Conference on Modelling Fluid Flow (CMFF'15)
The 16th International Conference on Fluid Flow Technologies
Budapest, Hungary, September 1-4, 2015

CHALLENGES IN EVALUATING BEAMFORMING MEASUREMENTS ON AN INDUSTRIAL JET FAN

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ABSTRACT

The aim of this paper is to illustrate the difficulties that arise during the evaluation of phased array microphone measurements on ducted fans in an industrial environment, and draw attention to them. A case study was carried out, and the results were processed resulting in beamforming maps, but their interpretation is not straightforward. Firstly, some fine details are found that seem to correspond to true physical phenomena, but should not be dealt with as separate sources on the basis of the spatial resolution given by Rayleigh's criterion. These results together with some theoretical objections raise concerns about the validity of Rayleigh's criterion in case of beamforming. Secondly, in some frequency bins the noise peaks are found on the axis of revolution. Literature shows that this might truly be motor noise, but it might also be an artefact, that causes beamforming algorithms to falsely locate rotating noise sources onto the axis of revolution [1, 2]. Central noise source peaks might even result from the presence of axial duct modes [3]. These questions are to be answered before beamforming on industrial ducted fans may become a standard noise diagnostics tool.

Keywords: beamforming, fan noise, phased array microphone, Rayleigh criterion, spatial resolution

NOMENCLATURE

a	[m/s]	speed of sound
B	[dB]	beamform map value
BPF	[Hz]	blade passing frequency
D	[m]	diameter
f	[Hz]	frequency
L	[m]	minimum resolvable distance
N	[-]	number of blades
x	[m]	beamform map horizontal coordinate
y	[m]	beamform map vertical coordinate
z	[m]	rotor – microphone array distance
λ	[m]	wavelength
ν	[-]	hub-to-tip ratio
Θ	[rad]	angle between two sources

Subscripts and Superscripts

g	guide vane
mid	third-octave band mid-frequency
OPT	optical
r	rotor
S	Sparrow limit
t	rotor tip

Abbreviations

DS	Delay-and-Sum method
PAM	Phased Array Microphone
ROSI	Rotating Source Identifier

1. INTRODUCTION AND OBJECTIVES

Noise reduction is an important task in the 21st century, and regulations are becoming more and more stringent in connection with axial fans, too. Beamforming using phased array microphone (PAM) measurements presents means to localize sound sources even in a rotating reference frame. These source maps give invaluable information about the distribution of noise that can be related to its generation mechanisms.

Benedek and Vad [4-6] have investigated aerodynamic and acoustic properties of an unducted axial fan through a case study. Using on-site measurements and the PAM technique they have obtained spanwise distributions of boundary layer momentum thickness, and sound pressure level in third-octave bands. Analysis shows that these functions are in correlation for the dominating low frequency ranges. This suggests the possibility of reducing noise while improving efficiency in case of short ducted axial fans.

Similar tests on ducted fans are reported in [7, 8]. In [7] a turbofan engine is investigated using two microphone arrays, one in the inlet, and one in the bypass section of the duct. The source maps clearly show the periodicity related to the fan blades, and the location of maximum noise sources is visible. This measurement was however carried out in a special test rig in an anechoic chamber using wall-mounted microphones, therefore it is not applicable for on-the-field diagnostics. Such a measurement is described in [8] for a wind tunnel fan describing the difficulties of the experiments: reverberant space, high aerodynamic loading on the microphones, low spatial resolution, and the presence of other noise generating mechanisms.

In the current study the authors have implemented the same diagnostic methodology as in [4-6] for the case of ducted fans. This scenario however differs from the original one in several points. The duct length limits accessibility, and spatial resolution of the microphone array. Duct modes are also expected to form, and affect the measurements in different ways depending on duct geometry. The presence of coherent sources in the rotating frame of reference might also cause unrealistic results, in the form of false noise sources appearing on the axis of the rotor [1, 2]. In the following, this will be referred to as the "Mach radius effect". These phenomena are investigated below.

The spatial resolution of beamforming appears to be a concern. It was tested in [9] for several algorithms, conventional and deconvolution-based, too. This investigation is different however, as our aim is to make practically relevant comments on the resolution when measuring turbomachinery acoustics instead of developing new beamforming methods.

This paper is considered as a Technical Note for the Workshop "Beamforming for Turbomachinery Applications" organized at CMFF'15, aiming at provoking a discussion on the topics outlined herein.

