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Diagnostic of axial flow fans involving the phased array microphone technique

Thesis booklet

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1 Introduction

The regulations regarding the efficiency of axial flow fans are increasingly stringent. If the machine operates in the vicinity of people, the emitted noise is also a critical issue. Accordingly, during the design of axial fans the low-noise operation is also a primary objective, in addition to the desired output power and the good efficiency. Any axial flow fan in an industrial environment may exhibit aerodynamic as well as acoustic behavior being different from that suggested by the measurement data specified in the catalogue because the operation conditions may significantly differ from the conditions assumed in the design or realized in the performance curve measurements. In this case, an aerodynamic-acoustic diagnostics of the fan is required, which takes into account the mounting conditions of the fan. Based on the results it is possible to create an installation environment which grants a more efficient and silent operation, or to design an impeller, which is more suited to the circumstances. During such a diagnostic investigation the spatially resolved information is essential from an aerodynamic and acoustic point of view, in order to better understand the noise and loss generation phenomena.

A significant part of the noise emitted by an axial flow fan is aeroacoustic noise and it originates from different sources:

- *Gutin-noise*: in a point of the plane of the rotor there is pressure fluctuation when the blade passes, which is the source of the Gutin-noise.
- *Interaction noise*: because of the disturbed flow around the stationary objects (stator blades, struts, etc.) near the impeller the fan blades pass through different velocity fields periodically, this causes a periodic alternate force on the blades, which produces a tonal noise.
- *Turbulent noise*: the noise generated by turbulent fluctuations in the flow.
- *Selfnoise of the blades:* the noise generated by the blades, like by bodies placed in the flow.

The selfnoise of the blades originates from different flow phenomena, which are the following based on the literature:

- *Turbulent ingestion noise*: it is generated by the pressure fluctuations on the leading edge caused by the upstream turbulence.
- *Turbulent boundary layer noise:* it originates from the wall pressure fluctuations due to boundary layer turbulence.
- *Separated flow noise:* in case of high angle of attack, the blades behave like bluff bodies, the suction side boundary layer separates from the blade surface and the emitted noise increases significantly.
- *Vortex-shedding noise:* it is generated by the coherent vortices shedding over the blade profile and the trailing edge.
- *Turbulent boundary layer - trailing edge (TBL-TE) noise:* the noise scattered by the attached turbulent boundary layer past the trailing edge.
- *Tip leakage flow noise:* it is generated by the turbulent leakage flow over the blade tip.

The power of the noise emitted by a fan can be determined by several methods: I) by estimating from the data of the operating point of the fan, II) by calculation from local flow characteristics, III) by measurement.

In the I) case the emitted noise power can be estimated from the operating point by using theoretical or semi-empirical model laws. The drawback of these methods is the limited application range and the moderate accuracy.

In the II) case it is necessary to determine the spatially and time resolved flow characteristics (pressure, velocity) with the help of measurement or simulation. From the local velocity and pressure perturbations the source terms of the inhomogeneous acoustic wave equation can be calculated using acoustic analogies.

III) The noise emitted by a fan can be measured in different ways.

With one microphone it is possible to measure the total emitted noise and the noise emitted by one source as well. The measurement of the total emitted sound power with one microphone is accurate, but it is costly because the measurement requires special infrastructure.

Using multiple microphones the locally emitted noise can be determined. In the literature in many cases the method is supplemented with the measurement of local flow characteristics, however the application is difficult because of the complexity of the required infrastructure and required low background noise.

By synchronously sampling with multiple microphones, placed in known positions a phased array microphone (PAM) can be made. The PAM measurement data are evaluated by beamforming algorithms. The result of beamforming is a noise source map, which shows the position and the strength of the noise sources at different frequencies.

The goals of the thesis:

- The development of an acoustic diagnostic method for axial flow fans placed in short cylindrical housing, which fulfil the requirements formulated above. Expansion of the literature regarding the two dominant noise sources of axial flow fans: the TBL-TE noise and the tip leakage flow noise.
- In the case of the TBL-TE noise the comparison of PAM measurement results with semi-empirical model results.
- Elimination of the noise source ambiguity in case of the noise sources related to the blade tips.
- Investigation of the effect of the inlet geometry on the tip leakage flow noise.

