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Analysis of Dynamic Data in Aeroengine Testing

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Introduction

This paper presents some special data analysis on high frequency measurements in aeroengine testing. Flow induced pressure fluctuations - sometimes named acoustic resonance phenomena - generate noise or high vibration levels in turbomachines /1/. The typical analysis methods in aerodynamics use the time domain. For a better understanding of unsteady aerodynamic phenomena, it is helpful to apply standard acoustic measurement techniques in the frequency domain.

In aeroengine testing, powerful workstations with multi-frequency analyser software are used for investigations in the time and frequency domain. Several traditional analysis techniques can be used for the analysis of unsteady signals /2/. This paper shows the methodology of aeroengine investigations. A combination of data of high sampling rates and data of low sampling rates like speed or traversing positions allow localisation and interpretation of resonance generation mechanisms. We will present a technical application for data reduction and correlation analysis.

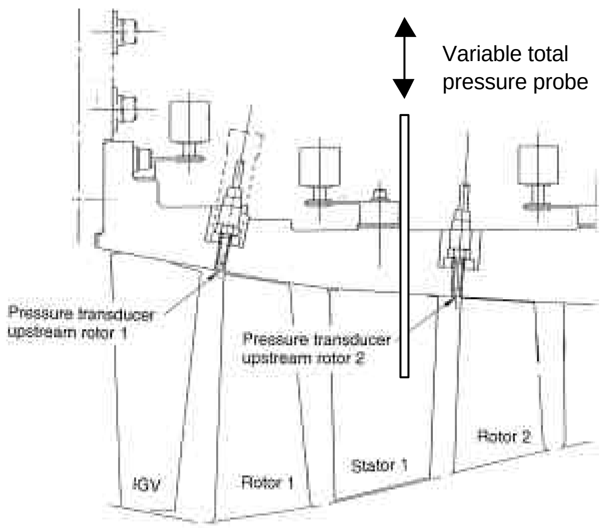

Fig.1: Front sketch of the compressor with experimental set-up of the pressure transducers.

Experimental Set-up and Measurement Technique

A modern civil aeroengine consists of several axial flow machines (fan, high pressure compressor,

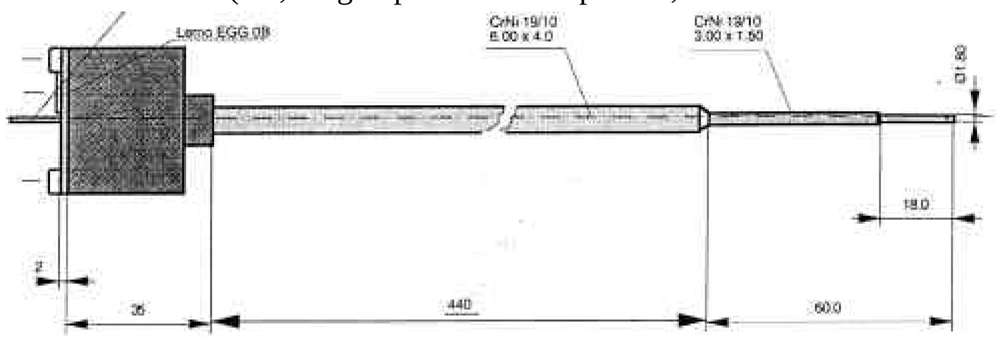

Fig.2: Schematic of the fast response total pressure probe, compare /3/.

turbines). Access for measurement equipment to the gas path and to the rotating parts is restricted. If strain gauge measurement on the rotating blades is impossible, measurement of pressure fluctuations to monitor the dependency of rotating blade vibration on operating conditions is common. Fast responding pressure transducers (Kulite XTE 190, Kulite XCE062 or Endevco 8540) are mounted flush with the inner casing wall of the gas path, see Fig.1. Standard measurement positions for rotor blade vibration monitoring are upstream of the rotor blades leading edges in a multi-stage compressor. The most highly-stressed structural parts are the long thin blades in the front stages of the compressor with high aerodynamic loading. Measurement of unsteady wall pressure fluctuations allows the qualitative flow conditions to be determined. The amplitude of the pressure wave decreases with the inverse of the distance (~1/x). In addition, the amplitude value measured by piezoresistive pressure transducers depends the ambient conditions of the transducer, i.e., the temperature. Only with well known or constant ambient conditions as well as microphone calibration is it possible to measure amplitudes of pressure fluctuations (cf Gossweiler (1993)/4/).

