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TOWARDS A BETTER UNDERSTANDING OF TURBOMACHINERY BEAMFORM MAPS

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ABSTRACT

Beamforming processes developed specifically for rotating sources have provided a nonintrusive means by which turbomachinery noise sources can be localized. Investigations by Horváth et al. have shown that for unducted rotating coherent noise sources beamforming will localize the noise sources to their Mach radii rather than their true noise source positions. As a further step, Horváth et al. have shown that beamforming investigations utilizing beamforming processes developed specifically for the investigation of rotating noise sources in an absolute as well as a rotating reference frame need to take noise sources appearing on the hub into consideration in order to accurately identify all noise sources. The investigations showed that for certain frequencies this noise source can result from a combination of motor noise which is truly located on the hub, rotor-stator interaction noise radiating from along the rotor blade span, and even rotor-stator interaction noise radiating from along the span of the stationary guide vanes. The present investigation continues this study by investigating certain parameters and providing further guidelines for separating the beamform peak which is localized to the hub into its true noise source components, which are located on the axis as well as along the span of the rotor and the stator, making it possible to better understand turbomachinery beamform maps.

Keywords: axial flow turbomachinery, beamforming, Mach radius, tonal noise sources

NOMENCLATURE

B	[-]	blade count
L_B	[dB]	beamforming peak level
L_p	[dB]	sound pressure level
M_t	[-]	blade tip Mach number
M_x	[-]	flow Mach number
n	[-]	harmonic index
p	[Pa]	sound pressure
p_a, p_b	[Pa]	sound pressures of coherent noise sources
p_{ref}	[Pa]	reference sound pressure
p_t	[Pa]	total sound pressure
x	[-]	number of equal strength coherent in phase noise sources
y, z	[m]	coordinates in the plane of the fan
z^*	[-]	Mach radius
α	[°]	phase angle
Θ	[°]	angle of the viewer

Subscripts and Superscripts

one	contribution form one source
1	acoustic harmonic
2	loading harmonic

1. INTRODUCTION

As legislations and regulations have become more stringent along with the expectations of customers, the amount of research in the field of turbomachinery aeroacoustics has progressively increased. As a result of this, turbomachinery design requirements are continuously evolving, often pushing the limits of design practices. The drive to further increase efficiency and reduce noise levels is also pushing technology to develop at a fast pace. Design, simulation, and measurement technologies are therefore being refined and even radically reformed in the process. With regard to acoustic measurement technology, microphone technology has been improved, measurement techniques have been developed, and a combination of the two has helped us gain more information from the recorded acoustic data than ever before possible.

Traditionally, microphones have been set up and recorded individually, with the spectrum of the individual microphone signals providing a vast amount of information regarding the radiated noise field of the investigated phenomena. The development of phased array microphone beamforming technology has made it possible to extend these capabilities, simultaneously recording multiple microphone signals and then processing the results in order to learn more about the noise sources which are being investigated. Beamforming processes developed specifically for rotating sources have provided a nonintrusive means by which the noise sources of turbomachinery can be localized [1-3]. Utilizing phased array microphones and these advanced beamforming algorithms we are able to collect data for identifying turbomachinery noise sources, which is becoming a common practice [1-5]. On the other hand, the results are not so easily understood. Most beamforming algorithms assume that the noise is generated by compact incoherent noise sources, in most cases resulting in beamform maps which localize the noise sources to their true locations. If the investigated noise sources are coherent, the beamforming algorithms often have a hard time distinguishing one source from the other, resulting in the noise sources being incorrectly located on the beamform maps. This publication is one in a series that aims at understanding the beamform maps of various unducted turbomachinery applications. The goal is to first understand these beamform maps and then use the newly gained knowledge for developing methods of evaluating them, while in the long run taking this a step further and developing new beamforming methodologies specifically for the investigation of rotating noise sources. Questions which are addressed in this investigation are: If a noise source which is localized to the axis by beamforming is looked at in an absolute or rotating reference frame, will the source strength be the same? When we have multiple coherent noise sources which are localized to the same Mach radius position, how can we determine the individual contributions? With regard to the second question, only a few specific cases are looked at here, since there are many possibilities which need to be investigated.

