Localization and characterization of rotating noise sources on axial fans by means of an irregularly shaped microphone array

O Amoiridis¹, R Zamponi¹,*, A Zarri¹, J Christophe¹ and C Schram¹

¹ Environmental and Applied Fluid Dynamics department, von Karman Institute for Fluid Dynamics, Waterloosesteenweg 72, 1640 Sint-Genesius-Rode, Belgium

E-mail: riccardo.zamponi@vki.ac.be

Abstract. Aerodynamic noise emitted by low-speed axial fans has been receiving increasing attention in various sectors of high societal impact, such as automotive and HVAC systems. In this framework, turbulence interaction, flow non-uniformities, trailing-edge boundary layer fluctuations and blade-tip leakages are different mechanisms generating aeroacoustic sources on the rotating blades and contributing to the overall emitted sound. An accurate localization of the sound sources on the surface of the blade is instrumental in separating and isolating these contributions and, therefore, in designing novel sound mitigation concepts. The main objective of this paper is to present an inexpensive and efficient way to isolate and quantify the noise generating mechanisms on rotating blades by means of an irregularly shaped microphone array. The technique is based on ROtating Source Identifier (ROSI) and has been implemented and validated at the von Karman Institute for Fluid Dynamics (VKI). Simulated benchmark datasets that refer to rotating point sources emitting white noise have been considered for the validation of the method. The accuracy in the source localization and in the source strength reconstruction has been evaluated for a fixed and a variable angular rate. Moreover, the algorithm implementation has been parallelized with the purpose of reducing its computational time, which represents the main drawback of ROSI. Finally, the developed technique has been applied to measure the noise sources generated by a forward-skewed subsonic axial fan operated at maximum efficiency. In this case, it has been possible to successfully localize and characterize the major noise sources on the blades. Although further investigation will be necessary to gain better insight into the topic, the present work constitutes an important step for a better understanding of the physical phenomena occurring in the noise generation of an axial fan.

1. Introduction

The sound field emitted by a rotating machinery constitutes an increasing environmental concern in several industrial sectors. Especially in modern automotive engines, the low-speed cooling fan has been already established as one of the major contributors to the overall noise [1]. A solid understanding of the acoustic phenomena occurring on the axial fans is required to design innovative quieter solutions. Microphone array techniques are able to provide information on the location and the amplitude of the noise sources at different operating points for various configurations. However, conventional methods cannot be applied directly to rotating objects since the Doppler effect must be taken into account. Sijtsma et al. [2] have approached this challenge by deriving a transfer function for a moving monopole source in a uniform flow in order to reconstruct the time-domain signal and to develop an algorithm able to deal with rotating sources, named ROtating Source Identifier (ROSI). They validated ROSI using rotating whistles.
and applied it to localize and characterize sound sources on a hovering helicopter rotor and on wind-turbine blades. The capability of this algorithm has been further examined by Oerlemans et al. [3] for the investigation of a real-scale wind turbine, whereas Benedek and Tóth [4] employed it for localizing the sound sources occurring in a ducted fan in a realistic acoustic environment.

A different approach to deal with rotating sources in the frequency domain is represented by the Virtual Rotating Array Method (VRAM), proposed by Herold and Sarraj [5]. The technique is based on the generation of a virtual array that rotates together with the focus point. Zenger et al. [6] applied VRAM to characterize the sources of an axial fan for several operating points, whereas Herold et al. [7] tested it in fans with different blade configurations: backward-skewed, unskewed and forward-skewed. An extensive comparison between VRAM and ROSI has been conducted by Kotán et al. [8], pointing out the increased computational cost of ROSI against VRAM. Nevertheless, both techniques seem to accurately predict the location and the strength of the rotating source. In addition, ROSI does not require a specifically-designed circular array whose center is aligned with the center of rotation in order to tackle the problem and can be used with an irregularly shaped antenna not necessarily coaxial with the rotating framework of interest. This aspect turns out to be particularly useful in wind-tunnel experiments with a limited space at disposal.

The objective of this study is to show the implementation and the validation of an in-house beamforming technique based on ROSI. The algorithm has been firstly applied to two different simulated benchmark datasets featuring rotating point sources. The capability of the method to correctly localize and quantify noise sources has been evaluated. Subsequently, the technique has been employed for the real case of a low-speed cooling fan by means of an inexpensive irregularly shaped microphone array placed in the ALCOVES facility of VKI.