Estimation of flow conditions in jet engines is possible with the knowledge of the frequencies of flow disturbances. The frequencies of interest are related in amplitude to the amplitude of the blade passing frequency of the adjacent rotors.

A fast responding total pressure probe, Fig.2, was used to investigate the unsteady flow along the radial blade height in the high pressure compressor. We tried to find a relation between the vibration and the location of total pressure fluctuations in the blade trailing edge region of the first rotor. For our measurements the sensor position was in the stator passage downstream of the rotor, Fig.1. The probe could be moved radially.

The complete transient data information was recorded on a digital data acquisition unit. A HP VXI E1498A UNIX workstation controlled the data acquisition and the processing unit, a HP VXI E1432A with anti-alias protection, FFT and averaging processor on each channel. A standard multi-channel FFT-Analyser software (PAK by Müller-BBM VibroAkustik GmbH 82141 Planegg near Munich, Germany) evaluated the recorded data.

The same data acquisition unit recorded parameters with a slow rate of change (i.e., the radial position of the total pressure probe or the speed signal). Plots of measured data versus different parameters allow conclusions of the location of the generation mechanism of the pressure fluctuation in the high pressure compressor (HPC).

3-D plots (Z-Mode) of frequency versus speed or radial height and coloured amplitude are used for data reduction. To minimise noise effects each plotted spectrum in the Z-Mode is an arithmetic average of 4 measured spectra. The frequency spectra contain 1600 lines with a frequency resolution of 8 Hz thus allowing an averaged spectrum every 0.5 second. The total pressure probe is continuously moved radially from the blade tip to the hub in approximately 3 minutes. All other operating conditions are constant during this maneuver.

Cross-Correlation Measurements

A cross-correlation method was adapted to determine the propagation direction of tonal frequency components /5/. A propagation-time analysis of the unsteady pressure field of two locations allows conclusions of the propagation direction and, in certain circumstances, of the propagation velocity. Two observers spaced at Δx register a relative time Δt for a pressure field propagating from one to the other. Assuming a correlated time function of the pressure fluctuation at both locations, i.e. the averaged amplitude spectra at two locations are equal (G_{11}=G_{22}), the cross-power-spectrum can be formulated as:

$$G_{12}(\omega) = G_{11}(\omega) e^{i\omega\Delta t} \quad . \qquad (1)$$

G_{11} represents the auto power spectrum at the location 1, ω the angular frequency, and Δt the time delay between the two signals. The phase angle $\hat{\varphi}_{12}$ of the cross-spectrum in eq.(1) is a function of the propagation time

$$\hat{\varphi}_{12} = \omega \Delta t \quad . \qquad (2)$$

The sign of the phase angle represents the direction of the coherent sinusoidal components. The measured power spectra at two locations are dependent upon the coherence function. The coherence function shows these signal parts which dominate in both signals for a sufficient number of averages. The definition of the coherence function reads

$$\gamma^2 = \frac{G_{21}(f) \cdot G^*_{21}(f)}{G_{11}(f) \cdot G_{22}(f)} \qquad (3)$$

with the complex cross-power spectrum G_{21}, its complex conjugates G^*_{21} and the power spectra at location 1 and 2. The value "1" in the coherence function γ^2 signifies either that one signal causes the other, or that both signals have the same origin. The value "0" shows an independence of the signals from each other. The power spectra and the cross-power spectrum are separately averaged. Increasing the number of averages increases the statistical reliability of the measurement results.

