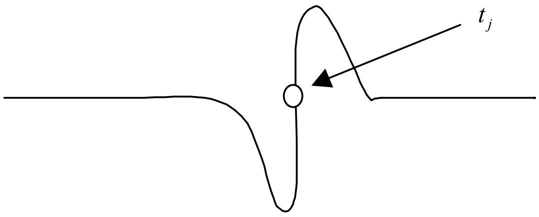

Fig. 4 Sketch of 1-p signal used to determine the period of one revolution of the shaft

Fig. 5 The Rolls-Royce Ansty Noise and Combustion Test Facility (ANCTF)

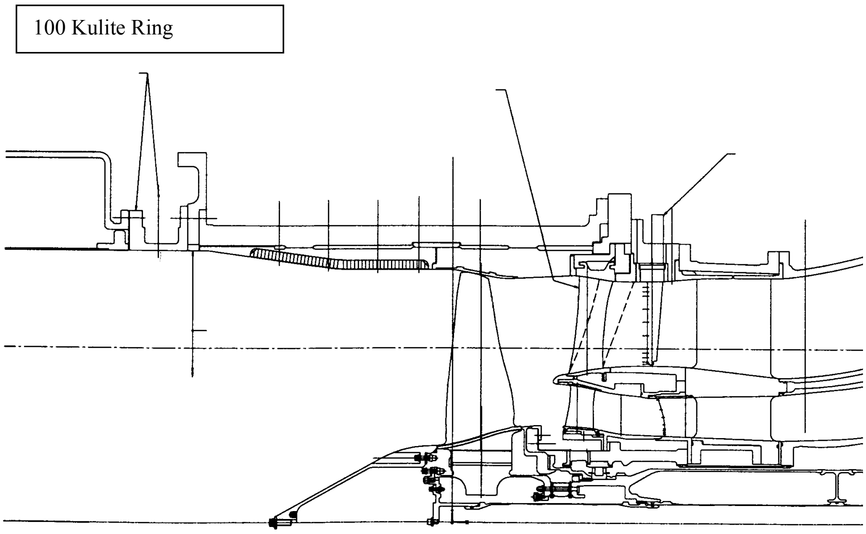

Fig. 6 The 0.86 m diameter model fan rig

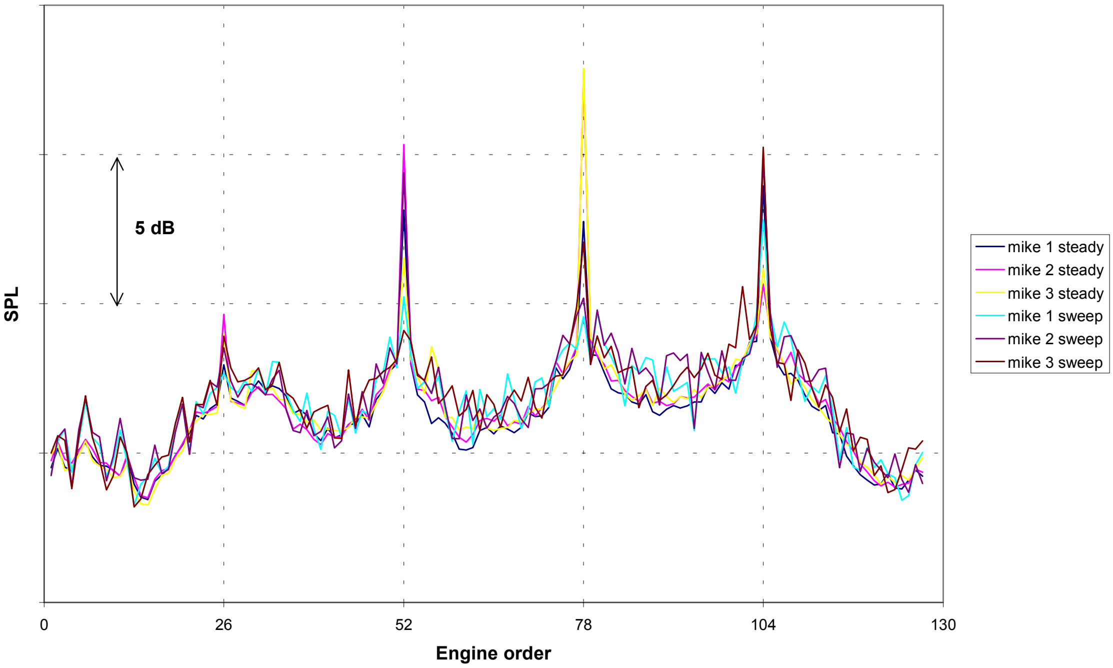

Fig. 7 Comparison between measured auto-power spectra of microphones 1, 2 and 3 of the sparse array, steady and sweep conditions, 60% reduced engine speed, high working line

