Toward the development of a beamforming method for centrifugal turbomachinery

M Abdelkhalik[1], M Tadros[1], B Kocsis[1], B Soós[1], B Lendvai[1], K Tokaji[1], M Probst[2], B Pritz[2] and Cs Horváth[1*]

[1] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Fluid Mechanics, Budapest, Hungary

[2] Karlsruhe Institute of Technology, Institute of Thermal Turbomachinery, Karlsruhe, Germany

[*]Corresponding author, e-mail: horvath.csaba@gpk.bme.hu

Abstract. Investigating turbomachinery noise sources using phased array microphones and beamforming methodologies is becoming standard practice. Methods are available to investigate axial flow turbomachinery, but no methods for centrifugal turbomachinery have been published. The reason behind this is twofold. First, it requires an acoustically transparent yet hydrodynamically sealed window to see into the test rig, which contains many walls and complicated passages. Second, it requires a beamforming method that can organize and process the data collected from the rotating sources. This investigation presents a few of the first steps taken toward developing such a measurement methodology.

1. Introduction

The aim of this study is to localize noise sources of centrifugal turbomachinery successfully. Centrifugal turbomachinery provide a rather challenging test case, as they consist of rotating noise sources that are spinning at high speeds in a closed (acoustically sealed) environment. As a result of these challenges, most centrifugal turbomachinery measurements do not attempt to localize the noise sources directly, but rather carry out measurements at the ends of the inlet and outlet ducts, analyzing the spectra of the results in order to understand the noise sources better. Such investigations are helpful but do not provide a clear and concise picture regarding the noise sources, not to mention the hardships associated with correctly interpreting the data, which is highly influenced by the duct modes. Numerical investigations can be used to take a look inside ducts, but this leads to other challenges, such as high computational costs associated with the asymmetry of the centrifugal turbomachinery test cases and the necessary (time and space) resolution that is required of acoustic simulations. There are two main elements that had to be further developed in order to accurately carry out beamforming investigations on centrifugal turbomachinery and localize the noise sources. First, a hydrodynamically sealed yet acoustically transparent housing had to be developed in order to have acoustical access to the noise sources. Second, the Segmented ROtating Source Identifier (Segmented ROSI) beamforming method had to be customized for the task at hand. This paper introduces the reader to the steps that have been taken to achieve a measurement method that can be applied in the acoustic investigation of centrifugal turbomachinery noise sources. The methodology will provide researchers with an opportunity to understand the noise sources better and make steps toward eliminating them.

2. Centrifugal fans under investigation

The collaboration between the 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) has been ongoing for a number of years. Multiple topics have been and are being investigated within the partnership. The current investigation focuses on a centrifugal test fan, the aerodynamics of which have been studied by colleagues at KIT using Particle Image Velocimetry (PIV) measurements and Computational Fluid Dynamics (CFD) simulations [1]. A simple schematic of the test rig can be seen in figure 1. The test rig has an access window, which can easily be changed. The test rig can be seen in figure 2 during PIV testing. The laser sheet is being introduced into the test section through the described access window, which is located on the upper left portion of the figure. The radial walls, as well as the axial wall closer to the viewer, are currently made of plexiglass, allowing for visual access to the test section. Further information regarding the test case can be found in [1].

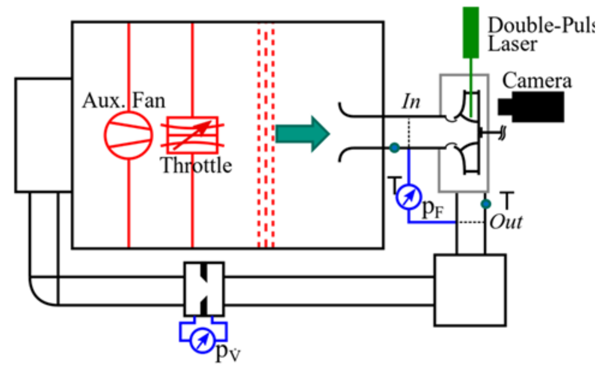

Figure 1. Schematic of the centrifugal test rig located at KIT.