2. CASE STUDY

A ducted fan was investigated having a rotor tip diameter D_t=0.355 m, hub-to-tip ratio ν=0.57, N_r=8 rotor blades, and N_g=7 guide vanes. Rotor speed was 2856±1 RPM measured using a handheld stroboscope, corresponding to a rotor blade passing frequency BPF=381 Hz. Noise was measured from a distance of 2 d_t between the PAM and the fan inlet plane for 30 s with a sampling frequency of 44100 Hz on 24 channels on the suction side of the fan. The equipment used was an OptiNav, Inc., Array 24 multi-purpose portable array system. The PAM was placed perpendicular to the axis of rotation, with its centre coinciding with the rotor axis. Data was evaluated using an in-house beamforming software applying the "Rotating Source Identifier" (ROSI) [10] technique to localize rotating sources. Noise source maps of equal dynamic range were constructed showing the spatial distribution of beamform peak values in the fan inlet plane, together with the location of the hub and the annulus. Note that due to the lack of any rotor position transducer, the angular position of the rotor cannot be assigned to the noise source maps. However, with a knowledge of the accurate rotor speed, the ROSI processing algorithm principally enables the pitchwise resolution of the noise sources.

The authors have attempted to determine the most important noise generation mechanisms based on the source maps. They have however faced the problem of Rayleigh's criterion for resolving power and the problem of noise maxima appearing on the axis of revolution. These problems are detailed in the following.

3. RESOLUTION

3.1 Rayleigh's criterion

The applied ROSI method is basically an extension of the frequency-domain Delay-and-Sum (DS) beamforming technique with a special step called deDopplerization to place the rotating sources into a co-rotating reference frame, thus make them stationary. The step consists of adjusting the time delays and amplitudes in order to remove the effect of rotation from the measured noise signals.

In case of beamforming measurements the spatial resolution is of importance because it determines the smallest distance between two sources that can be regarded as separate ones. This way it also shows the minimum size of structures can be positively identified, since regions smaller than the resolution might be the effect of neighbouring source regions.

The spatial resolution is especially important in the case of rotor blades, for which an improper spatial resolution may lead to dissolving the contribution of the adjacent blades in the noise source maps.

Because the spatial resolution of the microphone array and the beamforming method is a very complex phenomenon, the spatial resolution of DS beamforming is usually determined by applying a simplified optical analogy.

The resolving power of an optical aperture is given using Rayleigh's criterion [11]. Assume a point source radiating light of wavelength λ infinitely far from a perfect circular aperture, i.e. the wave fronts incident to the aperture are assumed to be planar waves. The diameter of the aperture is D_{OPT}. The image created by the aperture is the so-called Airy disk, a circularly symmetric diffraction pattern. In case of two sources of identical strength the image is the superposition of the two identical Airy disks. Rayleigh has defined the limit case of resolving the image when the intensity peak of one source falls into the first intensity minimum of the other source.

In such case for the Θ angle between the two sources the following holds:

$$\sin\Theta \approx 1.22\frac{\lambda}{D_{OPT}} \tag{1}$$

In between the two intensity peaks, the intensity of the resultant pattern drops to 73.7 % of the maximum value. The 26.3 % dip relative to the maximum is presumed arbitrarily in Rayleigh's criterion as being sufficient for the human eye in making a distinction between the two optical sources.

The minimum distance between two resolvable sources is usually given based on Eq. (1) by assuming a small angle between the sources. The measurement plane is parallel to the plane of the microphones and offset by z. The minimum resolvable distance is L [11, 12] assuming plane wave propagation:

$$L \approx z\Theta \approx 1.22\frac{z\lambda}{D_{PAM}} \tag{2}$$

Table 1 shows the minimum resolvable distances calculated using Eq. (2) for some representative third-octave frequency bands, being significant from the viewpoint of human audition. The spatial resolution L at a third-octave frequency range is calculated by taking the wavelength corresponding to the mid-frequency f_{mid} in the following way: $\lambda = a / f_{mid}$, then substituting it into Eq. (2) above. In this expression a is the speed of sound.