2 Methods

The investigations were made on an axial flow fan (Fig. 1) with 4 different rotational speed. The diameter of the impeller was 300 mm. The fan had 5 thin, cambered blades, didn't have stator and was placed in a short cylindrical house with short-tapered entry. The acoustic measurements were carried out with a PAM from the upstream direction of the fan. The PAM data was evaluated with the ROSI beamforming algorithm, with which the noise source maps can be made in a co-rotating reference frame in order to investigate the noise emitted by the blading. The acoustic measurements were supplemented with inlet velocity profile measurements in every case.

In the case of the TBL-TE noise, the radial distribution of the suction side displacement thickness was calculated with the help of 2D cascade correlations. The spectrum of the TBL-TE noise was estimated by semi-empirical model from the displacement thickness distributions.

In the case of the noise sources related to the blade tips new PAM measurements were carried out using bellmouth entries with various radii and CFD simulations were made in order to better understand the flow phenomena.

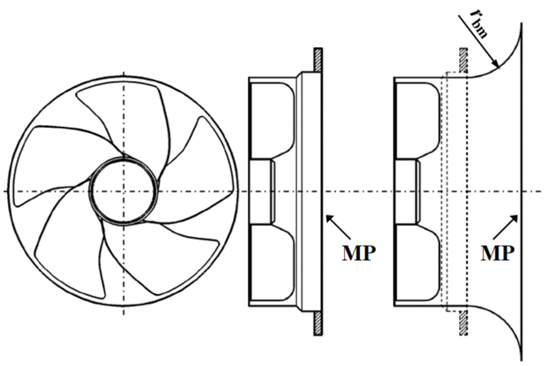

Figure 1: Fan of the case-study - front view and side segment

3 Results

In the case of the TBL-TE noise, it was difficult to compare the noise source maps of the PAM measurements and the model results. The problem was that the beamforming maps show the values of the point spread function in the case of one pointsource, and the superposition of the point spread functions in the case of more, incoherent sources. In order to solve the problem, a method was developed, with which the radial distribution of the source strength from the used BPM model [T1.1] and from the source maps of the PAM measurements are comparable. The method takes into account the effect of the point spread functions. (Fig. 2.) With this method it was proved, that the BPM model - which was developed for standalone wings - gives back the PAM measurement results with +/- 3 dB accuracy in 90% of the investigated cases.

The results are summarized in the I. thesis of the dissertation.

In the case of noise sources related to the blade tips (Fig. 3/a) a noise source ambiguity appeared, the tip leakage flow and also the turbulent ingestion could be labelled as the noise source. In order to eliminate the ambiguity, a method was developed with which the ambiguity can be eliminated during the measurements and the evaluation of the data. The PAM measurements were repeated with different bellmouth entries and CFD simulation was carried out.

The essence of the noise source ambiguity elimination method is the reduction of the leakage flow by reducing the tip clearance of one blade. After the repeated PAM measurements, the source of the noise can be determined by the investigation of the change of the noise peaks in the blade passages after the elongated blade. In the case study (Fig. 3/c) the source strength levels decreased in the first and the second blade passages after the elongated blade (label 1 and 2 in the fig), which is circumstantial evidence of the intensive leakage flow and the double-leakage flow. The CFD simulations confirmed the results. In the left hand side of Fig. 4 the visualisation of the leakage flow with pathlines can be seen, in the case of the short-tapered entry. The LE and TE labels show the leading and the trailing edge of the blades. The red circle shows the impingement of the tip leakage flow from the previous blade and the development of the double leakage flow.

By affixing the bellmouth entries the strength of the noise sources near the leading were decreased. (Fig. 3/b) The investigations proved that the cause of the noise reduction is the moderation of the stagnation zone near the casing, and with that the moderation of the leakage flow and the double-leakage flow. (right hand side of Fig. 4) The results were confirmed by the noise source ambiguity elimination method as well, the noise strengths in the blade passages after the elongated blade didn’t decrease. (Fig. 3/d)

The results are summarized in the II. III. and IV. theses of the dissertation.