The publications of Horváth et al. regarding unducted rotating coherent noise sources have shown that the noise sources are pinpointed to their respective Mach radii rather than their true locations by beamforming methodologies [6]. The name "Mach radius" or "sonic radius" refers to the mode phase speed, the speed at which the lobes of a given mode rotate around the axis, having a Mach number of 1 at the Mach radius ($z*$, a normalized radius, where $z* = 1$ refers to the blade tip) when examined from the viewpoint of the observer [7]. See Eq. (1). Based on these findings, Horváth et al. have explained the beamform maps of rotating coherent noise sources with regard to counter-rotating open rotors that are investigated from the sideline [8] as well as explaining why certain noise sources are localized to the axis in the case of a generic unducted axial flow fan test case which is investigated from the axial direction [9].

The investigation of a generic unducted axial flow fan test case by Horváth et al. focused on the noise sources appearing on the axis of the fan [9]. In many similar investigations, noise sources located on the axis have been associated with motor noise with no further investigations being considered [1, 5]. Taking into account what is known from [6] regarding unducted rotating coherent noise sources appearing at their respective Mach radii, it was shown that the noise sources appearing on the hub can for certain frequencies be resulting from noise sources located along the span of the rotor or the guide vane. This occurs when the wave fronts of coherent noise sources experience constructive and destructive interference, interacting with the phased array in the same manner as the wave front of a single monopole noise source located at the Mach radius of the given instance would. In the test case described in [9] the Mach radius is zero and therefore the noise source is localized to the axis. The Mach radius is calculated using Eq. (1), with n being the harmonic index, B being the blade count or guide vane count, M_t being the blade tip Mach number, M_x being the flow Mach number, and Θ being the angle of the viewer with regard to the axis (upstream direction referring to 0°), with subscripts 1 and 2 referring to the rotor or guide vane of the acoustic harmonic and loading harmonic, respectively. The equation is formulated for a turbomachinery system consisting of two rotors or one rotor and one guide vane which are moving relative to one another. Acoustic harmonic refers to the rotor or guide vane which is radiating noise while being loaded by the potential field and/or the viscous wake of the other, which is referred to as the loading harmonic. Both rows of rotors or guide vanes need to be considered as acoustic as well as loading harmonics in order to receive a complete and accurate sound field, since each blade row loads the other blade row and also radiates sound simultaneously [7].

$$z^* = \frac{(n_1 B_1 - n_2 B_2)}{(n_1 B_1 M_{t,1} + n_2 B_2 M_{t,2})} \frac{(1 - M_x \cos\Theta)}{\sin\Theta} \tag{1}$$

The results presented in [9] therefore provide an explanation as to why the investigated noise sources appear on the axis. Three tonal components of unducted axial flow turbomachinery noise were investigated: motor noise, interaction noise radiating from the guide vanes as they interact with the rotors, and interaction noise radiating from the rotors as they interact with the guide vanes. The present report makes a further contribution to these results, providing information regarding how to distinguish between the contribution of the motor, each rotor, and each stator to the level of the apparent noise source appearing on the axis. This is done by individually investigating the effect of each of these noise sources on the beamform peak which is localized to the axis. In this way further guidelines are provided which will help in separating the noise source appearing on the axis into its components.

This investigation is motivated by a desire to better understand the beamform maps of unducted axial flow turbomachinery, which is necessary in order to accurately process the results of rotating coherent as well as incoherent noise sources which are processed using currently available beamforming methods, and which will provide the basis of a new beamforming investigation method designed specifically for the investigation of unducted rotating coherent noise sources.

2. TURBOMACHINERY NOISE SOURCES

In categorizing turbomachinery noise sources, they can be split into two main groups, tonal and broadband noise sources. Tonal noise sources are characterized by a discrete frequency, and are associated with the regular cyclic motion of the rotor blades with respect to a stationary observer and with the interaction of the rotors with adjacent structures [10]. These are referred to as Blade Passing Frequency (BPF) tones and interaction tones, respectively. With respect to the present investigation, the coherence of the noise sources also needs to be taken into consideration. Coherent noise sources are characterized by a time invariant phase relationship. While in most cases broadband noise sources are not coherent, many tonal turbomachinery noise sources often are. Broadband noise sources are characterized by a wide frequency range, and are associated with the turbulent flow in the inlet stream, boundary layer, and wake [10].