2. Materials and methods

2.1. ROSI implementation

The beamforming algorithm implemented in this work is based on the approach proposed by Sijtsma et al. [2]. This time-domain method evaluates the beamforming results on a scanning grid of potential sources that rotates together with the sound sources of interest at constant or varying angular rates1. As mentioned in Section 1, the significant higher computational cost with respect to other frequency-domain methods constitutes the main drawback of ROSI. A special focus has been therefore put by the authors on the parallelization of the algorithm implementation in order to face this problem. The multi-processing module of Python has been exploited to parallelize the reconstruction procedure of the emitted source signal at each focus point. In terms of computational cost, a serial implementation (1 processor) has required more than 30 h to evaluate the results in the case of the scanning grid described in the following subsection, whereas the parallel procedure (8 processors) has taken one fourth of this computational time.

2.2. Synthesized test case

The algorithm has been validated through its application to two benchmark datasets featuring simulated rotating point sources [9]. These data have been recently used to evaluate array method algorithms and their implementations by Herold et al. [10]. Time signals have been generated at 64 microphone positions placed in an equidistant arrangement on a circumference forming an array of aperture \( d_{array} = 1 \text{ m} \). The distance of the array plane to the rotational plane is \( z = 0.5 \text{ m} \), whereas the array center is axially aligned with the axis of rotation of the sources, as shown in Figure 1a and Figure 1b.

The first synthesized dataset (subcase A) includes one monopolar point source rotating at a radius of 0.25 m in a clock-wise direction and with a constant angular rate of 1500 rpm. The source emits a white noise signal with an amplitude of 94 dB. The second one (subcase B) consists

1 detailed information about the architecture of the code can be found in the work of Sijtsma et al. [2]
of three uncorrelated point sources rotating in a clock-wise direction at the same angular rate that slightly varies over the time around the value of 1500 rpm with a maximum deviation of ±20 rpm. In this case, the sources emit white noise at different intensities. The different relative positions and sound-pressure levels of the sources are displayed in Figure 1b. In particular, the louder source of 94 dB and the intermediate one of 91 dB rotate along a circumference having a radius of 0.25 m, whereas the weaker source of 88 dB rotates along a circumference having a radius of 0.125 m. The sound levels displayed in Figure 1a and Figure 1b correspond to the sound-pressure level at 1 m of distance from the point sources. Finally, the data-processing parameters considered to process the datasets are reported in Table 1.

![Figure 1: Scheme of the benchmark datasets containing the projection of the microphones (black dots) in the x-y plane and the rotating point sources (red dots): one rotating point source with constant angular rate (a) and three rotating point sources at a varying angular rate (b).](image)

**Table 1: Data-processing parameters of the simulated benchmark data sets.**

| Parameter                  | Value                        |
|----------------------------|------------------------------|
| Measurement time           | 10 s                         |
| Sampling frequency         | 48 kHz                       |
| FFT block size             | 1024 samples                 |
| FFT window                 | Hanning, 50% overlap         |
| Grid translation           | \((x, y) = (0\,\text{m}, 0\,\text{m})\) |
| Grid resolution            | 0.01 m                       |
| Grid points                | \(61 \times 61\)            |

### 2.3. Experimental setup

The experimental measurements have been conducted in the ALCOVES anechoic chamber of VKI, characterized by a cut-off frequency of 150 Hz and composed of two anechoic rooms separated by a modular wall partition that accommodates the engine cooling module [11]. The flow inside the wind-tunnel is driven by an auxiliary fan placed in a downstream circuit, generating a pressure difference across the two rooms. A detailed scheme of the anechoic chamber can be found in the work of Zarri *et al.* [12]. The investigated low-speed cooling fan has been designed by the automotive supplier-company Valeo at La Verrière, France, and consists of 7 not-equally spaced forward-skewed blades with a rotating L-shaped ring of diameter \(d_{\text{fan}} = 0.38\,\text{m}\) [12]. The rotational speed of the automotive fan has been kept constant and evaluated using a diode probe with a reflective aluminium tape fixed at the hub of the rotor. An accurate estimation of this parameter has been found to be crucial for a correct application of the method and needs to be determined with an accuracy of ±1 rpm. In addition, the diode signal has been acquired synchronously to the microphone data and the angular position of the fan at the
beginning of each measurement has been computed. Lastly, the fan has been driven at its maximum-efficiency operating point.