Experimental Results

Results are shown for high-pressure compressor tests. Fig.3 shows the Z-Mod plots versus speed of the pressure fluctuations on the casing wall (top) and the stress of the rotating blade (bottom) for a slow acceleration of the engine. The upper diagram (see Fig.3) displays a frequency span of 8.5 kHz for the wall pressure and the lower diagram a frequency span of 3 kHz for the blade vibrations. Notice, in Fig.3 the frequency spans are not corresponding to each other caused by the different frames of

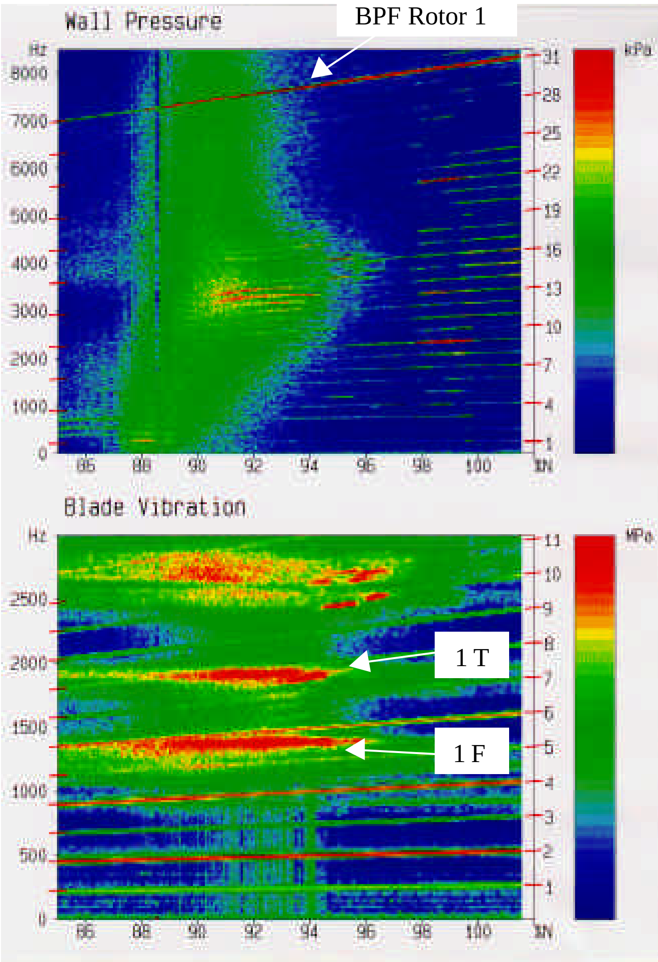

Fig.3: Comparison of blade vibrations and wall pressure fluctuations of HPC Rotor 1.

reference (pressure = fixed frame, stress = rotating frame). The blade passing frequency (BPF) shows in the wall pressure picture as a thick 31 engine order (EO) line. Between 89.5-96.5 % of rotor speed, high wall pressure fluctuations occur. At this speed range high blade vibration amplitudes for the 1F (flap) and 1T (torsion) modes build the maxima and do not intersect with the engine order lines. Detailed information of the physical effect is given in /1/. Averaging and carefully chosen frequency resolution results in detailed pictures.

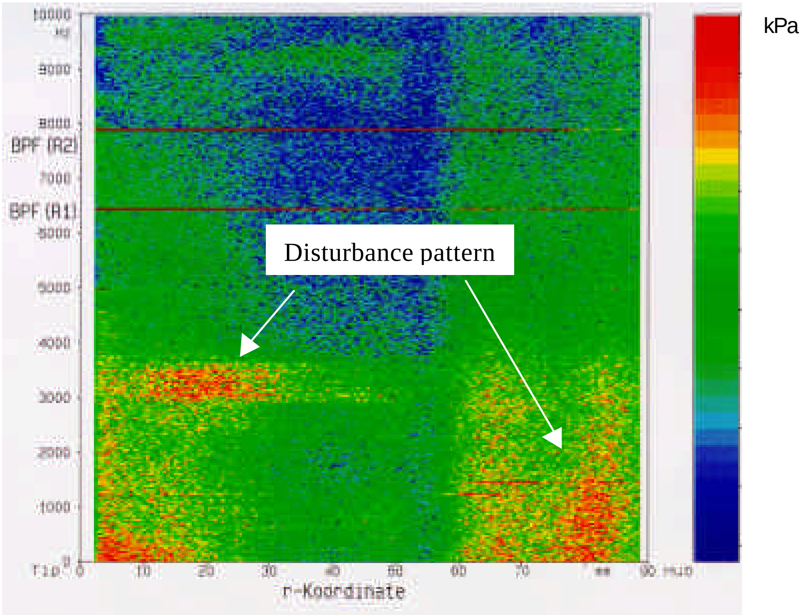

Fig.4: Radial distribution of total pressure fluctuation, 90% aerodynamic speed.

