BeBeC-2016-D18

FREQUENCY DOMAIN DECONVOLUTION FOR ROTATING SOURCES ON AN AXIAL FAN

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Abstract

The capture of moving sound sources is a challenge for high-resolution beamforming algorithms. In general, time domain formulations are necessary to acoustically track a source. In the special case of rotating sources, the application of frequency-domain algorithms is possible using a circular microphone array in alignment with the rotational axis. Measured signals are interpolated between neighboring microphones in synchronization with the rotating object, simulating a rotating array. This allows the use of time-invariant steering vectors and therewith frequency domain beamforming with subsequent deconvolution. In this contribution, the virtual rotating array method is applied to analyze sources occurring on an axial fan. The technique facilitates the identification of major noise sources as well as evaluating spectra of subcomponents such as leading and trailing edges. Requirements on the array geometry and necessary adaptations of the steering vectors will be discussed.

1 INTRODUCTION

Identifying dominant sources is a necessary step for possible primary noise reduction measures in turbomachinery and turbine engines. The detection of sources occurring on rotating parts, e.g. fan blades, is an additional challenge for the assessment with microphone array methods.

One possibility is the real-time adaptation of steering vectors to the position of the moving object with subsequent time domain beamforming [9, 14]. However, this "moving focus" is not only costly in terms of computational time, it also does not permit the application of sophisticated deconvolution algorithms working in the frequency domain.

Taking advantage of the rotational symmetry, another approach is to adapt the steering vectors such that they account for a constant rotation [8, 10]. Since a non-varying rotational speed is inherent to this method, however, in many cases it is not applicable.

A third technique consists of interpolating the measured data in time domain so as to simulate a virtual rotating array and then perform beamforming or similar methods as if the rotating object would be non-moving. This can be done with an assumed constant rotational speed [3], but also if the rotational speed is changing during the measurements [5].

In this contribution, the virtual rotating array method is applied to in-duct measurements conducted on a rotor-stator configuration in order to enable calculations with frequency-domain deconvolution algorithms.

2 MEASUREMENT AND METHODS

2.1 Measurement setup

Measurements were performed at the Advanced Noise Control Fan (ANCF) facility at NASA Glenn Research Center [7]. The ANCF is a configurable test bed developed to examine fan-generated noise.

The configuration used for the experiments evaluated in this study is shown schematically in Fig. 1. The duct diameter is 1230 mm. A rotor with 16 blades and a stator with 14 vanes are

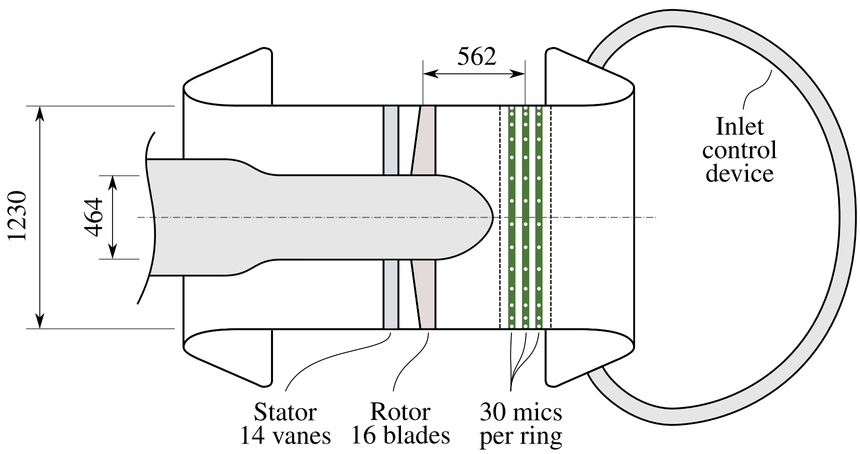

Figure 1: Schematic of the ANCF configuration used for the measurement, all values in mm.

positioned on a hub with a diameter of 464 mm. Upstream from the rotor, 90 wall-mounted microphones are arranged in three rings. Each ring features 30 evenly-distributed microphones. The distances between the center ring and the upstream and downstream rings are 73 mm and 76 mm respectively. The plane of focus is set inside the rotor, 562 mm from the center ring. The average rotational rate was 2029 rpm; the rotation was tracked with a one-trigger-per-revolution signal. Measurement conditions and data processing parameters are summarized in Table 1.

