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DEVELOPMENT OF A MEASUREMENT METHODOLOGY FOR THE BEAMFORMING INVESTIGATION OF CENTRIFUGAL FANS

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ABSTRACT

The investigation of turbomachinery applications using beamforming technology is rather common in the aeroacoustics community, but usually restricted to the investigation of axial flow turbomachinery. This investigation presents the development of a measurement setup and beamforming methodology that enables the investigation of centrifugal turbomachinery. A test setup utilizing Acoustically Transparent Duct technology has been built and tested on a centrifugal fan testbench at the Karlsruhe Institute of Technology. Measurements have been carried out on the test setup using a planar phased microphone array as well as a radial phased microphone array by colleagues from the Budapest University of Technology and Economics. The data has been processed using the ROSI beamforming method and the Segmented ROSI beamforming method. The investigation presents sample data for each approach and discusses the advantages and disadvantages of each. It is shown that the beamforming investigation of a centrifugal test bench can successfully be carried utilizing this technology, with each approach having its advantages and disadvantages.

1 INTRODUCTION

The aeroacoustic investigation of turbomachinery applications via beamforming methodologies is not uncommon in the literature, as many methodologies and resulting studies have already been published. On the other hand, it is essential to mention that a large portion of the published material deals with axial flow turbomachinery, which makes up a significant portion of the market but is not all-encompassing. It is relatively rare to see the beamforming investigation of centrifugal turbomachinery, not because there is no interest in the noise reduction of such turbomachinery applications but rather because such test cases provide many further challenges beyond those already associated with axial flow turbomachinery. First, such investigations need to be carried out using acoustically transparent yet hydrodynamically sealed casings that allow one to see into the blade passages, which would otherwise not allow for a direct view of the noise sources. Second, the applied beamforming methodology must organize and process the data collected from the rotating sources, considering when the noise sources are within direct view and when asymmetries such as the volute tongue play a role in the noise generation.

The acoustical investigation of a centrifugal fan has been undertaken within the scope of a collaboration between Karlsruhe Institute of Technology, Institute of Thermal Turbomachinery (KIT), and the Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Fluid Mechanics (BME). One of the first major goals of the collaboration is to develop a measurement methodology for beamforming investigations on centrifugal turbomachinery. Further configurations and operation points can be tested once the measurement methodology can be applied reliably. To date, two joint beamforming test campaigns have been carried out on the centrifugal test rig located at KIT with phased array microphone systems provided by BME.

In the first test campaign, the centrifugal fan test rig has been investigated through a small service window. Though the results of preliminary measurements and the first test campaign have provided a great deal of information on behalf of the participants, investigating the noise sources in greater detail has not been possible [1]. Based on the findings, the team has further developed the approach, creating a complete casing out of acoustically transparent material and refining how the data has been collected and processed. The results of the second test campaign have been considered successful, as the results show much greater detail than could be reached in the first test campaign. This paper describes the further development of the test rig and the phased array microphone system, and a description of the beamforming methods utilized in processing the data.

2 SEGMENTED ROSI METHOD

Investigating unsteady cyclically repeating phenomena, such as turbomachinery applications, calls for specially designed methods. Beamforming algorithms generally start with a discretized investigation region and synchronously recorded continuous time signals. The recorded acoustic signals are collected by the individual microphones of the phased microphone array and, by applying time shifts and amplitude corrections, can compute the source amplitudes in each investigated grid point to generate a source amplitude distribution. The Delay & Sum algorithm, the most fundamental beamforming method, is the foundation for several more complex beamforming methods in the time and frequency domain [2]. The results observed on beamforming maps can be enhanced using deconvolution techniques, providing a better sidelobe ratio and a narrower beamwidth. Although these algorithms can extract the genuine noise sources from the sidelobes that contaminate the beamforming maps of the Delay & Sum approach, they all assume that the noise sources under investigation are stationary. Beamforming methods designed for stationary noise sources cannot be applied to turbomachinery test cases, as the noise sources will be smeared around the circumference of the investigated region of interest [3].

The phased microphone array data from the two measurement campaigns described herein has been processed and analyzed using an in-house beamforming code. The beamforming method applied is a further development of the ROtating Source Identifier (ROSI) beamforming method. The ROSI method, developed by Sijtsma et al. [4], is a beamforming method designed for subsonic rotating noise sources. As the noise sources are moving, and their relative distances from the listener continuously change, a Doppler shift is experienced in the collected data [5]. The ROSI method takes microphone sound pressure data and angular position information and evaluates the potential noise source positions at each timestep, compensating for position, amplitude, and frequency. Therefore, the method reconstructs the acoustic signals of the potential noise sources on each microphone at given reference positions. This is referred to in the literature as the de-Dopplerization process. The reconstructed signals are then interpolated to provide an equidistant time series and converted into the frequency domain for further processing using a Discrete Fourier Transform having a given window length.