The theme of the dissertation is a recent topic in the literature. In [1] the results of phased array microphone measurements and the BPM model results of the TBL-TE noise are compared in the case of a standalone airfoil, and the noise generated by the tip vortex also investigated. In [2] the TBL-TE noise model and the phased array microphone measurements are compared for a rotor with three blades, but the investigated case is not a real fan geometry. In [3] phased array microphone measurements of real fan geometries were carried out, but the results are not compared to model results, and the investigated noise sources are mostly the leading and trailing edges. With my dissertation, I have demonstrated that the BPM model can be applied to real fan geometries and that a microphone array can also be used to investigate the noise sources associated with the blade tips.

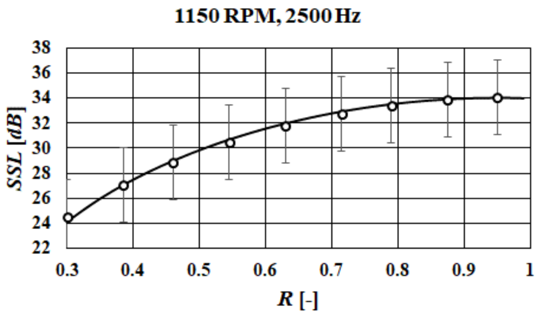

Figure 2: Example for the radial distribution of the source strength levels
○ BPM model, ▬ PAM measurement

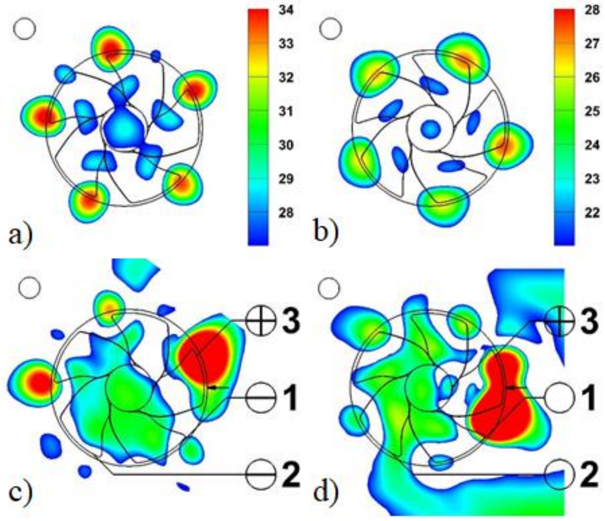

Figure 3: Noise source maps [dB], f_{mid} = 5 kHz, n = 1400 [RPM], rotation direction: counter clockwise a): short-tapered entry; b): bellmouth entry; c): short-tapered entry with reduced tip clearance; d): bellmouth entry with reduced tip clearance

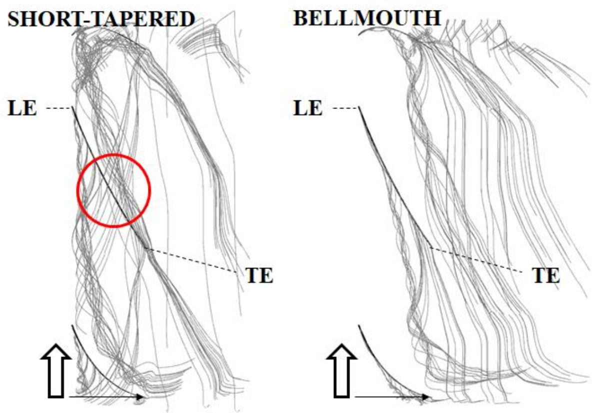

Figure 4: Visualisation of the tip leakage flow with pathlines,
n =1400 [RPM] (CFD)
LE: leading edge, TE: trailing edge
black arrow: axial direction, white arrow: circumferential direction

4 Theses

I. THESIS: **The process showed in Fig. T1.1 serves the following purposes:**

- Extension of the turbulent boundary layer - trailing edge noise model which can be found in the literature [T1.1] to rotor-only axial fan impellers with thin cambered blades, placed in short cylindrical housing.

- Comparison of the model results with phased array microphone measurements from the upstream direction of the fan.