2.2 Microphone array methods

The classic formulation of a beamformer in frequency domain is

$$b(\boldsymbol{x}_t) = \boldsymbol{h}^{\mathrm{H}}(\boldsymbol{x}_t)\, \boldsymbol{C}\, \boldsymbol{h}(\boldsymbol{x}_t)\ , \qquad t = 1 \ldots N, \tag{1}$$

Table 1: Data acquisition and processing parameters.

Number of microphones	3×30	Resolution of focus grid	0.02 m
Evaluated measurement time	12 s	CLEAN-SC iterations	500
Sampling rate	96 kHz	CLEAN-SC damping	0.6
FFT block size	4096 samples	OB number of eigenvalues	32
FFT window	von Hann	DAMAS iterations	500
	50% overlap	CMF regularization	BIC [15]

with N being the number of focus points $\boldsymbol{x}_t$, and $b(\boldsymbol{x}_t)$ the squared sound pressure originating from one of these points. $\boldsymbol{C}$ is the cross-spectral matrix approximated using Welch's method. The time signal is divided into overlapping blocks, onto which an FFT is applied. The cross-spectra between the M channels are calculated for each block and then averaged.

The main diagonal of $\boldsymbol{C}$ containing the autospectra is removed for the calculations. With this, uncorrelated noise, such as induced by the flow, is effectively removed in the evaluation.

The entries of the steering vector $\boldsymbol{h}$ are calculated via [12]

$$h_m = \frac{1}{r_{t,0} r_{t,m} \sum_{l=1}^{M} r_{t,l}{}^{-2}} \, \mathrm{e}^{-\mathrm{j}k(r_{t,m}-r_{t,0})} \, , \qquad m = 1 \ldots M \, . \tag{2}$$

The formulation of the steering vector is based on a monopole source model in a resting fluid under free-field conditions. Basically all of these assumptions are no longer valid for the case at hand. It can be argued that a monopole source model is sufficient as long as it can be assumed that major dipole or otherwise directional sources are not oriented such that they radiate with inverted phases to different parts of the microphone array.

In addition to the flow, the fluid is also swirling relative to the rotating reference system. This has to be taken into account when calculating the sound travel times from the focus area to the microphones. Therefore, the distances between focus points and microphones $r_{t,m}$ in Eq. (2) are corrected such that they do not correspond to the physical distance between the points, but to the numerically approximated retarded times multiplied by the speed of sound.

Furthermore, the effect of the duct geometry on the sound propagation is not taken into account by the free-field model. For this, the transfer function from the grid points to the microphones has to be determined. It can either be measured or modeled through a superposition of duct modes [8]. While modal steering vectors promise to better represent the correct sound field, it has been shown that meaningful results can be obtained using a free-field formulation [4].

The deconvolution methods compared in the following section are:

- CLEAN-SC [13], which subtracts portions coherent to major sources from a sound map,
- Orthogonal Beamforming (OB) [11], which utilizes an eigen-decomposition of the cross-spectral matrix to identify major sources,
- DAMAS [2], which uses a modified Gauss-Seidel algorithm to remove the influence of a modeled point spread function on the beamformer map,

- Cross-spectral Matrix Fitting (CMF) [6], which is a standalone inverse method, minimizing the difference between the actual cross-spectral matrix and the cross-spectral matrix calculated from the unknown source distribution and a modeled transfer function.

3 RESULTS

With transforming the time data into the rotating system, the spectra at the (virtual rotating) microphones change. Figure 2 shows the spectra in the stationary and the rotating reference