Assuming that the window length does not coincide with the number of samples in one revolution, the ROSI method reconstructs the noise sources by processing the recorded acoustic signals over random portions of a revolution, the beginning and ending points of which depend on the rotational frequency of the test case along with the sampling frequency and window length applied in the data processing. By doing so, important information regarding the behavior of the noise sources along given portions of each revolution can be lost as all the data is processed together, providing insight into the typical behavior that is not dependent on angular position.

In this paper, a further development of the ROSI method, named Segmented ROSI, has been applied. This method divides the sound-pressure signal of a single rotation into a predefined number of segments [3]. In this way, the Segmented ROSI method overcomes the shortcomings of the original ROSI method described above. Until the de-Dopplerization step, the Segmented ROSI method applies the abovementioned steps. Following the de-Dopplerization step, the Segmented ROSI method applies the segmentation process from which it has received its name. Here the time-domain signal is separated into revolutions. Each revolution is then further divided into a whole number of segments. The Discrete Fourier Transform step is then used to convert these segments into the frequency domain, where the cross-spectral density matrices are calculated. The cross-spectral density matrices are used to obtain beamforming maps for each segment within a revolution. How many segments a revolution is divided into depends on the application and the user. As the investigated phenomenon is cyclic, each reoccurrence of the same segment can be utilized in averaging Fourier transforms to help reduce noise in the spectra. Furthermore, if the number of samples in one segment allows it, the window length can be chosen such that multiple 50% overlapped Fourier transforms can be extracted from each segment. This comes at the cost of limiting the window length, the narrowness of the resultant narrowband bandwidth, and the extent of the lower frequency that can be investigated. The advantages of the Segmented ROSI method are associated with the above-mentioned segmentation. By making the segments shorter than one revolution and associating them with specific angular positions of the impeller blades, it is possible to investigate the noise sources along the various segments. Therefore, the Segmented ROSI beamforming method allows for examining details associated with various rotation segments that could not be seen with the original ROSI method. An all-encompassing description of the Segmented ROSI beamforming method can be found in [3].

3 ACOUSTICALLY TRANSPARENT DUCT

Acoustic investigations of ducted turbomachinery should be carried out in a hydrodynamically sealed environment to guarantee the flow conditions experienced under normal operating conditions. One can find methods in the literature for the acoustic investigation of ducted systems using phased microphone arrays [6,7,8,9]. The methods range from mounting microphones on the inner surfaces of the ducts [6,7] to investigating the turbomachinery from beyond the ends of the duct upstream or downstream of the investigated turbomachinery [8,10]. If the microphones are mounted within the duct, there are many difficulties associated with the measurements, including the disturbing effects of duct modes and flow-induced microphone self-noise. The latter can be dealt with using an appropriate surface treatment, such as a Kevlar cover over a recess [11]. The acoustic duct modes [12], on the other hand, will influence the results of the beamforming investigations, making it difficult to separate the various components of the noise in the measured microphone signals and localize them to their source regions [6, 13,14]. Moving the microphone array outside the duct in the upstream or downstream direction, where there is no longer flow, such as in [8,10], will help avoid microphone self-noise, but the duct modes can still be an issue. While applying such methods proves useful in some investigations, to gain direct access to the noise radiating from a ducted source and to eliminate the effects of duct modes, it is best to use an Acoustically Transparent Duct (ATD) [15]. An ATD is designed to be an acoustically transparent and hydrodynamically impenetrable duct section. Straight duct sections of ATD have already been designed and built by our research team. They have sufficiently transmitted acoustic signals, enabling beamforming investigations on ducted low-speed fans for a wide frequency range while providing a hydrodynamically impenetrable duct surface for the flow [15]. In the design method detailed in [15], a perforated sheet metal duct section provides the duct's shape, while a layer of stretch film, characterized by low acoustic impedance, provides hydrodynamic impenetrability sufficient for use with low-pressure rise fan systems. The ATD technology described herein has been used in this investigation

4 CENTRIFUGAL FAN TEST RIG

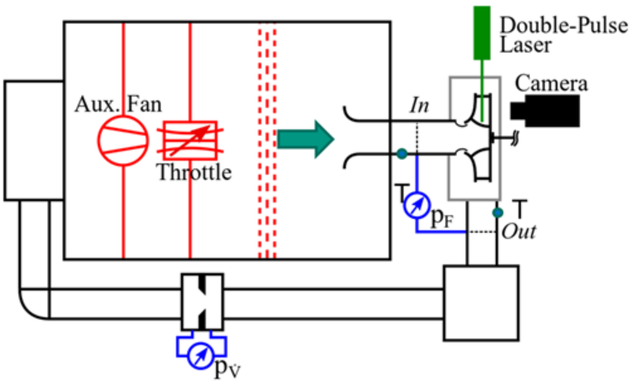

Fig. 1. Schematic of the radial fan test rig.