The microphone array considered for the present study is a planar Dougherty array [13] with 64 microphones distributed over seven logarithmic arms and with a diameter of $D_a = 1.5$ m. The antenna, shown in Figure 2b, is characterized by a light and easily transportable structure and is equipped with inexpensive capacitor-based Knowels electrets (model FG-23329-P07 with a frequency response $\pm 3$ dB and a frequency range of 100 Hz to 10 kHz). The microphone array is installed at a distance of $d_{a-ss} \simeq 2.5d_{fan}$, perpendicular to the rotation axis of the fan, on the suction side, as depicted in Figure 2a. With the present setup, the minimum resolvable source separation is given by the Rayleigh criterion [14] as

$$R \simeq d_{a-ss} \tan \left( \frac{1.22 c_0}{f D_a} \right),$$  \hspace{1cm} (1)

where $c_0$ is the speed of sound and $f$ is the investigated frequency.

$$
\begin{array}{c}
\text{Upstream room} \\
\sim 2.5d_{fan} \\
\text{Motor} \\
\text{Microphone array plane}
\end{array}
$$

Figure 2: (a) Position of the microphone array in the ALCOVES upstream room with respect to the axial fan. (b) 64 microphones Dougherty array employed for the campaign.

In addition, the calculation of the coordinates of the center of rotation has been performed by applying a conventional beamforming method [15] to the acoustic data generated by a loudspeaker installed at the center of the fan and emitting a white noise signal. The position of the monopolar source displayed in the sound map thus obtained has been taken into account to translate the scanning grid, making it possible for the algorithm to follow the movement of the the sources rotating together with the fan.

Table 2: Data-processing parameters of the experimental test case.

| Measurement time | 5 s       | Grid translation $$(x, y) = (0.09 \text{ m}, 0.18 \text{ m})$$ |
|-----------------|----------|---------------------------------------------------------------|
| Sampling frequency | 51.2 kHz | Rectangular grid $x = \pm 0.25 \text{ m}, y = \pm 0.25 \text{ m}$ |
| FFT block size   | 1024 samples | Grid resolution 0.01 m                                     |
| FFT window       | Hanning, 50 % overlap | Grid points 51 $\times$ 51                                    |

3. Results

3.1. Method validation

The VKI implementation of ROSI has proved to be able to accurately locate and quantify the synthetic rotating sources of the tests case detailed in Section 2.2. Figure 3a and Figure 3b depict the sound maps referring to the one-third octave frequency band $f_{1/3} = 5$ kHz for the subcase A and subcase B, respectively. The maps are presented using the same dynamic range
of 15 dB. For both cases, the positions of the monopolar sources have been successfully retrieved. Moreover, the sound peak levels in the subcase B differ by 3 dB from each other, hinting at a corrected reconstruction of the source amplitude.

![Figure 3](image)

Figure 3: ROSI sound maps for $f_{1/3} = 5$ kHz for the subcase A corresponding to a monopolar synthetic source rotating at a fixed rpm (a) and for the subcase B corresponding to three monopolar synthetic sources rotating at a varying rpm (b).

Subsequently, the sound maps have been integrated in order to perform a quantitative comparison. The integration is performed by summing the squared pressure levels included within a 1.5 dB dynamic range from the main peak. Figure 4a shows the relative sound-pressure level $\Delta L_{p,1/3}$ for the one-third octave frequency bands ranging from 1 kHz to 12.5 kHz for the subcase A. The data are referred to a reference pressure of $p_{ref} = 20 \mu$Pa. The integrated spectra show a general good agreement with the simulated ones for the investigated frequency range, with a deviation from the expected amplitude that is contained within $\pm$1 dB for frequencies up to 8 kHz. Above this threshold, the integrated spectra increasingly underestimate the source amplitude level, reaching a difference of $\Delta L_{p,1/3} = -2$ dB at $f_{1/3} = 12.5$ kHz. This deviation is probably due to the integration procedure as a wider region surrounding the source peak should be integrated to retrieve the correct level in this case.