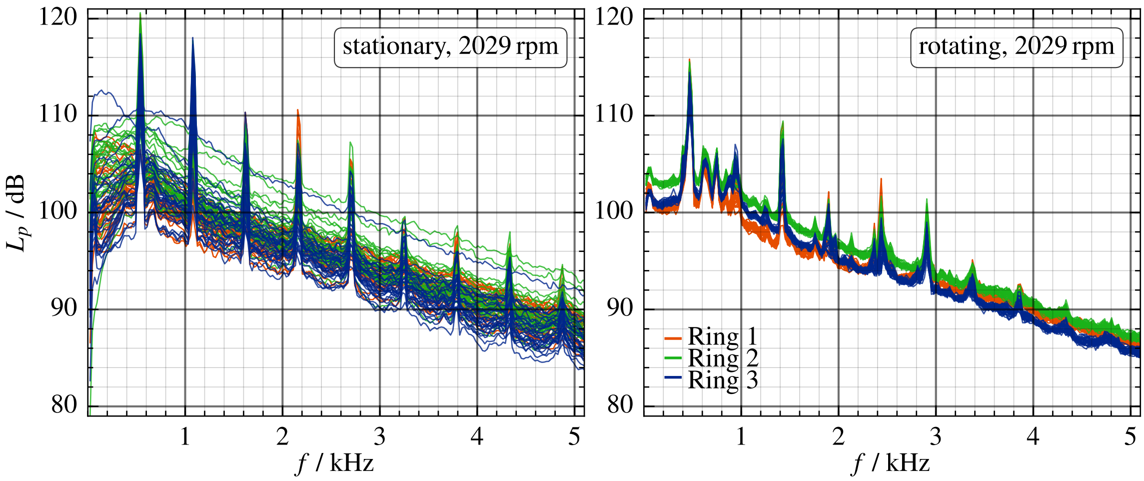

Figure 2: Microphone spectra in the stationary (left) and the virtual rotating (right) reference system. The rings are numbered against stream direction, i.e. Ring 1 is closest to the fan and Ring 3 is closest to the inlet.

system. The most prominent effect is that the spectra of the channels in each respective microphone ring are very similar to one another due to the averaging effect of the virtual microphones "running" through every physical microphone in its ring.

Aside from that, the peaks of the blade passing frequency and its higher harmonics appear to have been shifted to lower frequencies. This is in fact the vane passing frequency (VPF) of the stator (featuring 14 vanes, as opposed to 16 rotor blades), which rotates itself in the rotating system while the former rotor acts as a stator.

Sound maps calculated with the chosen microphone array methods are shown in Fig. 3. The focus points are evenly distributed on a circular grid set inside the rotor (562 mm from the center ring, see Fig. 1). The frequency band for each plot encompasses the range from one VPF to the next, starting at the first VPF of 473 Hz. Each map is displayed with a dynamic range of 30 dB (including the highest occurring sound pressure level). Viewed from upstream, the fan is rotating counter-clockwise.

For orientation purposes, a grid of 16 equal ring segments is overlaid onto the maps, also marking the position of the hub and the duct wall. The actual position of the rotor blades at the trigger instant was not recorded, thus the actual alignment from segment to blade is unknown.

In general, the maps generated with classical beamforming (CB) show a poor dynamic range and spatial resolution in comparison to the maps generated with the other methods. At the low-