The test rig being investigated herein is a centrifugal fan test rig located at KIT. It has primarily been used in aerodynamic investigations. Published investigations have presented Particle Image Velocimetry (PIV) data collected on the test rig [16] as well as Computational Fluid Dynamics (CFD) simulations of the same test case [17]. A simple schematic of the test rig can be seen in Fig. 1. The test rig consists of a closed-loop system, allowing for seeding particle recirculation during PIV investigations. The volume flow rate can be adjusted using the throttle and auxiliary fan upstream of the settling chamber, which precedes the centrifugal fan inlet section. The pressure rise of the centrifugal fan can be measured between the inlet and outlet ducts. Volume flow rate measurements can be carried out using the through flow orifice meter located on the return leg of the test rig.

The centrifugal fan under investigation has 9 backward curved blades. The diameter of the blade tip is 306 mm, while the diameter of the flange and backplate is slightly larger, having a value of 325 mm. The fan has been designed for a volume flow rate of 0.15 m^3/s and a total pressure rise of 390 Pa at 1500 rpm [17]. As provided above, the centrifugal fan and test rig have already been investigated in [16,17]. The description in [17] suggests that one must be careful of unsteady phenomena that can occur in centrifugal fans, such as surge and rotating stall, as they can be key contributors to the resulting noise and vibration of the system. The conclusions in [17] discuss how interactions between the closed pipe system and the fan may lead to temporary drops in the flow rate during operation, which needs further study.

The setup used during the first test campaign described herein can be seen in Fig. 2. This setup only differs slightly from the original test rig setup for aerodynamic investigations. The casing of the original test section has been constructed from Plexiglas, allowing for visual access during PIV measurements. The test rig has an access window along the straight section of the casing leading to the outlet duct. This can easily be removed and replaced. The Plexiglas window has been replaced by an ATD window during the first test campaign. This acoustically transparent window can be seen on the left side of the test rig in Fig. 2. The phased array microphone system has been positioned such that the microphones would have the best possible direct view of the rotors through the window. The results of the first test campaign and the preliminary measurements carried out in parallel have provided a great deal of useful information on behalf of the authors, as described in [1], but the data collected through the ATD window has not allowed for an in-depth analysis of the centrifugal fan under investigation. On the other hand, the results and gained experience have provided the necessary information to design the setup for the second test campaign.

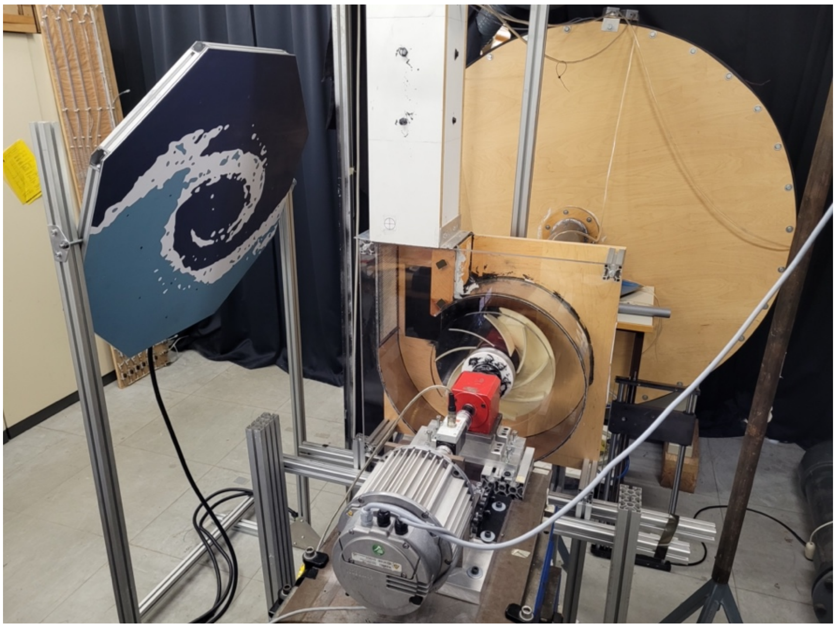

Fig. 2. Centrifugal fan test rig, as investigated during the first test campaign.

The test section has been refurbished for the second test campaign to provide a larger acoustic window on behalf of the phased array microphone system. As seen in Fig. 3, the entire casing has been replaced, except for the side of the outlet duct where the tongue is located and the wooden back wall of the test rig, which is on the inlet side of the fan. As described in the section about ATD technology, the has been designed according to the method described in [15] and produced from perforated sheet metal, providing a frame for the volute. This can be seen in the figure on the right side of Fig. 3. Compared to Fig. 2, the wooden back wall has been painted black for PIV testing. The frame has been covered with a layer of stretch film to make the volute hydrodynamically impenetrable. This can be seen in the figure on the left side of Fig. 3. All the tests have been carried out with the layer of stretch film sealing the surface of the volute.