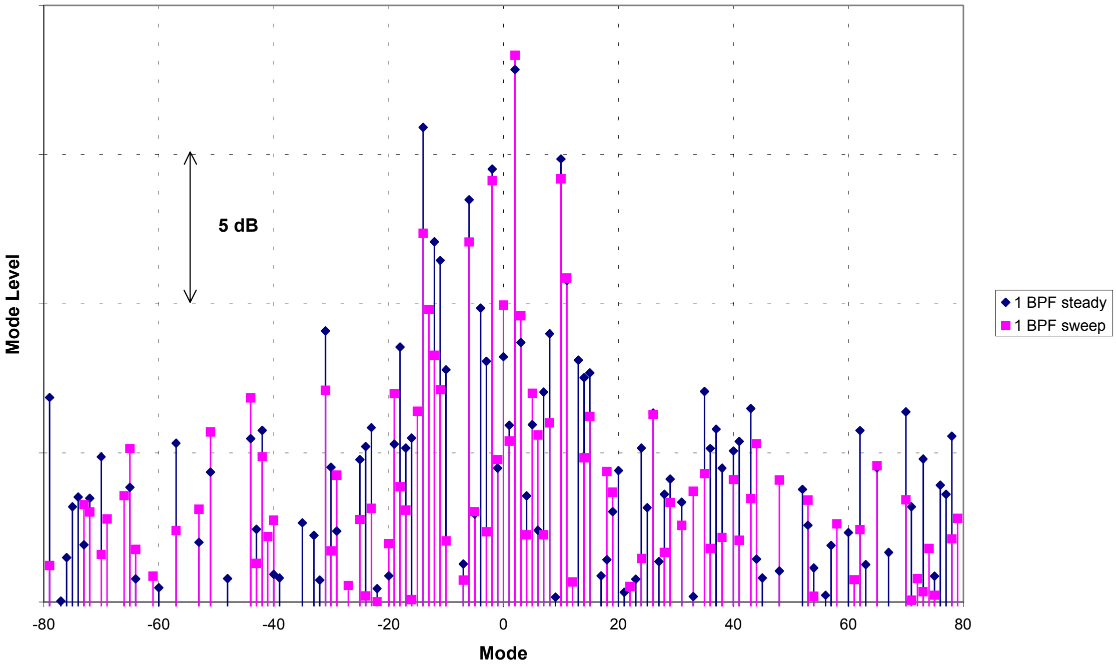

Fig. 8 Comparison between measured circumferential modal spectra at 1 BPF, steady and sweep conditions, 60% reduced engine speed, high working line

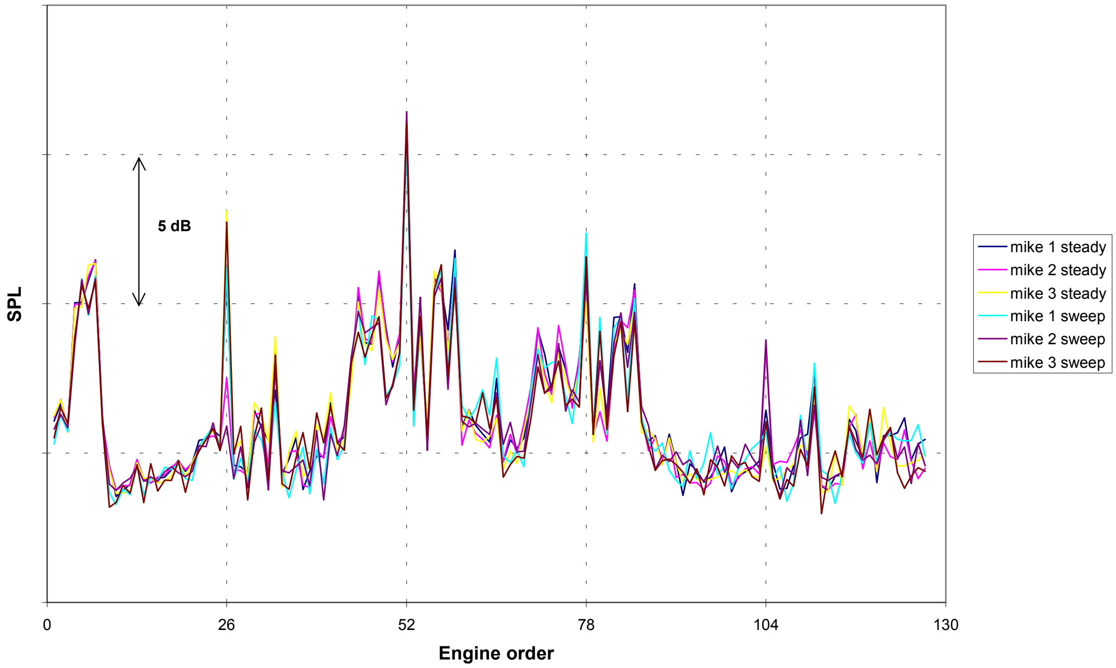

Fig. 9 Comparison between measured auto-power spectra of microphones 1, 2 and 3 of the sparse array, steady and sweep conditions, 80% reduced engine speed, high working line