Table 1. Minimum resolutions in frequency bands, based on Rayleigh's criterion

f_{mid} [Hz]	L [m]	L/D_t [-]
2000	0.42	1.20
2500	0.34	0.96
3150	0.27	0.76
4000	0.21	0.60
5000	0.17	0.48
6300	0.13	0.38

The spatial resolution calculated using Rayleigh's criterion is quite weak due to the fact that the distance is the same order of magnitude as the size of the PAM, D_{PAM}=1 m. Each L/D_t value significantly exceeds 1) the rotor blade height of 0.22 D_t, 2) the rotor blade pitch (spacing) of 0.31 D_t at misdspan. These facts *anticipate the following limitations*, if one would take Rayleigh's criterion as a basis for the available spatial resolution: 1) Even the rotor annulus area, as a whole, could not be expected to be clearly distinguished from the rotor hub area as a noise source, if both sources are of equal magnitude, 2) No pitchwise resolution of noise sources related to the individual rotor blades would be expected at all.

Dougherty et al. also consider the Sparrow limit shown in Eq. (3) for the quantification of resolution [9]. This corresponds to the distance between two sources, at which the dip between their Airy disk diffraction patterns first appears.

$$L_S \approx z\Theta \approx 0.94\frac{z\lambda}{D_{PAM}} \tag{3}$$

The Sparrow limit is less conservative, than Rayleigh's one, by taking values that are roughly 80% of the latter. As customary in optics however, we focus our attention on Rayleigh's criterion.

3.2 Measurement results

In Figure 1 a source map is shown with 6 dB dynamic range showing the rotor from the upstream side in a co-rotating frame. This figure is a representative narrowband result taken from the third-octave band centred on 5 kHz. The two concentric circles indicate the fan annulus area: the inner one shows the hub, while the outer one corresponds to the tip diameter.

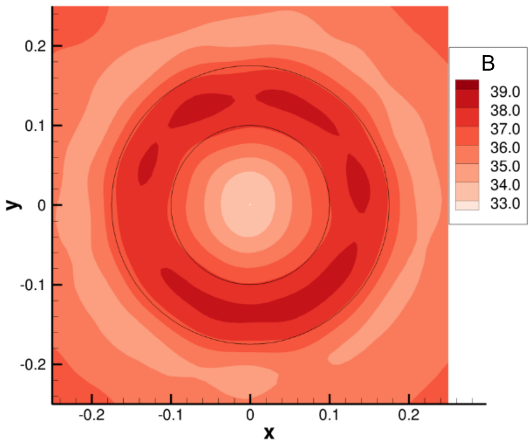

Figure 1. Rotor narrowband beamform map

Despite the anticipated limitations in spatial resolution, originating from Rayleigh's criterion, and formerly described in points 1) and 2), the following observations are made in Fig. 1, in contrast to those points.

1) The rotor annulus area – characterized by the minimum length scale being equal to the blade height of 0.22 D_t – is clearly distinguished from the hub area in the source map.

2) The periodicity in the source map corresponding to the rotor annulus, being in accordance with the eight rotor blades of midspan spacing of 0.31 D_t, is apparent in the upper half of the figure. Some small structures are detected in the

vicinity of the blade tips, whose size is much less than the calculated resolution of 0.48 D_t.

The above suggest that Rayleigh's criterion is a pessimistic approach in the case study presented herein, and, as such, it is to be treated with criticism.

3.3. Criticism of Rayleigh's Criterion

The above discussion suggests that Rayleigh's criterion exhibits some limitations in estimating the spatial resolution of PAM-based fan rotor noise source maps. This experimental finding described above is further supported by the following differences between optical systems and a PAM:

- In general, a microphone array does not necessarily represent a *circular aperture*. In references [1-3], the microphones of the array are arranged along a logarithmic spiral curve, where the shape of the aperture is not known. In case of a linear array however the aperture shape is certainly not circular.
- In the investigated frequency range no cut-on plane modes waves exist in the duct. Due to the proximity of the PAM plane wave propagation out of the duct is a poor approximation.
- The *distance* between the acoustic source and PAM is *finite*. It is often confined to the order of magnitude of some times the rotor tip diameter. Besides the current investigation, references [4-6] also report case studies in which the array was installed at a distance of $\approx 2\, D_t$ from the fan inlet.
- The rotor noise sources to be resolved are not necessarily of *identical intensity*. The studies documented in [1-3] especially aimed at discovering the spanwise non-uniform intensity distribution of rotor noise sources.
- The criterion is based on the visibility of structure of optical diffraction patterns to the human eye, the applicability of which is doubtful from the viewpoint of human audition, and even more so in connection with microphones and digital signal processing.
- The 26.3 % dip in intensity is presumed *arbitrarily* as a quantitative criterion for resolution.