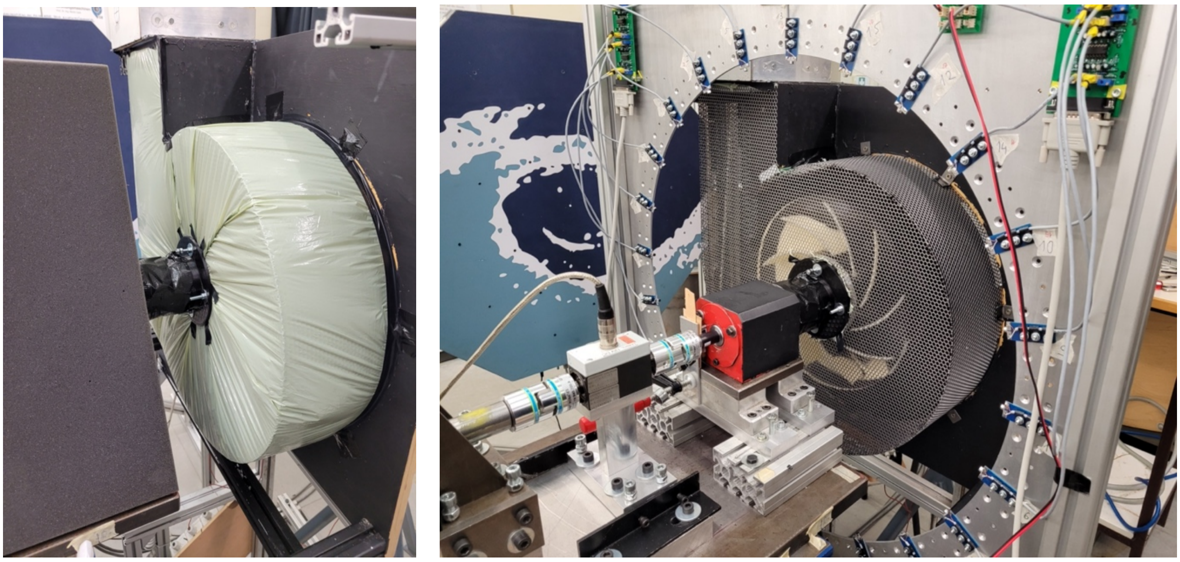

Fig. 3. Centrifugal fan test rig, as investigated during the second test campaign (left side). Perforated sheet metal frame (right side).

5 PHASED MICROPHONE ARRAY SYSTEMS

Two phased array microphone systems have been utilized during the investigations. The first one has been a planar array having 24 microphones. This array can be seen in Fig. 2 and the background of Fig. 3. The planar array has been used during both the first and second test campaigns. It has been developed in-house at BME. The array's diameter is 0.74 m and comprises 24 microphones arranged in logarithmic spirals. The array has been built from low-cost, general-purpose miniature condenser microphones, as done by many others in the industry. The microphone signals are pre-amplified using an in-house pre-amplifier designed for phased microphone array systems. The microphones have been flush mounted on an aluminum plate, resulting in a flat, smooth face for the phased microphone array. A layer of rubber and glue has been used to prevent any electrical contact between the microphone housing and the aluminum structure. The pre-amplified microphone signals have been sent to a 24-channel audio interface manufactured by MOTU, where the signal conditioning and the A/D conversion occur. The audio interface has sampled the microphone signals at a sampling frequency of 44.1 kHz. The analog signals have been converted to 24-bit digital signals and recorded on a laptop. The measurements have been repeated multiple times, positioning the array in multiple positions on both sides of the test rig, as can be seen in Fig. 4. A top view of the measurement setup can be seen in the figure. The 0, 0, 0 point of the coordinate system is fixed to the center point of the centrifugal fan. The vertical direction in the laboratory is the *y* direction in the figure, which is pointing out of the page. The outlet duct of the test rig can be seen overlapping the rotor. The planar array has been positioned in positions A-D, while the radial array has been positioned in positions E-G. The little arrows on the planar arrays show the direction in which the array is facing. In positions A and B, the array has been located on the side of the centrifugal fan where the outlet duct leaves the volute. This has provided an opportunity to investigate the noise sources related to the tongue. On the far side of the test rig, in positions C and D, the effect of the tongue has the least noticeable effect on the data. A series of tests have been carried out on each side of the test rig with the array centered on the center of the centrifugal fan. These are positions A and C. In these positions, the phased microphone array has been centered on the rotor, but the test rig's wooden back wall has partially blocked the direct view of the rotor for a small portion of the microphones. The wooden back wall is depicted by the wall with a finite thickness. The tests have been repeated in positions B and D so that all the microphones would be in direct view of the rotor. The green lines depicting the arrays are drawn to scale, depicting the diameters of the arrays. Table 1 provides the coordinates of the center points of the phased microphone arrays, according to the coordinate system provided on Fig. 4.