3. AXIAL FLOW FAN TEST CASE

In this investigation a synthetic axial flow fan test case is presented. The synthetic fan is used instead of a real fan in order to provide a means by which multiple noise sources can individually be investigated while easily manipulating certain variables. Figure 1 provides a schematic of the fan test case which is synthesized herein. An axial flow fan having a variable number of rotor blades (5 are pictured in the figure) and downstream guide vanes (1 is pictured in the figure) is investigated by a microphone phased array located 0.3 *m* in the upstream axial direction. The fan has a diameter of 0.4 *m*. The diameter of the phased array is 1m. The microphones of the array are arranged along a logarithmic spiral, based on the design used in the OptiNav Inc. Array 24: Microphone Phased Array System.

The following three components of turbomachinery noise are investigated: motor noise, guide vane noise radiating from the guide vanes as they interact with the rotors, and rotor noise radiating from the rotors as they interact with the guide vanes. The motor is represented by 1 stationary monopole noise source located on the axis. The guide vanes are represented by stationary coherent monopole noise sources located at the blade tips, and the rotors are represented by coherent rotating monopole noise sources located at the blade tips. Figure 2 shows a schematic of the monopole noise sources which replace the true noise sources. They are represented by small spheres in the figure.

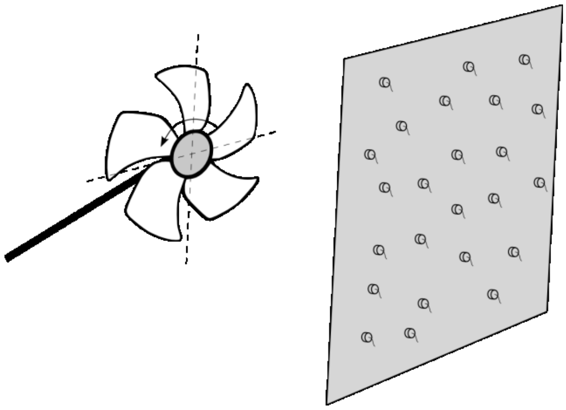

Figure 1. Schematic of the fan test case which is synthesized in the investigation.

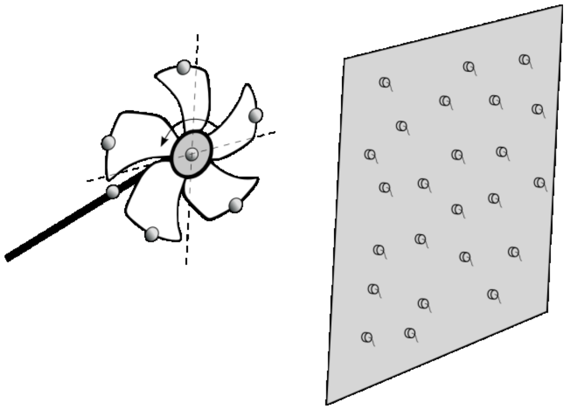

Figure 2. Synthetic fan test case, with monopole noise sources replacing the rotors, guide vanes and motor.

Only simulations of the synthetic test cases are presented in this investigation, but it should be mentioned that [9] showed that the simulations correctly localize the noise sources to their Mach radii and therefore these simulations can be used in further investigating other parameters. In order to account for the limited resolution of the finite aperture array, the investigated frequency is chosen as 3000 *Hz* for all test cases, and therefore the results provide beamform maps which clearly depict the investigated noise sources. Being a synthetic case, the sound pressure amplitude is defined at each noise source position instead of the sound power and whenever possible defined as having a sound pressure value which would be equivalent to a sound pressure level of 60 *dB* if measured at the source position. This investigation does not investigate the effect of phase difference at the source location, and therefore the phase of each noise source was set equal. The stationary monopole noise source located on the axis and representing the motor radiates at the investigated frequency, and should be considered as a harmonic of the motor noise. The stationary monopole noise sources representing the guide vanes also radiate at the same investigated frequency, as a result of the potential field and/or the viscous wake of the rotor blades rotating at a given RPM and interacting with the guide vanes or a harmonic of this tone. The coherent rotating monopole noise sources located at the blade tips and representing the rotors radiate at the same investigated frequency, which is resulting from the potential field and/or viscous wake of the guide vanes interacting with the rotor blades or one of its harmonics.