The steps of the process are the following:

I. Based on the measurement of the radial distribution of v_{1ax}, calculation of the radial distribution of Θ using empirical cascade correlations, then determination of the radial distribution of δ^* using the H distribution in Table T1.3 which is based on the literatures [T1.2]-[T1.7].

II. Calculation of the $\overline{p^2}$ distribution of the turbulent boundary layer - trailing edge noise in the required frequency bands, then the calculation of the $\overline{ss}_{BPM}$ distributions with help of the $\overline{PSF}$-s, which were calculated from the microphone positions.

III. Making noise source maps from the phased array microphone measurement results in the required frequency bands, then the calculation of the $\overline{ss}_{PAM}$ distributions with circumferential averaging.

IV. Calculation of the source strength level distributions from the source strength distributions of the two methods, then bringing them to the common level with one frequency and radius independent offset.

The difference between the measurement and model results are +/- 3 *dB* in 90% of the cases within a 40 *dB* wide range in the validity range of Table T1.3. Figure T1.2 shows the distribution of the differences.

Publications related to the thesis: [P1] [P2] [P3] [P4] [P5] [P6] [P7] [P8] [P9]

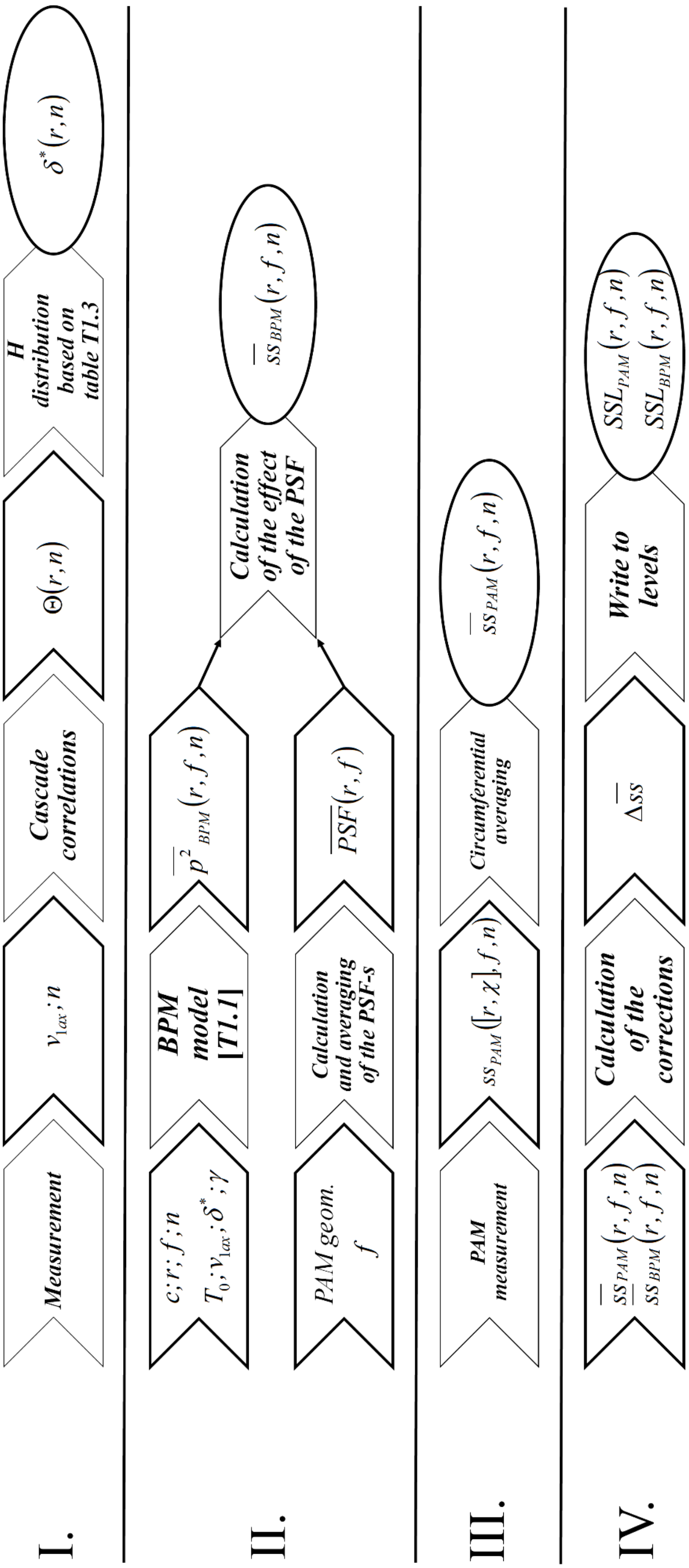

Figure T1.1 - The process of the comparison of the phased array microphone measurements and BPM mode

Table T1.1 - References

Nr.	Reference
[T1.1]	*Brooks, T. F., Pope, D. S. & Marcolini, M. A., 1989. Airfoil Self-Noise and Prediction, NASA Langley Research Center: NASA Reference Publication 1218.*
[T1.2]	*S. Deutsch and W. C. Zierke, "The Measurement of Boundary Layers on a Compressor Blade in Cascade at High Positive Incidence Angle," NASA Contractor Report 179491, Cleveland, Ohio, USA, 1986.*
[T1.3]	*P. Kool, J. DeRuyck and C. Hirsch, "The Three-Dimensional Flow and Blade Wake in an Axial Plane Downstream of an Axial Compressor Rotor," in ASME International Gas Turbine Confernce and Products Show, ASME Paper 78-GT-66, London, England, 1978.*