Figure 4b presents the relative sound-pressure levels for the one-third octave frequency bands ranging from 1 kHz to 12.5 kHz for the subcase B, computed with a reference pressure of $p_{ref} = 20 \mu$Pa. Also in this case, the integrated spectra exhibit a fairly good agreement with the simulated ones. Particularly, the spectra for the louder source show a similar trend of the one for the subcase A. This result indicates that ROSI is able to correctly reconstruct the source amplitude for a variable rpm when the information on the angular velocity variation is well documented. Comparable results have been obtained also for the integrated spectra of the intermediate source. In this case, a higher deviation up to 1.8 dB is observable around $f_{1/3} = 2$ kHz. For the weakest source, the sound amplitude reconstruction is found to be less accurate, especially at lower frequencies, where the integrated spectrum overestimates the simulated ones with a maximum $\Delta L_{p,1/3}$ value of almost 4 dB at $f_{1/3} = 1$ kHz. This is mainly due to the difficulty of beamforming to properly isolate non-dominant source contributions. Moreover, the distance between the louder and the weaker source is lower than the minimum resolvable source separation distance given by the Rayleigh criterion in Equation (1), which, for the benchmark simulated setup geometry, corresponds to approximately 0.2 m. Finally, also for the subcase B, an underestimation of the correct sound level up to 2 dB for the first two dominant sources and 4 dB for the third one is visible at higher frequencies.
3.2. Experimental test case

The validated beamforming approach has been able to successfully characterize the noise sources on the low-speed cooling fan at its maximum-efficiency operating point for frequencies above 3.15 kHz. In this configuration, no flow separation is typically expected [12]. The sound maps for third-octave frequency bands of 3.15 kHz, 4 kHz, 5 kHz, 6.3 kHz, 8 kHz and 10 kHz are reported in Figure 5 considering a dynamic range of 5 dB. For \( f_{1/3} \geq 3.15 \) kHz, the dominant noise sources are located at the tip of the blades due to the higher relative flow velocities in these regions, with a similar contribution given by each blade, despite the not equal spacing. The maps are characterized by a spatial resolution that improves as the frequency increases. For \( f_{1/3} < 3.15 \) kHz, the algorithm is not able to separate the different noise contributions of each blade and this can be explained by means of the Rayleigh criterion in Equation (1). Indeed, considering the distance between two consecutive blades, i.e., \( R = 0.10 \) m, as the minimum separation distance of two sources, the resulting frequency is \( f_{\text{min}} \approx 2.5 \) kHz. As a consequence, only the sound maps related to one-third octave frequency bands above this threshold will provide a clear separation of the noise sources generated by each blade.

Furthermore, for \( 3.15 \) kHz \( \leq f_{1/3} \leq 8 \) kHz, clear peaks can be observed. In this range, the noise sources appear to be located at the leading edge at the tip of the blades. This hints at a noise generation due to the interaction of the leading edge with incoming turbulence and/or with secondary flows developing in the gap between the fan casing and the rotating ring [16]. Furthermore, at \( f_{1/3} = 10 \) kHz, noise source contributions can be found in the circular area of the rotating ring of the fan. This can be attributed due to the presence of small-scale vortical structures passing over uneven surfaces, e.g., the transition area between fan blades and fan shroud, and generating noise, similarly to what has been observed by Zenger et al. [6].

Interestingly, no significant noise generation in the regions close to the trailing edge of the fan is observed, despite contributions at higher frequencies can be expected [17]. This is consistent with the results obtained by a previous study of Herold et al. [7], where a forward-skewed fan had been tested. Indeed, the noise produced by the interaction of the boundary layer with the trailing edge is low compared to the leading-edge noise and cannot be detected by the beamforming algorithm. However, further investigation is needed to clarify which noise mechanism is the responsible for the concentration of the sound sources on the leading edges.

The ability of the algorithm to correctly reconstruct the sound amplitude in an experimental test case has been evaluated by comparing the ROSI integrated spectrum with the one computed
Figure 5: ROSI sound maps of the low-speed cooling fan referred to (a) $f_{1/3} = 3.15$ kHz, (b) $f_{1/3} = 4$ kHz, (c) $f_{1/3} = 5$ kHz, (d) $f_{1/3} = 6.3$ kHz, (e) $f_{1/3} = 8$ kHz and (f) $f_{1/3} = 10$ kHz.