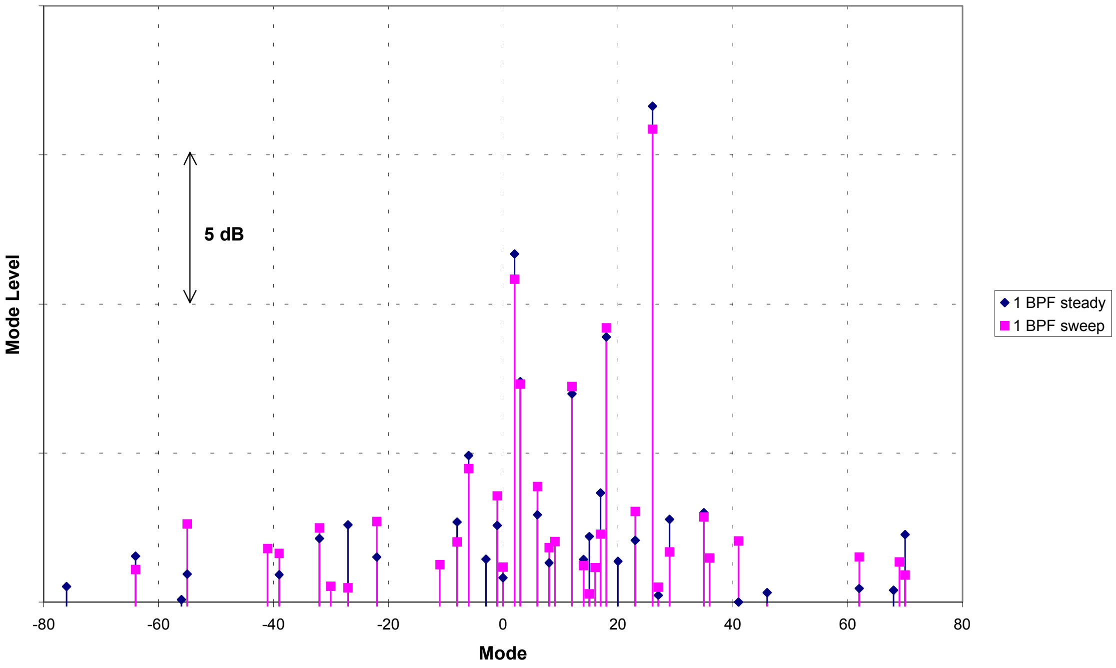

Fig. 10 Comparison between measured circumferential modal spectra at 1 BPF, steady and sweep conditions, 80% reduced engine speed, high working line

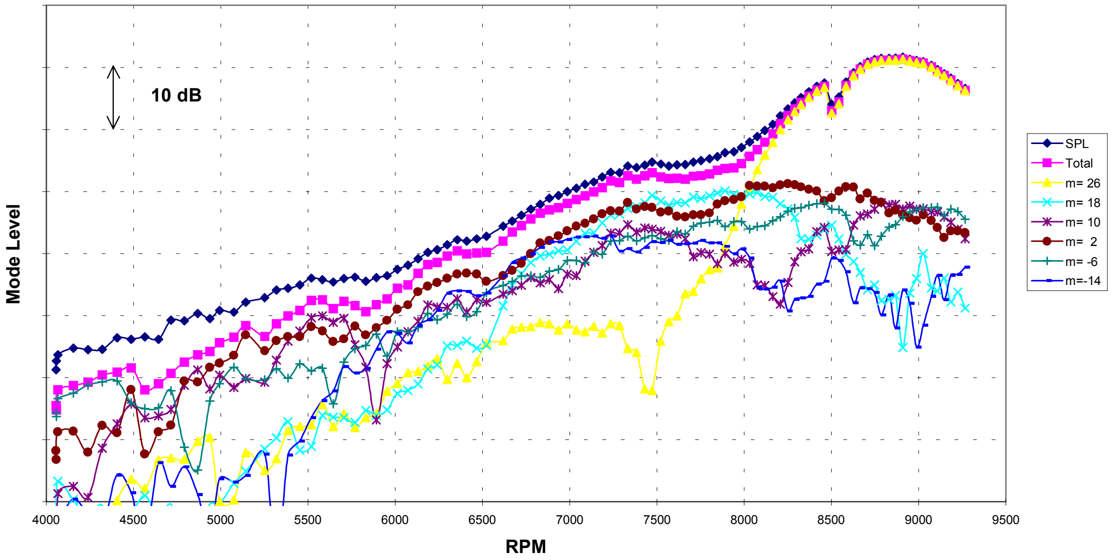

Fig. 11 **Dominant m-mode spectra at 1 BPF as a function of shaft speed**