4. BEAMFORMING

For the simulations presented herein, in-house virtual noise source generation and propagation software is used for creating virtual microphone signals at the microphone positions. The in-house code is able to produce noise sources which are moving at subsonic speeds, while taking into account sound intensity attenuation with distance and the Doppler Effect. The simulation data is processed by versatile in-house beamforming software. Two types of algorithms are used: the classical frequency-domain based Delay & Sum (DS) method [11], which can localize incoherent stationary sources in an absolute reference frame, and the Rotating Source Identifier (ROSI) method [1], which can localize the incoherent sources which are stationary in a rotating reference frame. The results provide beamform maps, which display the magnitudes and the positions of the strongest sources located in the investigated plane for a given frequency range. The magnitudes of the beamform map sources are presented as levels which are calculated from sound pressure squared values which have been corrected for sound intensity attenuation with regard to distance. The values are therefore given with regard to the source position. The reference value used in the calculation of the levels is $2*10^{-5}$ *Pa*. Using these two algorithms, the sound sources originating from both the stationary and rotating elements of the fan can be localized.

Beamforming utilizes the phase differences measured between the microphone signals to determine the direction of arrival of the wave fronts. By adjusting the phase shifts (time delays) of the microphone signals relative to each other, a maximum correlation can be obtained between them. The corresponding phase shifts give information as to the direction of arrival of the wave fronts and hence the locations of the noise sources. This forms the basis of the DS beamforming method [11]. The method can be considered as forming a sensitivity curve, called mainlobe that is directed toward possible compact monopole noise source positions by phase adjustments. These possible source positions are defined by the user, providing focus points for the beamforming methodology, and the beamform maps display the strengths of the investigated sources.

The ROSI beamforming method is an extension of the DS method for rotating source models [1]. The main difference between the two methods is that the ROSI method applies a so called deDopplerization step in order to place the rotating noise sources into a rotating reference frame and hence make them stationary. The positions and velocities of the possible noise sources are accounted for by correcting the time difference and amplitude data with regard to each receiver position. The corrected source signals are then processed with a beamforming method that corresponds with the DS method. For a more detailed description of the ROSI method, see reference [1]. A more detailed description of the phased array microphone system and of the beamforming algorithms applied in the in-house code is available in [5].

In processing the test data the following parameters are applied. A sampling rate of 44100 *Hz* is used and 2 seconds worth of data are processed. A Hanning window is applied with a windowing size of 2048, which is applied with a 50% overlap. The narrowband beamform peak data is presented in the beamform maps and diagrams. It should be mentioned that the rotor noise sources were modelled in a rotating reference frame and when needed transferred into an absolute reference frame (making them rotating sources) by processing the data with the ROSI method. Vice versa, the stator noise sources were modelled in an absolute reference frame and when needed transferred into a rotating reference frame (rotating the stationary sources) by processing the data with the ROSI method.

5. RESULTS

As stated in the introduction, this paper further investigates turbomachinery noise sources which are localized to the axis by beamforming. The goal is to understand the effect of rotor blade number, stator blade number, and noise source amplitude on the resulting apparent noise source located on the axis, in order to help determine the contribution of each individual noise source.

The first test investigates the effect of motor noise source level on the level of the noise source located on the beamform map. The test examines changing the level of a single tonal noise source which is physically located on the axis and beamforming the results in both an absolute as well as rotating reference frame using the DS and ROSI beamforming methods. Figure 3 presents a diagram which compares the sound pressure level of the defined amplitude at the source location to the calculated beamform peak value, which is also calculated with regard to the source location. It can be seen that the values coincide well for the absolute and rotating reference frame results, having a constant difference of approximately 0.1 *dB*. This shows that the magnitude of the noise source which is physically located on the axis is independent from the coordinate system in which the noise source is investigated. Looking at Fig. 3, it can also be seen that with regard to the magnitude of the noise source there is a linear relationship between the source magnitude and the beamforming peak value. This suggests, as is customary in the beamforming literature, that for tonal sources physically located on the axis, the array can be calibrated with the help of a known source, after which the integral of the beamform map can be used in order to quantify results [11].

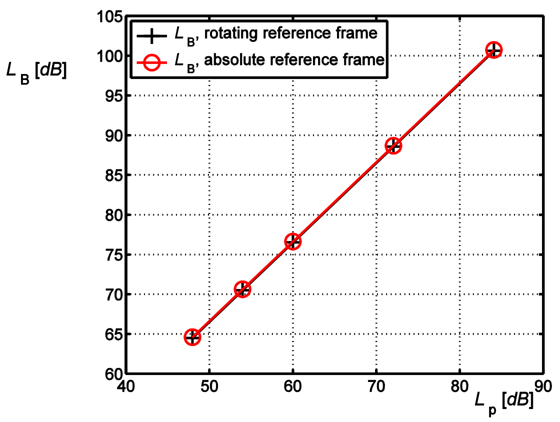

Figure 3. Relationship between the beamform peak level and the sound pressure level of the motor noise calculated with respect to the source.

