Extraction of the acoustic modal content of a turbofan engine in non stationary conditions using order analysis

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Abstract

A modal analysis of tonal fan noise is applied to deceleration measurements collected during the European project TurboNoiseBB at the Anecom test facility. Measurement data are preprocessed using two approaches for order extraction, one based on angular resampling of signals and the other based on instantaneous extraction of the complex envelopes. The instantaneous modal content is then obtained using modal identification and results from both preprocessing methods are compared. The azimuthal mode content of the three first Blade Passing Frequencies (BPF) is obtained through an iterative Bayesian inverse approach. Particularly the modal spectrum for the second BPF shows an interesting pattern with peaks and troughs throughout the deceleration. It suggests that detected modes are influenced by the azimuthal distribution of probes.

1 Introduction

The analysis of acoustic fields in turbofan engines is a challenging task due to the geometrical complexity of the ducts, the multiple noise generation mechanisms and the poor signal-to-noise ratio (SNR) related to the strong flow noise. Ducted fan noise has been analyzed with several mode detection techniques [1–8]. Recently, a Bayesian approach has been applied to estimate the broadband modal content at steady operating conditions [9]. The data has been collected during a fan test campaign carried out in the framework of the EU project TurbonoiseBB at the Anecom facility. The current work extends this technique to the case of deceleration tests obtained during the same experimental campaign. The focus is given to the tonal components of the fan noise at the blade passing frequency (BPF) and its first harmonics.

2 Theory

For a cylindrical duct, the in-duct circumferential pressure field can be expressed as a weighted sum of azimuthal modes by

$$\hat{p}(\phi) = \sum_{m=-\infty}^{\infty} C_m \mathrm{e}^{\mathrm{j}m\phi}, \tag{1}$$

with C_m the modal amplitudes.

In practice, this decomposition is associated with a circumferential array of microphones characterized by the azimuthal coordinate ϕ of the microphones. It can be expressed in a matrix-vector notation as,

$$\mathbf{p} = \mathbf{\Phi c} + \mathbf{n}, \tag{2}$$

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with $\mathbf{p} \in \mathbb{C}^K$ a vector of complex pressure coefficients at a given angular frequency ω (obtained from a Fourier transform), $\mathbf{n} \in \mathbb{C}^K$ a vector accounting for additive noise, $\mathbf{c} \in \mathbb{C}^L$ a vector containing the *unknown* complex coefficients and $\mathbf{\Phi} \in \mathbb{C}^{K \times L}$ a matrix with elements $e^{jm\phi}$, for discretized m and ϕ. K is the number of microphones and $L = 2M + 1$ where M is the highest resolved azimuthal order depending on the array configuration.

Beamforming is a well-known technique to solve Eq. 2 for the modal coefficients. This technique has however a limited resolution and poor quantification results. In addition it assumes that modes are uncorrelated, which is not the case for tonal noise due to rotor-stator interaction. To overcome these limitations, the iterative Bayesian Inverse Approach (iBIA) proposed in [9] is applied in the present work. This approach is briefly described in the next section.

2.1 Bayesian approach

The Bayes' theorem gives an estimate of $\mathbf{c}$ given the measurements $\mathbf{p}$ by:

$$[\mathbf{c}|\mathbf{p}] = \frac{[\mathbf{p}|\mathbf{c}][\mathbf{c}]}{[\mathbf{p}]}, \tag{3}$$

where $[\mathbf{p}|\mathbf{c}]$ is the probability density function (PDF) of the likelihood model, $[\mathbf{c}]$ is the PDF of the prior distribution on the unknown coefficients $\mathbf{c}$ and $[\mathbf{p}]$ is the marginal distribution of the observations. The Bayesian formalism reduces to modelling the different PDFs based on the specifics of the problem and then solving for the posterior PDF $[\mathbf{c}|\mathbf{p}]$. The approach employed here follows from previous work [9–11]. In particular the likelihood is modelled as a complex Gaussian distribution and the prior modelled by a Generalized Multivariate Complex Gaussian distribution. The details of the approach and the resulting algorithm are given in [9]. In brief, it comes down to a minimization problem involving a ℓ_2-norm on the data-fitting term and a ℓ_p-norm as a penalty term. Results in the next section have been obtained with a value of $p = 1$.