Total pressure fluctuation measurements may help to localise the radial extension of the flow disturbance pattern which generates the blade vibrations (shown in Fig.3). The total pressure fluctuations correspond with flow velocity fluctuations. Our measurements show that these pressure fluctuations may be used to estimate the flow conditions and answer the question: Is the flow separated in the hub or in the tip region of the blade or is it not separated at all? At constant operating conditions the fast responding probe (Fig. 1) was moved radially downstream of the rotor 1 in the stator 1 passage.

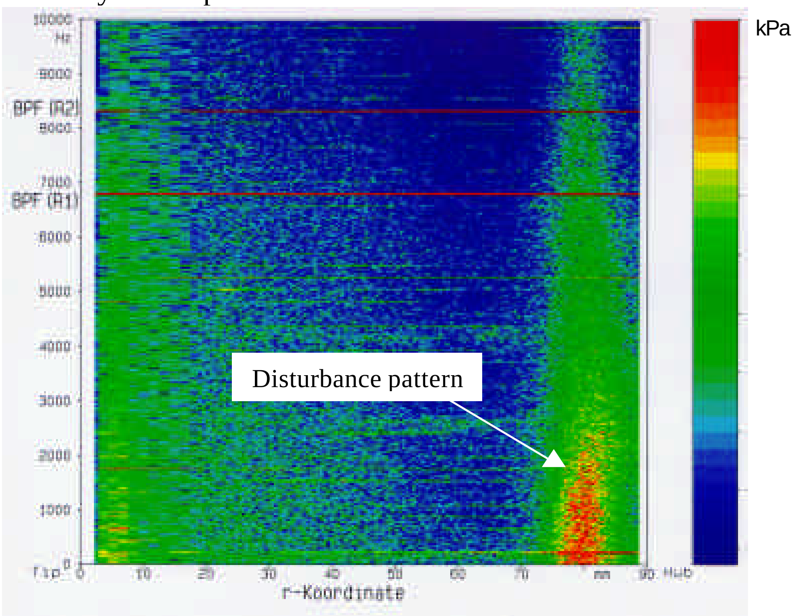

Fig.5: Radial distribution of total pressure fluctuation, 95% aerodynamic speed.

Fig.4 and Fig.5 show distributions of total pressure fluctuations radially measured for different aerodynamic speeds at constant operating conditions. The operating conditions are close to the compressor working line for this compressor rig test. Fig.4 shows high amplitudes near 3000 Hz between tip casing wall and a 30 mm position from the casing wall. Also, in the hub region the total pressure fluctuations are high which are caused by high blade loading and mismatched blades for those operating condition. At 95% of aerodynamic speed in a narrow region close to the hub wall the total pressure fluctuation has high levels, Fig.5. The disturbance is caused by the clearance flow through the hub gap of the variable stator 1. A quick overview of the flow conditions along the radial height in Fig.4 and 5 shows the progress of measurement analysis technique.

At constant operating conditions the phase difference of two adjacent transducers in the casing wall on the circumference can be used to determine the propagation direction of the flow disturbance, Fig.6. The phase angle of the averaged cross power spectrum, equation (1) and (2), results in the distance of two measurement locations in the aerodynamic propagation velocity. This proofs a relevant coherence between the two measurement signals, Fig.6 mid. In this case the disturbance pattern is propagating with app. half the rotational speed of the rotor, leading to the conclusion of a classical flow separation as the generation mechanism of this phenomenon.