Figure 6: (a) ROSI integrated spectrum (black solid line) compared with the spectrum of the array reference microphone (red dash-dotted line) and the background noise (grey dashed line). (b) Relative differences between the ROSI spectrum and the reference microphone spectrum.

by a reference microphone of the array aligned with the center of the fan. The integration is performed for each of the blades by summing the squared pressure levels included within a 1.5 dB dynamic range from the peak. Figure 6a shows the spectra comparison computed with a reference pressure of 20 µPa. At low frequencies, a significant overestimation of the beamforming method over the microphone spectrum is visible for $f_{1/3} < 4$ kHz. This result is consistent with the trend shown by the sound maps and is related to the inability of the method to separate noise contributions below the Rayleigh criterion, causing a source overlapping. At higher frequencies,
the spectra exhibit a fairly good agreement, especially for values over 5 kHz. This is better visible by the relative \( \Delta L_{p,1/3} \) in Figure 6b, where the absolute mean value of the relative error corresponds to \( |\Delta L_{p,1/3}| \approx 2 \text{ dB} \).

4. Conclusions
The objective of this work is to present the development of a beamforming method, based on ROSI, able to investigate rotating sound sources. The algorithm has been validated through the processing of two benchmark datasets consisting of synthetic monopolar sources rotating at constant and variable rpm. The results show that ROSI is able to successfully localize and quantify the sources within a range of ±2 dB for the dominant sources and of ±4 dB for the secondary ones.

Subsequently, the technique has been applied to a low-speed cooling fan installed in the ALCOVES anechoic chamber of VKI, driven at its maximum-efficiency operating point. The measurements have been performed using a non-circular antenna equipped with inexpensive electret microphones. The method has proved to properly isolate the noise contributions of the fan for frequencies above the minimum value at which the sources generated on two consecutive blades can be separated. The sound amplitude has been also reconstructed with an absolute mean value of the relative error of about 2 dB for \( f_{1/3} \geq 5 \text{ kHz} \). The most dominant noise sources have been located along the leading edge of the blades in the tip region, with a similar contribution coming from each of them. This suggests that the noise generation mechanism is linked to a possible interaction of the leading edge with incoming turbulence and/or with secondary flows generated in the gap between the fan casing and the rotating ring.

Finally, although more extensive analyses are required to investigate the noise generation mechanisms occurring in the fan, this approach represents a promising tool that can provide further insight into the aeroacoustics of rotating machinery.

Acknowledgments
The European Commission’s Framework Program ”Horizon 2020”, with the Marie Skłodowska-Curie Innovative Training Networks (ITN) ”SmartAnswer” grant agreement No. 722 401, are acknowledged for funding and supporting the present work.

References
[1] Allam S and Åbom M 2015 Noise reduction for automotive radiator cooling fans FAN 2015
[2] Sijtsma P, Oerlemans S and Holthusen H 2001 Location of rotating sources by phased array measurements 7th AIAA/CEAS (AIAA)
[3] Oerlemans S, Sijtsma P and Méndez López B 2007 J. Sound Vib. 299 869–883
[4] Benedek T and Tóth P 2013 Period. Polytech. Mech. Eng. 57 37–46
[5] Herold G and Sarradj E 2015 Noise, Control. Eng. J. 63 546–551
[6] Zenger F J, Herold G, Becker S and Sarradj E 2016 Exp. Fluids 57 136
[7] Herold G, Zenger F and Sarradj E 2017 Int. J. Aeroacoust. 16 418–430
[8] Kotán G, Tóth B and Vad J 2018 Period. Polytech. Mech. Eng. 62 261–268
[9] Herold G 2017 ”b11” https://www.b-tu.de/fg-akustik/lehre/aktuelles/arraybenchmark
[10] Herold G, Ocker C, Sarradj E and Pannert W 2018 A comparison of microphone array methods for the characterization of rotating sound sources 7th BeBeC (BeBeC)
[11] Bilka M, Antheoine J and Schram C 2011 JASA 130 3788–3796
[12] Zarrì A, Christophe J and Schram C 2019 Low-order aeroacoustic prediction of low-speed axial fan noise 25th AIAA/CEAS (AIAA)
[13] Dougherty R P 1998 Spiral-shaped array for broadband imaging Pat. US 5,838,284
[14] Rayleigh L 1879 Philos. Mag. 8 261–274
[15] Mueller T J 2002 Aeroacoustic Measurements (Springer Berlin)
[16] Sanjose M, Lallier-Daniels D and Moreau S 2015 Aeroacoustic analysis of a low-subsonic axial fan Turbo Expo (ASME)
[17] Brooks T and Hodgson T 1980 Prediction and comparison of trailing edge noise using measured surface pressures 6th AIAA/CEAS (AIAA)