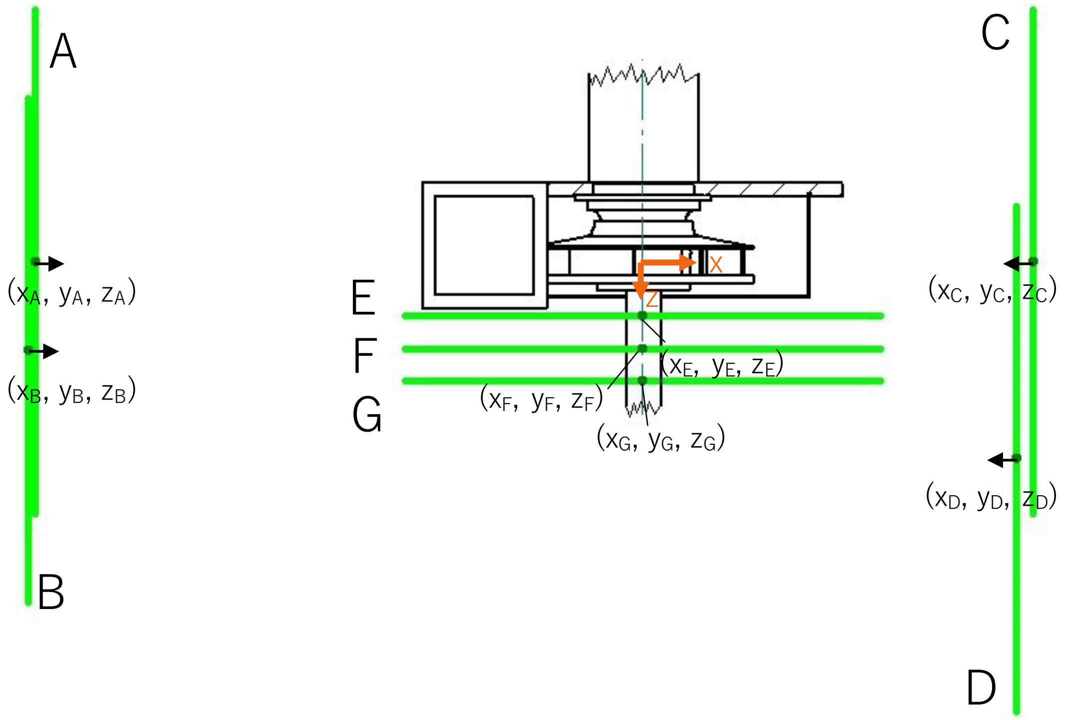

Fig. 4. Measurement positions of the phased microphone arrays.

The second phased microphone array utilized during the second test campaign has been a radial phased microphone array that has also been designed and built in-house. The array can be seen in the foreground of the right side figure of Fig. 3. It consists of 24 condenser microphones evenly distributed around a circle of diameter 0.696 m. The array frame has been designed so that it can be assembled around a duct. The microphones face radially inward toward the array's axis, aligned to coincide with the fan's axis. Axially, the fan has been positioned in multiple positions, slightly offset from the rotor in the axial direction, as provided in Table 1. The reason for offsetting the array has been that the outlet duct of the radial fan has not allowed for placing the phased microphone array any closer. The preamplifiers and other hardware components used in the radial phased microphone array measurements are the same as those used for the planar phased microphone array measurements.

Table 1. Coordinates of the center points of the phased microphone arrays in the rotors coordinate system, as provided in Fig. 4.

Array	Coordinates in mm		
	X	Y	Z
A	-900	0	0
B	-900	0	130
C	575	40	0
D	550	40	290
E	0	0	79
F	0	0	127
G	0	0	175

6 DISCUSSION

This investigation focuses on the second test campaign carried out at KIT, the primary goal of which has been developing and verifying a method for carrying out beamforming investigations on centrifugal fans. The first test campaign has been described above to provide background information regarding the starting point of this investigation. As seen in the earlier sections, the test rig has been further developed to provide better measurement conditions for centrifugal fan phased microphone array measurements. The first test campaign results published in [1] have shown that the reflections inside the casing and the small size of the ATD window have made extracting useful information from the results rather difficult. Further preliminary tests [1] not described herein have also shown that removing the casing in its entirety has made it possible to examine the noise sources of centrifugal fans using a planar phased microphone array positioned in the radial direction. This has motivated refurbishing the centrifugal fan test rig with an ATD casing. In this way, the acoustics can be directly measured while guaranteeing the aerodynamic operating conditions for which the centrifugal fan has been designed.