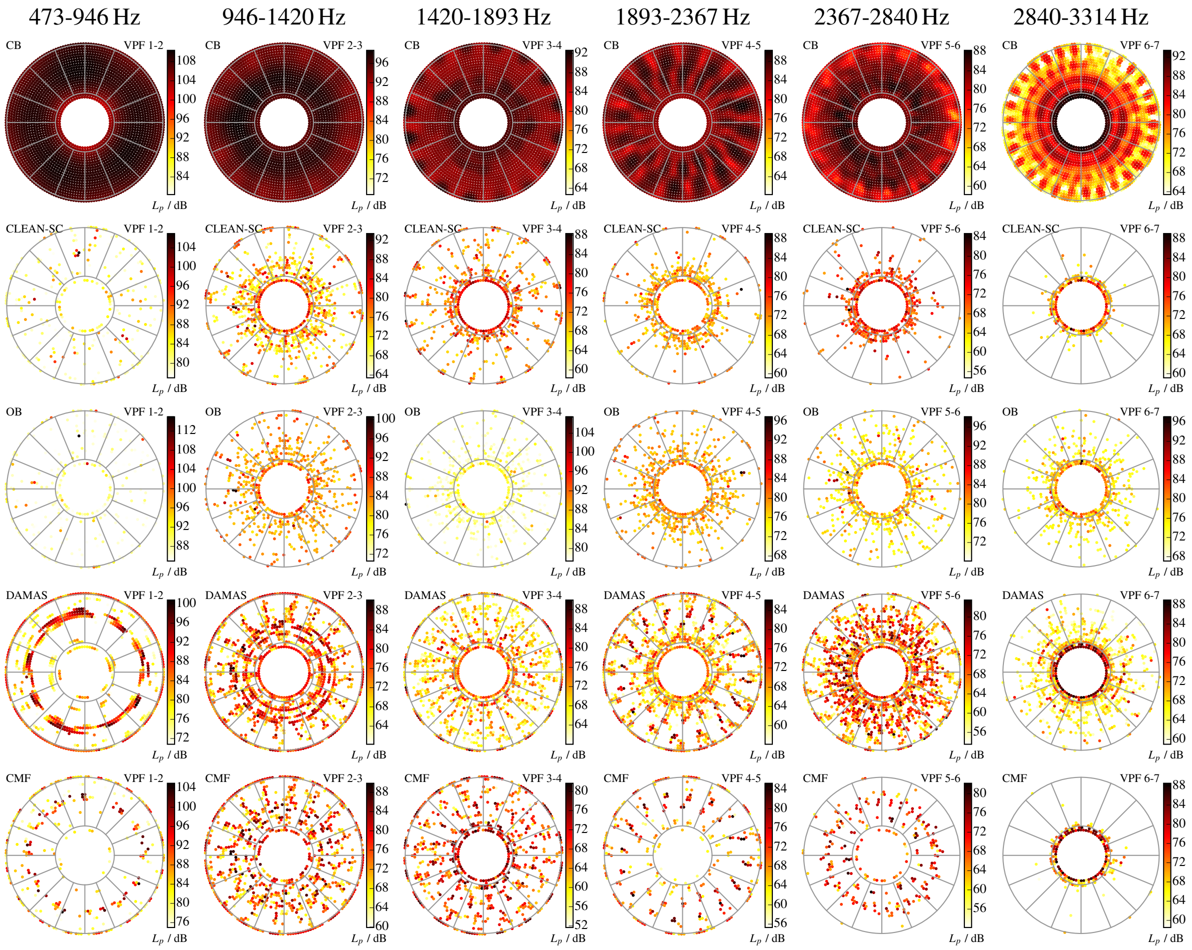

Figure 3: Sound maps for different methods and frequencies.

est evaluated band (VPF 1-2), none of the maps show resemblance to a sound source distribution caused by a 16-bladed structure.

A 16-segmented level distribution becomes vaguely visible in the CB case at VPF 2-3 and is most distinct at VPF 4-5. The clearly visible segmented distribution at VPF 6-7 is not caused by the fan blades, but is rather an artifact caused by the limited azimuthal sensor resolution: The 30 lobes at the outer radius correspond to the number of microphones per ring. Therefore, source level reconstruction with the virtual rotating array method in this case is limited to frequencies below 3 kHz. Evaluating this configuration at higher frequencies necessitates a higher number of microphones per ring.

With CLEAN-SC, a 16-segmented distribution is found for the three bands between VPF 2 and 5, with the most prominent sources being found at the tip region. Orthogonal Beamforming does not reveal any distinct source structure in any of the frequency bands. DAMAS and CMF show 16/32-source structures between VPF 2 and 6, with more sources distributed in radial direction.

As has already been pointed out, the exact blade orientation is not known and could only be approximately guessed from characteristics of the source distribution on the sound maps.

Therefore, it is not possible to deduct leading or trailing edge spectra by integrating the sound pressures over the corresponding sub-areas in the maps. However, the integration of sectors can be used to assess the plausibility of the results calculated with a given method.

In Fig. 4, spectra integrated over 32 sectors, each spanning 1/32 ring, are displayed. The inner radius of the sectors excludes the innermost focus grid points, which are set inside the hub to "collect" additional sources that are not rotating with the system. The color-coding is alternating between neighboring sectors.