3 Results

Since tonal fan noise is related to multiples of the rotational speed, measurement data are preprocessed using order analysis. The time-angle law $\theta(t)$ is obtained thanks to a 1 pulse/rev tachometer recorded synchronously with the microphones. Two different approaches are used in this work for order extraction. First, signals are angular resampled and then a Fourier transform is applied to blocks of fixed number of revolutions. The cross spectral matrix is then estimated using standard Welch's approach. For a deceleration measurement, this is equivalent to a fixed engine order resolution but a variable time interval for the Fourier transform. Second, microphones signals complex envelopes are extracted by multiplication with a complex envelop signal generated from the tachometer, and low pass filtering:

$$p_n(t) = LPF(t, f_c) * \left(p(t).e^{-in\theta(t)}\right) \tag{4}$$

where LPF stands for the low pass filter and f_c the cutoff frequency. Note that resulting complex envelopes can be strongly down-sampled depending on f_c in order to lighten calculations and data storage, ending up with a complex signal for each microphone and order n with a constant time interval. The iterative Bayesian inverse approach is applied to the cross spectral matrix of measurements $\mathbf{S_{pp}}$ obtained from both preprocessing techniques and results are compared hereafter.

The instantaneous overall mode level for the first three BPFs is presented in Fig. 1. As can be seen, there is an excellent agreement between the variable and constant time interval order extraction methods. The BPF2 shows an interesting pattern with peaks and troughs throughout the deceleration.

More insight on the modal content at BPF2 can be obtained from the colormaps in Fig. 2. The variable as well as the fixed time interval approaches give similar patterns. The rotor-stator interaction mode $m = -4$ stands out from the rest throughout the deceleration. The rotor alone mode $m = 40$ is important at high shaft speed before being cut-off around 7300 rpm.

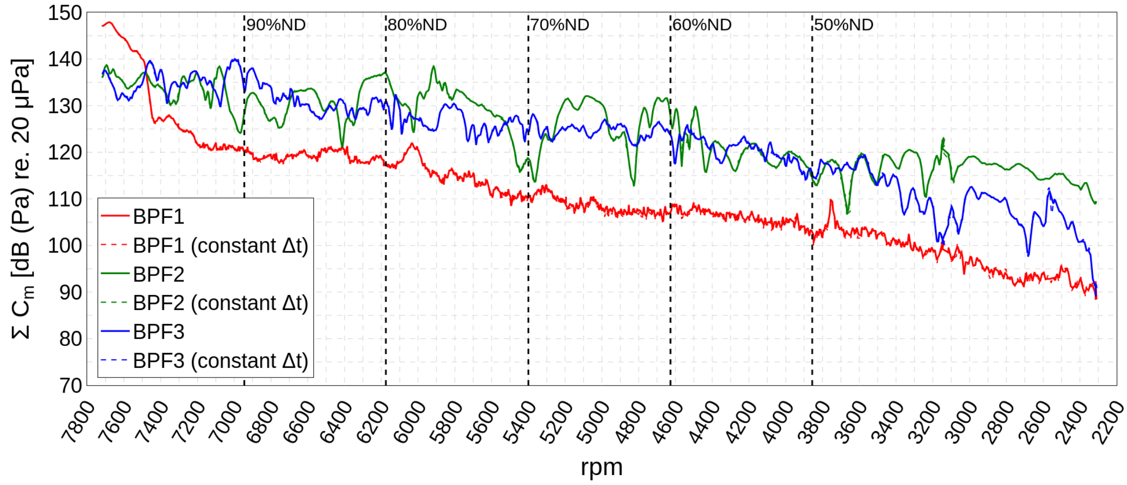

Figure 1: Overall mode level for the first three BPFs.

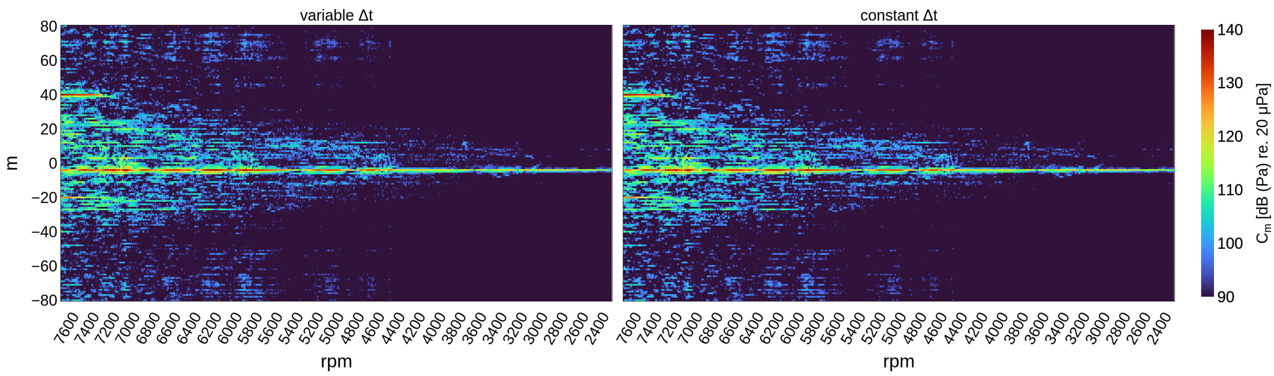

Figure 2: Map of mode amplitudes as a function of the shaft speed at the BPF2.

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