The second test case investigates the effect of blade number on the level of the apparent noise source located on the axis. Multiple coherent in phase noise sources were evenly distributed around the axis. The noise sources were investigated in an absolute as well as rotating reference frame in order to investigate the effects of stationary sources (stators) in an absolute as well as rotating reference frame. (This is the same as investigating rotating sources (rotors) in a rotating and stationary reference frame, respectively, and therefore only one set of data is presented.) The number of sources was varied while keeping the frequency the same and therefore the rpm of the rotor was varied accordingly for each case. Source numbers ranging from 15-20 were investigated. Since this investigation does not look at the effect of phase difference between the sources, the number of rotors and stators is always kept equal and therefore the noise sources are always in phase.

Regarding coherent noise sources, it is known from classical acoustics that Eq. (2) can be used to determine the sound pressure level, L_p, of a single microphone measurement, where p_{ref} is the reference sound pressure and p_{t} is the total sound pressure, which can be determined according to Eq. (3) [12]. Here p_{a} and p_{b} refer to the sound pressures of two coherent noise source signals and α refers to the phase angle between them. The equation can be extended to take into account multiple sources. With regard to beamforming maps and superimposed apparent noise sources the authors have no information which can help in determining the contribution of each individual coherent noise source. This test is designed to give us a better understanding of these contributions.

$$L_p = 10 \log_{10}\left(\frac{{p_{\mathrm{t}}}^2}{{p_{\mathrm{ref}}}^2}\right) \tag{2}$$

$${p_{\mathrm{t}}}^2 = {p_{\mathrm{a}}}^2 + {p_{\mathrm{b}}}^2 + 2 p_{\mathrm{a}} p_{\mathrm{b}} \cos\alpha \tag{3}$$

Typical beamform maps from this multiple noise source test can be seen in Figures 4 and 5. The fan is viewed from the upstream direction, as depicted in Fig. 1, with the axis passing through the 0,0 position. Fig. 4 shows the beamform map of 15 equal strength rotating coherent in phase noise sources (stationary noise sources which have been processed using ROSI). Fig. 5 depicts the beamform map of 15 equal strength stationary coherent in phase noise sources (stationary noise sources processed using DS). As expected from the earlier investigations of Horváth et al. [9], the noise sources are always localized to the axis by beamforming. A summary of the coherent in phase noise source results can be seen in Figure 6, which depicts the beamform peak level of the apparent noise source which is localized to the axis for both the rotating as well as stationary coherent in phase noise sources as a function of source number.

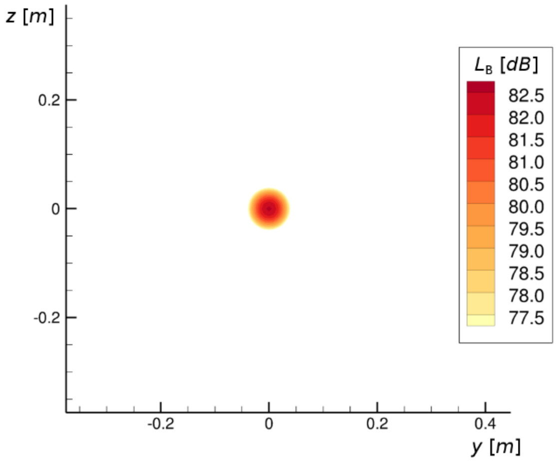

Figure 4. Beamform map of 15 stationary, coherent, in phase noise sources investigated in the rotating reference frame.

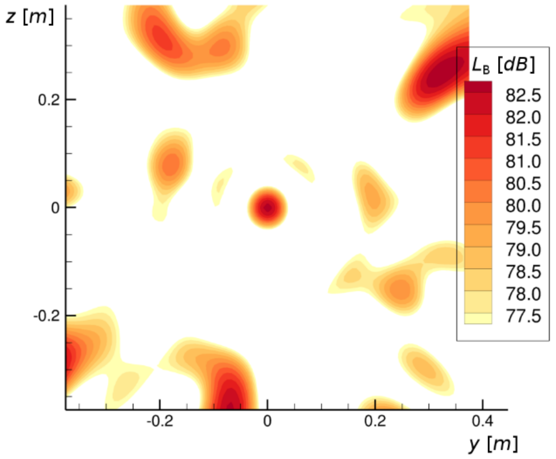

Figure 5. Beamform map of 15 stationary, coherent, in phase noise sources investigated in the absolute reference frame.