The first data set to be investigated herein has been recorded using the planar array placed in the B position, while the centrifugal fan has been operated at the design point. The mean rotational frequency of the rotor has been 1198 rpm, achieving a volume flow rate of 0.109 m^3/s and a total pressure rise of 198 Pa. The sampling frequency of the phased microphone array system has been 44.1 kHz. During the data processing, the investigated region of interest has been limited to 0.5 m x 0.5 m in the x and y directions, with the rotor's axis being the center point. The 9 backward curved rotor blades rotate clockwise on the beamforming maps, as the plane under investigation is viewed from the positive z direction. The discretized investigation plane consists of 81x81 grid points. The investigated plane passes through the 0,0,0 point parallel to the x-y plane. Therefore, the investigation plane is perpendicular to the face of the planar microphone array. This is the most difficult plane for data processing, as beamforming is the least sensitive to changes in this direction. This hardship has been overcome by placing the phased microphone array close to the investigation plane, providing the microphones with a relatively wide range of viewing angles.

In a first approach, the data has been processed using the ROSI beamforming method. As described above, this method carries out a de-Dopplerization step to correct for the motion of the noise sources before calculating the cross-spectral density matrices used in the beamforming calculations. An example result can be seen in Fig. 5. During the processing, the data acquisition time has been 3 s and the Fourier transform window length has been 1024 data points. The beamforming results have been evaluated for narrowband frequency bands, having a bandwidth of 43 Hz for the investigation parameters looked at in this case. On the beamforming maps, two circles have been drawn. The inner circle marks the radius of the rotor blade tip, while the outer one marks the outer diameter of the flange and backplate. The coordinate system and dimensions agree with those discussed above. The dynamic range of the beamforming maps has been limited to 6 dB. The center frequency values are presented at the top of each figure.

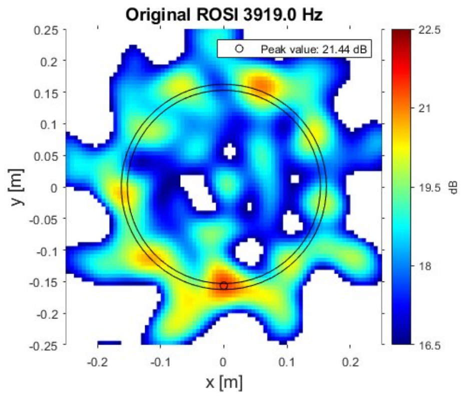

Fig. 5. ROSI beamforming map for center frequency 3919 Hz using the planar phased microphone array in position B.

The beamforming map provided in Fig. 5 is a typical example of the frequency range 3000-4000 Hz, where the test case can be characterized as having dominant rotor-related noise sources. Such examples have been presented herein, as they can help us understand the advantages and disadvantages of the various approaches since the rotor geometry provides us with a point of reference. The geometry of the centrifugal fan can be seen in detail in Fig. 6. The beamforming maps presented herein have a pattern that repeats nine times around the perimeter. In Fig. 5, the areas highlighting the noise sources of the largest amplitude are localized to the outer diameter of the rotor. There are noise sources localized to larger diameters, which can be identified as distinct noise sources.

Many parameters have been investigated while attempting to provide high-quality results using the planar array and the ROSI method. As with other moving noise source test cases, the given test case can be characterized as having unsteady noise sources. The unsteadiness is accentuated more than in axial flow turbomachinery test cases since the rotor blades, the backplate, and the flange provide only a small window for viewing the blade passages directly. Processing a long Fourier transform length is expected to help minimize the effect of such unsteadiness. It has been found that using a Fourier transform length of 1024 data points or longer is sufficient for the test case and processing parameters examined above.

For the case of 1200 rpm and a sampling frequency of 44.1 kHz, a Fourier transform length of 1024 data points results in one Fourier transform length utilizing data collected over a little less than half a revolution. A technical drawing of the centrifugal fan can be seen in Fig. 6. Viewing the rotor from positions A-D, where the planar phased microphone array has been positioned, at any instant, a maximum of three to four blade passages can be viewed with our phased microphone array. Therefore, carrying out the beamforming calculations according to the ROSI method, which processes data collected continuously as the rotor blades move along their cyclically repeating paths around the axis, less than half the data included in the calculations provides useful information about the noise sources. In other words, when the noise sources are passing on the far side of the measurement rig, there is no direct path along which the noise can reach the microphones. Do not forget that the flange and backplate of the rotor do not allow for viewing the blade passages from any other direction except for the radial one, and hence viewing the rotors from the axial direction is not an option.