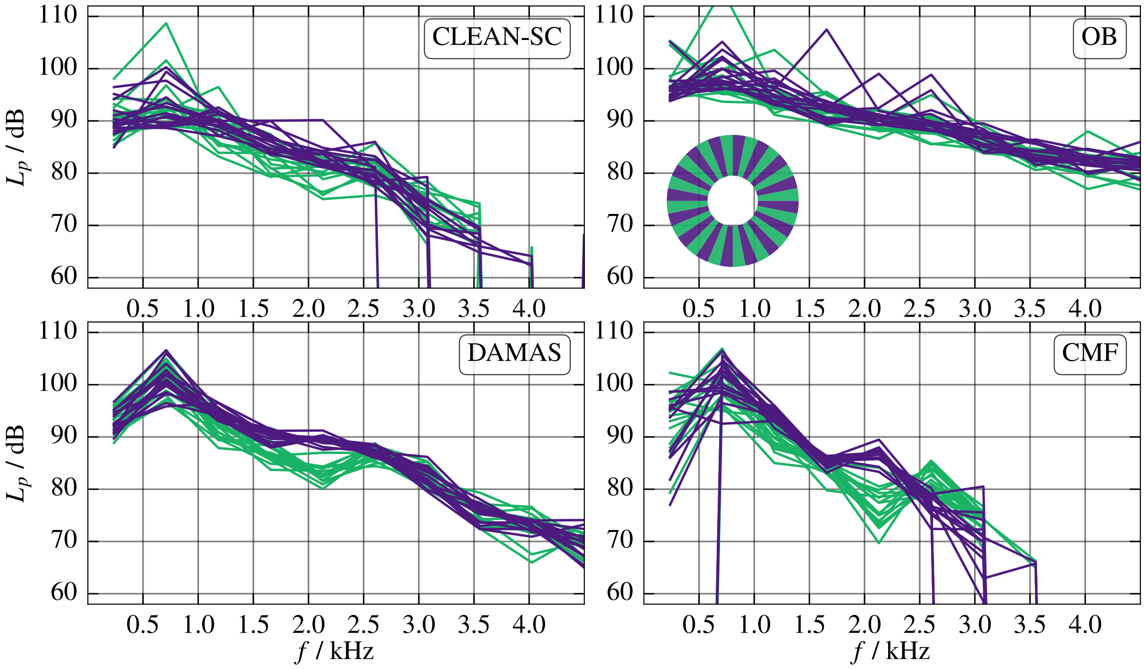

Figure 4: Integrated spectra for different methods.

The plausibility is rated by the following criteria:

- Spectra of the same color should be close to each other, as their sectors encompass similar fan areas.
- Spectra of different color should be clearly distinguishable as separate "groups", with a visible level difference, as different regions of a blade radiate at different frequencies [1, 5].

For the CLEAN-SC deconvolution, these criteria are met for frequencies roughly between 1 and 2 kHz. With Orthogonal Beamforming, the second criterion is never met. Additionally, the integrated levels deviate most in the spectral region below 3 kHz, where the results from the other algorithms are most promising. DAMAS shows a clear separation of the sector types between 1 and 2.5 kHz. The CMF spectra even show the two groups up to 3 kHz, albeit with more level scattering.

The small evaluable frequency range shows that the measured data is suited for the evaluation with the virtual rotating array method only to a limited degree. An improvement of the result by choosing a more adequate steering vector formulation may be possible. However, the frequency range is still limited by the artifacts introduced through the interpolation of microphone signals. To assess this problem, performing measurements with a higher number of microphones per ring would be beneficial.

4 CONCLUSION

The virtual rotating array method has been applied on measurements of an in-duct rotor-stator configuration. For this, the measured data were processed such that a microphone array rotating at the same rate as the rotor was simulated. In the rotating system, several frequency-domain based microphone array methods were tested on the data, evaluating sound sources occurring on the rotor.

It was shown that for this case the frequency range in which the methods can be applied is limited between 1 and 3 kHz. Within this range, the DAMAS deconvolution and the CMF method show the best performance. CLEAN-SC is applicable in a smaller frequency range, while Orthogonal beamforming is not capable of identifying major source regions here.

Potential better performance in general can be achieved by applying a steering vector model better fitted to the in-duct sound propagation and through additional measurements employing a higher number of microphones per ring.

5 ACKNOWLEDGEMENT

The authors would like to thank Daniel Sutliff from NASA Glenn Research Center for providing the ANCF measurement data.

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