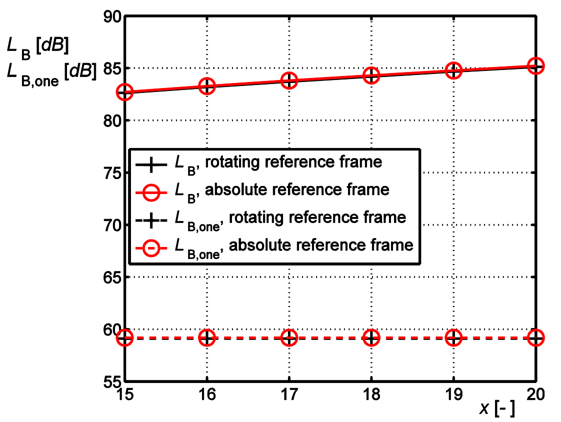

Figure 6. Beamform peak level of the equal strength coherent in phase apparent noise source as a function of source number.

In this investigation it is assumed that all of the coherent noise sources are of equal strength, which is known to be true in this case and generally true for axisymmetric turbomachinery noise sources. It is also known that the wave fronts of coherent noise sources experience constructive and destructive interference as they propagate, resulting in modes. In this test case a planar wave mode is traveling along the axis of the fan, the Mach radius of which is zero. Since the microphones used in the investigation are all relatively close to the axis and far enough away from the noise source for the planar wave mode to have already developed, it is expected that the contributions from each of the noise sources should be in the same phase at the in plane microphone positions as at the source positions. If this hypothesis is true, and the noise sources have the same phase difference at the microphones as they do at their source locations, then an equation which is analogous to Eq. (2) will describe the increase of beamform peak level at the Mach radius as a function of number of coherent in phase noise sources. According to the hypothesis, in this test case $\cos(\alpha)$ is equal to 1 since the phase of each noise source is the same, and Eq. (2) can be rewritten for the beamform peak level, L_B, of x coherent in phase noise sources of equal strength, as seen in Eq. (4). Here p_{one} refers to what would be the pressure amplitude of the beamform peak which could be calculated back from the beamforming results for one of the equal strength coherent in phase noise sources at the apparent source location. The equation can be rewritten for levels, as seen in Eq. (5). $L_{B,one}$ refers to the beamform peak level contribution from one of the equal strength coherent in phase noise sources at the apparent source location (Mach radius). Rearranging Eq. (5), one can solve for $L_{B,one}$, which should be equal for each instance investigated here, if the hypothesis is correct.

$$L_B = 10\log_{10}\left(\frac{p_{one}^2}{p_{ref}^2}\right) + 10\log_{10}\left(\frac{x^2}{p_{ref}^2}\right) \tag{4}$$

$$L_B = L_{B,one} + 20\log_{10}(x) \tag{5}$$

The values for $L_{B,one}$ are also plotted in Fig. 6 as a function of number of sources, where it can be seen that they are equal. It can therefore be concluded that though the noise sources are not physically located at the Mach radius position, the levels can be added using equations which are customarily used for the addition of coherent sound pressure levels. Taking advantage of this, one can determine the beamform peak amplitude contribution of one of the equal strength coherent in phase noise sources to the apparent noise source located at the Mach radius position.

The investigation is conducted in both the absolute as well as rotating reference frame with the help of the DS and ROSI methods, as can be seen in Fig. 6. Similar to the results for the noise source which is physically located on the axis, the difference between $L_{B,one}$ for DS and ROSI is approximately 0.1 *dB*. This shows that the results are independent of reference frame in which they are investigated, as was also the case for the noise source physically located on the axis.

Since the amplitudes of the noise sources used in the second test are defined as having a sound pressure level of 60 *dB* at the source position, they can be compared to the one case in the first test which also has a magnitude of 60 *dB*. The values of the beamform map peaks do not agree as can be seen in comparing Figs 3 and 6. Though beyond the scope of this investigation, further tests will investigate the relationship between the beamform peak level of one noise source which is physically located on the axis to the contribution from one of the noise sources which contributes to the apparent noise source which is located at the Mach radius.