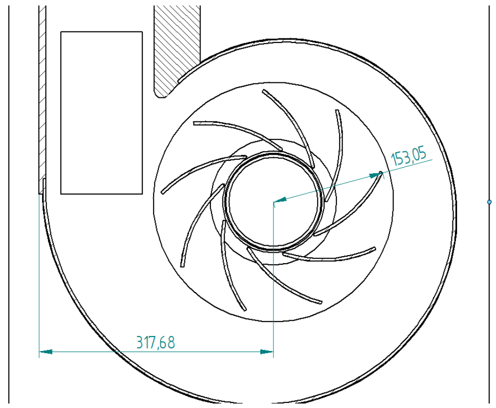

Fig. 6. View of the centrifugal fan from the axial direction.

The Segmented ROSI method described in earlier sections solves this problem. If the rotor blades passing in front of the phased microphone array are processed in smaller segments instead of processing all the data as a whole, information can be gained about each segment of the rotor. Portions of the cyclic pattern that do not contribute useful information to a given rotor segment can be left out of the analysis. Here the Segmented ROSI method will be applied to the same data set as has been looked at with the ROSI method. Since the Segmented ROSI method carries out the Fourier transform within each given segment, the maximum Fourier transform length is a function of the segment number and the rotational frequency. Ideally, one would like to segment the rotor into as many sections as there are blades. On the other hand, a larger segment number results in a smaller upper limit for the Fourier transform length. In this case, 9 segments result in an upper limit for the Fourier transform length of 245 data points. It has been discussed above that at any time, approximately three to four blade passages can be seen from the radial direction. Therefore, taking three segments is a logical lower limit, as the calculations will follow the motion of one blade across the face of the phased microphone array. For the data set investigated here, the upper limit of the Fourier transform length for three segments is 735 data points. The transform length needs to be a power of 2, and therefore the upper limit is reduced further to 128 and 512 data points for the 1200 rpm case for nine and three segments, respectively. Here, six segments have also been looked at. Six segments have a maximum number of 367 data points, and therefore up to 256 data points can be used. As described in the previous section, experience has shown us that, in this case, a minimum Fourier transform length of 1024 data points is needed to achieve beamforming maps that show good detail. As demonstrated by the calculations, this is not an option. Therefore, as an alternative solution, we have taken the shortest possible Fourier transform length that can still process the frequencies of interest. By doing this, the shortest possible length of time is taken for each

Fourier transform. This limits the unsteady effect of rotating the rotor blades past the microphones. Experience has shown that taking a Fourier transform length of 64 data points results in beamforming maps that have a significant amount of detail. The frequency bin falling in the range under investigation has been presented in Fig. 7 for processing the data using the Segmented ROSI method with 3 segments, Fig. 8 for 6 segments, and Fig. 9 for 9 segments. The reference position of the Segmented ROSI beamforming maps is the same as for the ROSI results presented in Fig. 5. Each beamforming map within a figure highlights a 1/3, 1/6, or 1/9 section of the rotor, which has been investigated on the given beamforming map. This is the section of each beamforming map having the largest amplitude noise sources, starting at approximately -120° (0° is taken as pointing in the +y direction from the 0, 0 point) and moving 1/3, 1/6, or 1/9 in the counter-clockwise direction with each new beamforming map. The other portions of the beamforming maps also contain data, but these portions do not contain any useful information. Therefore, the 1/3, 1/6, or 1/9 section associated with the given beamforming maps can be compared to the reference ROSI results above. The main difference, which needs to be kept in mind, is that the ROSI results are for a Fourier transform length of 1024 data points, while these are for 64 data points. It can be seen in the Segmented ROSI results, that the sections of the beamforming maps that are in the segments under investigation contain noise sources of significantly larger amplitude than experienced in the ROSI results. This is because the calculations do not include segments outside the range of the segment under investigation (such as those passing over the far side of the rotor). In summary, it can be seen that the Segmented ROSI beamforming maps do depict the noise sources seen above, but in much less detail than the ROSI results. It also has to be stated that it is much more difficult to analyze and extract information from these beamforming maps in their current form than for the ROSI results presented in this investigation.

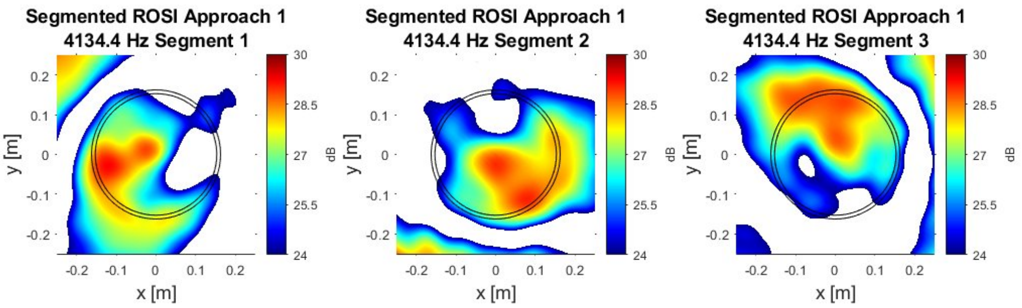

Fig. 7. Segmented ROSI beamforming maps for 3 segments and a center frequency of 4134.4 Hz in position B.