[T1.4]	*S. Lieblein, "Experimental Flow in Two-Dimensional Cascades," in Design of Axial-Flow Compressors, Chapter VI, Washington D. C., NASA SP-36, 1965.*
[T1.5]	*S. Lieblein and W. H. Roudebush, "Low-speed wake characteristics of two-dimensional cascade and isolated airfoil sections," National Advisory Comittee for Aeronautics, Technical Note 3771, Cleveland, Ohio, 1956.*
[T1.6]	*A. Ravindranath and B. Lakshminarayana, "Rotor Wake Mixing Effects Downstream of a Compressor Rotor," Journal of Engineering for Power, vol. 104, no. 1, pp. 202-210, 1981.*
[T1.7]	*B. Reynolds and B. Lakshminarayana, "Characteristics of Lightly Loaded Fan Rotor Blades," NASA Contractor Report 3188, Hampton, Virginia, USA, 1979.*

Table T1.2 - Nomenclature

Notation	Name		
c [m]	chord length	s [m]	spacing
D [-]	Lieblein diffusion factor	ss [Pa^2]	source strength
f [Hz]	frequency	$\overline{ss}$ [Pa^2]	circumferentially averaged source strength
f_{mid} [Hz]	middle frequency of the third-octave bands	$\Delta\overline{ss}$ [-]	source strength correction
H [-]	shape factor	SSL [dB]	source strength level
i [m]	camber	St [-]	Strouhal-number
Ma [-]	Mach-number	T_0 [$C°$]	temperature
n [1/s]	rotational speed	v_{1ax} [m/s]	inlet axial velocity
$\overline{p^2}$ [Pa^2]	square of the sound pressure	α_1 [°]	angle of attack
PSF [-]	point spread function	δ^* [m]	suction side boundary layer displacement thickness
$\overline{PSF}$ [-]	averaged point spread function	γ [°]	stagger angle (measured from the circumferential direction)
r [m]	radius	Θ [m]	suction side boundary layer momentum thickness
R [-]	dimensionless radius (non-dimensioned by the tip radius)	χ [°]	circumference angle
Re_c [-]	chord based Reynolds-number	$\mathscr{F}$ [-]	complementary cumulative distribution function
Abbreviations			
BPM	Brooks-Pope-Marcolini	*PAM*	Phased Array Microphone

Table T1.3 - The radial distribution of the shape factor

Span %	**0**	**25**	**50**	**75**	**100**
H [-]	1.8	1.1	1.1	1.1	1.0

Table T1.4 - Validity range

Quantity	**Lower range**	**Upper range**
Re_c [-]	23000	200000
c/s [-]	0.69	1.5
i/c [-]	0.0615	0.0138
γ [°]	27	35
α_1 [°]	0	5.5
D [-]	0.33	0.58
f [*Hz*]	2000	3150
St [-]	0.125	1.5
Ma [-]	0.012	0.07