6. CONCLUSIONS

This investigation is one in a series which looks at the beamforming results of coherent rotating noise sources through a turbomachinery fan test case. The goal is to better understand the beamforming results of currently available beamforming methods and to provide preliminary information which is needed in the development of a new beamforming method designed specifically for rotating coherent noise sources.

While earlier investigations provided information as to the localization of the rotating coherent noise sources to the Mach radius, which is the axis in this particular case, this investigation takes this a step further. The first test case investigates whether the level of a noise source which is physically located on the axis is affected by the choice of reference frame. The results show that the results are the same for the DS and ROSI investigations. The results also suggest that the results can be quantified by integrating the beamform maps, as is customary in beamforming investigations, though this is beyond the scope of the present investigation.

A second test investigates the contribution from equal strength coherent in phase noise sources to the magnitude of the apparent noise source located at the Mach radius. The noise sources are investigated in a rotating as well as absolute reference frame. The results show that the equations used in acoustics for adding levels can be applied in determining the contributions from equal strength coherent in phase noise sources to the apparent noise source located at the Mach radius. The results show that the same levels can be calculated for one test case independent of reference frame in which it is investigated. On the other hand, the beamforming peak level is dependent on whether the noise source is physically located at the given position or just an apparent noise source.

Though beyond the scope of this present report, further tests will investigate the relationship between the beamform peak level of one noise source which is physically located on the axis to that of the contribution from one of the noise sources which contributes to the apparent noise source which is located on the axis.

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REFERENCES

[1] Sijtsma, P., Oerlemans, S., and Holthusen, H., 2001, "Location of Rotating Sources by Phased Array Measurements", *National Aerospace Lab. Technical Report* Paper NLR-TP-2001-135.

[2] Pannert, W., and Maier, C., 2014, "Rotating Beamforming – Motion-Compensation in the Frequency Domain and Application of High-Resolution Beamforming Algorithms", *Journal of Sound and Vibration*, Vol. 333, Issue 7, pp. 1899-1912.

[3] Herold, G., and Sarradj, E., 2015, "Microphone Array Method for the Characterization of Rotating Sound Sources in Axial Fans", Proc. *International Conference on Fan Noise, Technology and Numerical Methods*, Lyon, France, paper 026.

[4] Kennedy, J., Eret, P., Bennett, G., Sopranzetti, F., Chiariotti, P., Castellinni, P., Finez, A., and Picard, C., 2013, "The Application of Advanced Beamforming Techniques for the Noise Characterization of Installed Counter Rotating Open Rotors" Proc. *19th AIAA/CEAS Aeroacoustics Conference*, Berlin, Germany, Paper AIAA 2013-2093.

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

[6] Horváth, Cs., Envia, E., and Podboy, G. G., 2014, "Limitations of Phased Array Beamforming in Open Rotor Noise Source Imaging", *AIAA Journal*, Vol. 52, No. 8, pp. 1810-1817.

[7] Parry, A. B., and Crighton, D. G., 1989, "Prediction of Counter-Rotation Propeller Noise", Proc. *AIAA 12th Aeroacoustics*

Conference, San Antonio, Texas, AIAA-89-1141.

[8] Horváth, Cs., 2015, "Beamforming Investigation of Dominant Counter-Rotating Open Rotor Tonal and Broadband Noise Sources", *AIAA Journal*, Vol. 53, No. 6, pp. 1602-1611.

[9] Horváth, Cs., Tóth, B., Tóth, P., Benedek, T., and Vad, J., 2015, "Reevaluating Noise Source Appearing on the Axis for Beamform Maps of Rotating Sources", Proc. *International Conference on Fan Noise, Technology and Numerical Methods*, Lyon, France, paper 013.

[10] Smith, M. J. T., 1989, *Aircraft noise*, Cambridge University Press.

[11] Mueller, T., Allen, C., Blake, W. K., Dougherty, R. P., Lynch, D., Soderman, P., and Underbrink, J., 2002, *Aeroacoustic Measurements: Chapter 3.*, Springer.

[12] Norton, M., and Karczub, D., 2003, *Fundamentals of Noise and Vibration Analysis for Engineers*, Cambridge University Press.