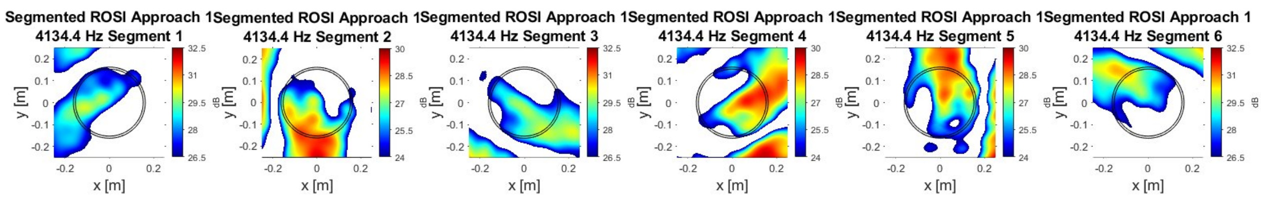

Fig. 8. Segmented ROSI beamforming maps for 6 segments and a center frequency of 4134.4 Hz in position B.

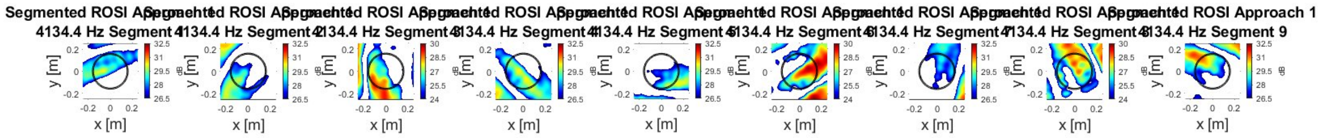

Fig. 9. Segmented ROSI beamforming maps for 9 segments and a center frequency of 4134.4 Hz in position B.

A radial phased microphone array has been utilized in this investigation to overcome the hardships associated with the planar microphone array discussed above. The data of the radial array has been processed using the ROSI method and a long Fourier transform length. By doing so, all the data collected on each microphone has been utilized in its entirety in creating each and every beamforming map, as each microphone continuously has a clear line of sight on some portion of the rotor. Investigating various Fourier transform lengths, it has been found that using over 1024 data points results in beamforming maps of adequate quality, as experienced when processing the planar array data with the ROSI method above. Figure 10 presents the beamforming map created from data collected with the radial array in position F, processed using the ROSI method and a Fourier transform length of 1024 data points. The frequency bin presented here agrees with the one presented above for the planar array and ROSI method in Fig. 5. Comparing the results, they present similar findings. For a center frequency of 3919 Hz, the areas highlighting the noise sources of the largest amplitude are localized to the outer diameter of the rotor (Fig. 5 and Fig. 10).

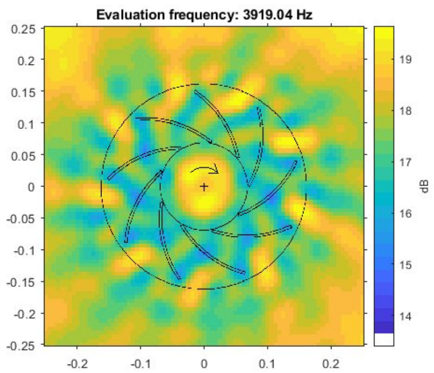

Fig. 10. ROSI beamforming map for center frequency 3919.04 Hz using the radial phased microphone array in position F.

7 SUMMARY

This investigation has been carried out to develop a methodology for investigating centrifugal turbomachinery using phased microphone array systems and beamforming. The test setup originally used for aerodynamic investigations has been further developed, providing an environment where the acoustics can be investigated while not altering the aerodynamics. Using an ATD and various phased microphone arrays has resulted in data sets that can successfully be processed using three different approaches. First, a planar array located on the sideline has been combined with the ROSI beamforming method. Next, the Segmented ROSI method has been combined with the same planar array on the sideline. Last but not least, a radial phased microphone array has been combined with the ROSI method. Each method has its advantages and disadvantages, and each method can provide beamforming maps that depict the noise sources accurately, though some results are harder to evaluate than others. Currently, the planar array measurements cannot resolve the noise sources in as fine a detail as the radial phased microphone array measurements combined with the ROSI beamforming method can. Further development of the beamforming methods is planned, as well as the study of the noise sources of the centrifugal fan under investigation.

8 ACKNOWLEDGEMENTS

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