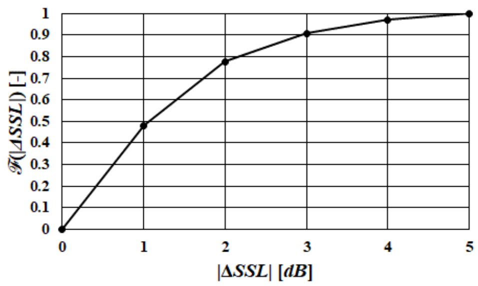

Figure T1.2 - The complementary cumulative distribution of the difference between the PAM measurements and the BPM model

***II. THESIS*: In the case of axial flow fans built in short cylindrical housing the replacement of the short-tapered entry with bellmouth entry contributes to the reduction of the broadband noise emitted from the tip region to the upstream direction of the fan:**

- Reduction of the peripheral separation zone due to the short-tapered entry.

- Therefore increasing the average angle between the leakage flow direction and the circumferential direction.

- Therefore the elimination of the impingement of the tip leakage flow on the following blade, and the development of the double leakage flow.

Publications related to the thesis: [P10]

***III. THESIS*: Strong noise source peaks can appear near the leading edge - tip region in axial flow fan's noise source maps created in co-rotating reference frame causing a noise source ambiguity. Since these peaks can be related to the following phenomena:**

- The flow phenomena related to the leading edge of the given tip, or

- the phenomena related to the leakage flow of the preceding blade in the circumferential direction.

In order to eliminate the noise source ambiguity the following process is recommended:

a) Reduction of the tip clearance - and tip leakage flow - of an arbitrarily chosen blade with a flexible, light weighted, firmly fixed plate.

b) Repetition of the phased array measurements with the elongated blade and creation of noise source maps. Comparison of the noise source maps of the uniform and the reduced tip clearance in the third-octave bands where the noise source peaks appear.
c) If the noise source peaks reduce systematically in the blade passages following the elongated blade, than the noise source peaks are related to the tip leakage flow.

Publications related to the thesis: [P7] [P9]

***IV. THESIS*: With axial flow fan's noise source maps created in co-rotating reference frame the presence of the double-leakage flow can be diagnosed, and its noise generation effect can be investigated with the extension of the noise source ambiguity elimination method. If the noise source peaks in the investigated third-octave bands reduce systematically in the second blade passage following the elongated blade in the circumferential direction, that is the circumstantial evidence of the double leakage flow.**

Publications related to the thesis: [P7] [P9]

Publications related to the theses

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[P2] T. Benedek and P. Tóth, "Beamforming Measurements of an Axial Flow Fan in an Industrial Environment," *Periodica Polytechnica, Mechanical Engineering*, vol. 57, no. 2, pp. 37-46, 2013.

[P3] T. Benedek and J. Vad, "Concerted Aerodynamic and Acoustic Diagnostics of an Axial Flow Industrial Fan, Involving the Phased Array Microphone Technique," in *ASME Turbo Expo 2014, Paper GT2014-25916*, Düsseldorf, Germany, 2014.

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[P9] T. Benedek and J. Vad, "An industrial on-site methodology for combined acoustic-aerodynamic diagnostics of axial fans, involving the Phased Array Microphone technique," *International Journal of Aeroacoustics*, vol. 15, no. 1-2, pp. 81-102, 2016.

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[E2] C. Horváth, B. Tóth, P. Tóth, T. Benedek and J. Vad, "Reevaluating Noise Sources Appearing on the Axis for Beamforming Maps of Rotating Sources," in *International Conference on Fan Noise, Technololgy and Numerical Methods*, *Paper 13*, Paris, France, 2015.

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[2] B. Zajamsek, C. J. Doolan, D. J. Moreau, J. Fischer and Z. Prime, "Experimental investigation of trailing edge noise from stationary and rotating airfoils," *The Journal of the Acoustical Society of America,* vol. 141, pp. 3291-3301, 2017.

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