Note that besides these problems already the approximation $\sin\Theta \approx \Theta$ means an error of about 15 % in case of the large angles experienced in the current measurement.

4. ON-AXIS NOISE SOURCES

Besides the sources on the annulus regions several source maps show high peak levels on the axis of rotation. Such a source map is shown in Figure 2. It is a representative narrowband result taken from the third-octave band centred on 3000 Hz.

This peak might be attributed to motor noise. However, it is known from literature [3] that axial plane wave modes will appear in the duct. The beamforming method will localize these to the centre of the beamforming map.

Furthermore, Horváth et al. [1-2] have shown that beamforming measurements on a rotating object will falsely locate some coherent sound sources onto the axis of revolution when the PAM is perpendicular to the rotor axis. How to separate the contribution of real on-axis sources and the "Mach-radius effect" in these specific cases is an open question requiring further investigations.

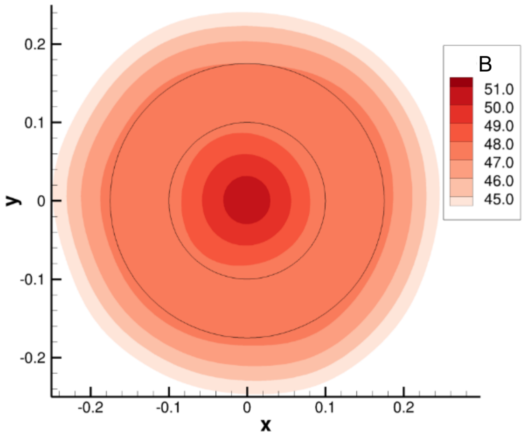

Figure 2. Narrowband beamforming map showing maximum values in the hub region

5. SUMMARY AND FUTURE REMARKS

Beamforming and phased array microphones present effective means of noise source localization that is a major step towards understanding and reducing noise generation. Using the ROSI algorithm rotating sources can also be dealt with effectively. A powerful application of this method is the investigation of industrial axial fans. However, in this case some special concerns arise.

The spatial resolution of beamforming maps obtained by PAM measurements is an important parameter, it is however quite difficult to obtain an expression describing this quantity. In several cases an analogy with wave optics is used, where the Rayleigh criterion is a classic result that presents a minimum distance between two sources if they are to be resolved separately.

While the criterion is well-known and accepted in optics, in the framework of beamforming its assumptions are at least questionable. Based on these reasons the authors consider Rayleigh's criterion in some cases ill-suited for the quantification of spatial resolution of beamforming measurements on rotating fans. The following question is arisen. What amount of dip between two peaks is to be considered as a practically relevant criterion for resolving two neighbouring sources in beamforming?

Another question is the case of noise sources appearing on the axis of beamforming maps. These might indicate true noise source positions on the axis, e.g. motor noise, but might also results from the "Mach radius effect". Possible causes of the phenomenon are the formation of axial duct modes and the interference of coherent sources in the rotating frame.

On the basis of above, some future tasks of departmental research on beamforming applied to industrial fans are as follows.

1) Elaboration of a widely applicable methodology for a realistic estimation of the spatial resolution of beamforming, with a special focus on rotating sources, as a critical revision of Rayleigh's pessimistic criterion. Comparison of resolution in case of stationary and rotating sources, e.g. DS and ROSI methods.

2) Elaboration of a systematic evaluation method for a comprehensive judgment on the origin of a local noise maximum apparent on / near the rotor axis, whether a) it is a virtual (physically non-existing) source, due to the Mach radius effect; or b) it is the representation of any duct modes; or c) it indicates indeed the local dominance of the hub as a noise source (e.g. due to the noise of the driving electric motor incorporated in the hub).

ACKNOWLEDGEMENTS

This work has been supported by the Hungarian National Fund for Science and Research under contract No. OTKA K 112277. Gratitude is expressed to Hungaro-Ventilátor Kft. for providing the test fan, and for making possible the tests at the premises of the company.

The work relates to the scientific programs "Development of quality-oriented and harmonized R+D+I strategy and the functional model at BME" (Project ID: TÁMOP-4.2.1/B-09/1/KMR-2010-0002) and "Talent care and cultivation in the scientific workshops of BME" (Project ID: TÁMOP-4.2.2/B-10/1-2010-0009).

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