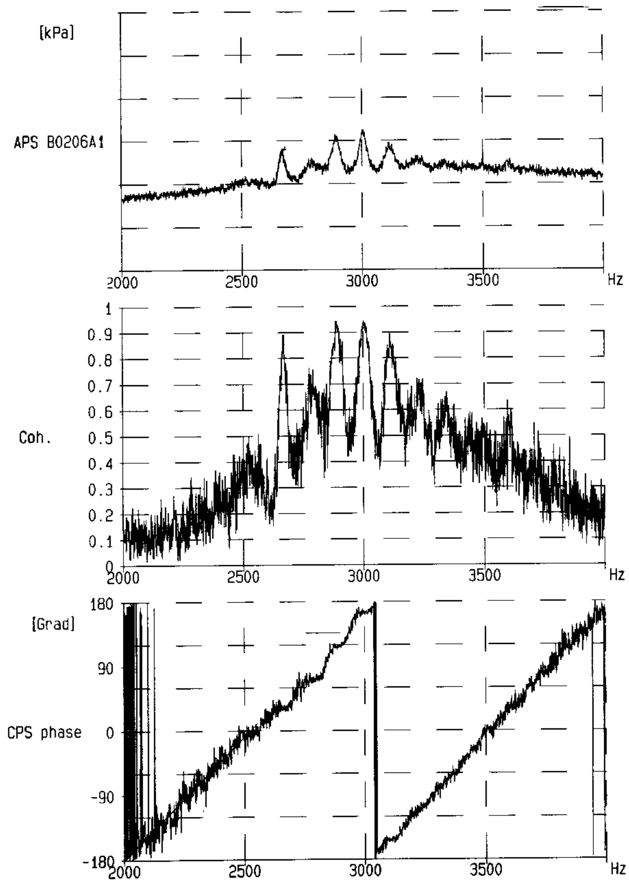

Fig.6: Averaged power spectrum, coherence spectrum and phase spectrum of two adjacent wall pressure measurement positions along the circumference.

Fig.7 shows a further application of the coherence function. The coherence of two wall pressure fluctuations on different axial positions is plotted in this diagram. The spectrum in the front stage (top plot) shows a disturbance which looks like it disappeared in the wall pressure fluctuation of compressor stage 10. The coherence function shows that there is still a coherent structure in the signal below the noise level, although the coherence level is less than 0.5.

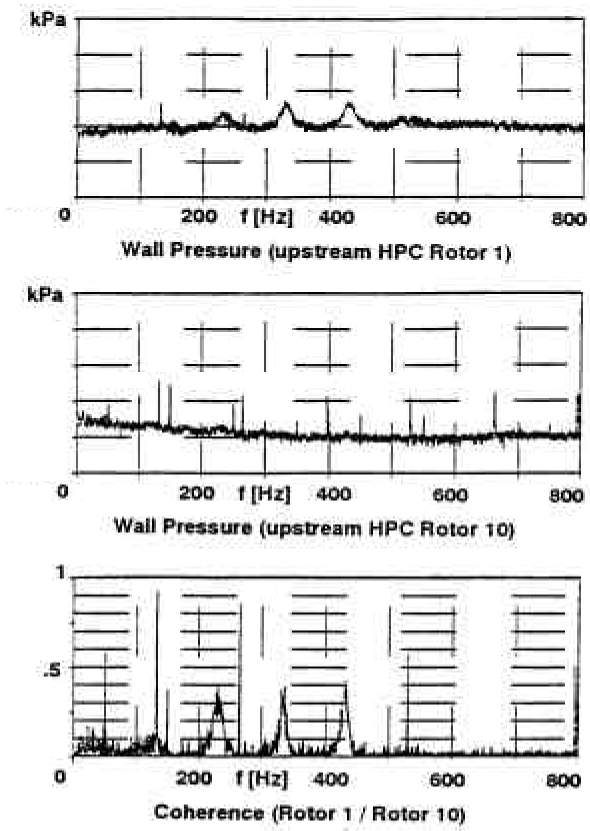

Fig.7: Averaged power spectra upstream of Rotor 1 and upstream of Rotor 10 and coherence spectrum of these wall pressure fluctuations /6/.

Conclusions

Some applications of signal analysis for jet engine testing are described. The Fast Fourier Transformation (FFT) is a well established and known technique for acoustics and vibration analysis. To detect flow separation or losses in aerodynamics it is not usual to use averaged frequency spectra. As demonstrated, continuous frequency analysis of a moving, i.e. traversing, probe gains a special flow visualisation. Changes in flow condition are very obviously depending on operating conditions.

Correlation analysis in the frequency domain may be used as a helpful tool for investigations of propagation speed of pressure waves. A high coherence level is needed for easy interpretation.

Connection and transfer path of pressure waves are detectable using the coherence spectrum. A well averaged coherence spectrum shows connections of the signal which are sometimes not visible in power spectra.

Powerful analysis computers and reliable software are indispensable tools in experimental data analysis of industrial applications in aerodynamics.

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