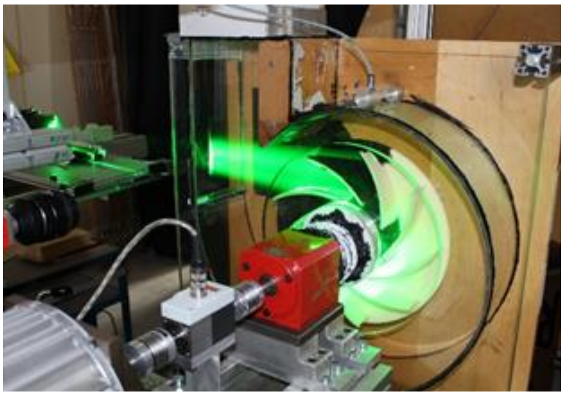

Figure 2. Picture of the centrifugal test rig during PIV testing.

The aerodynamic data from the PIV measurements and CFD simulations provide insight into the noise generation mechanisms associated with the technology. This is what has encouraged the collaboration between the institutions and which has resulted in the choice of the given centrifugal fan as the primary test case to be investigated. On the other hand, the currently restricted access to the test case has foreshadowed challenges that have to be dealt with during the course of the investigation. Therefore, a second test case has also been included in the investigation, on which preliminary tests have been carried out. The fan is located in the BME laboratory, making it more easily accessible on behalf of the colleagues at BME. Figure 3 shows the centrifugal fan in its true working order, while figure 4 shows the centrifugal fan with its housing removed, as it has been tested during this investigation. Further information regarding the second investigated centrifugal fan can be found in [2].

Figure 3. Centrifugal fan located at BME [2].

Figure 4. Centrifugal fan located at BME, as measured, without its housing [2].

3. Beamforming

Beamforming is a measurement method that utilizes an array of microphones for localizing the positions of sound sources. Worded in a simple manner, the goal is to determine the amplitude and the direction of arrival of each wavefront that passes over the array. By accurately determining these parameters, one can trace the wavefronts back to their sources and localize them. This is done by processing the acquired microphone data using beamforming algorithms. In general, beamforming algorithms start with a discretized investigation region. Utilizing the recorded acoustic signals collected by the individual microphones of the phased microphone array, they compute the source amplitudes in each investigated grid point to generate a source amplitude distribution. The Delay & Sum algorithm is the most fundamental beamforming method. It serves as the foundation for several more complex beamforming methods [3].

Beamforming maps present a visual representation of the processed data. They are useful in pinpointing the positions of the sources [3]. The results that are observed on beamforming maps may be enhanced by using deconvolution techniques, which can provide a better sidelobe ratio as well as a narrower beamwidth. Although the above-mentioned algorithms can offer findings that emphasize the genuine noise sources considerably more clearly than the Delay & Sum approach, they all assume that the noise sources under investigation are stationary. Applying beamforming methods designed for stationary noise sources to turbomachinery test case data results in beamforming maps that are dominated by sizeable donut-shaped noise sources that are distributed around the circumference of the turbomachinery being investigated [4].

4. Segmented ROSI

The data from the phased microphone array has been processed and analyzed using an in-house beamforming code. The core of the code is the ROtating Source Identifier (ROSI) beamforming method. The ROSI method, developed by Sijtsma et al. [5], is a beamforming method that has been designed for subsonic rotating noise sources. As the noise sources are moving, and their relative distance with regard to the listener is continuously changing, a Doppler shift is experienced in the collected data [6]. The method is provided with sound pressure data from the microphones and source rotational information from a tachometer. It evaluates the potential noise source positions at each time instant based on this information, compensating for position, amplitude, and frequency. The method therefore 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 then need to be interpolated back to equidistant time series and converted into the frequency domain for further processing. The method reconstructs the noise sources by processing the observed acoustic signals over a significant portion of time. When this is done, some information regarding the noise sources, such as the directivity of the trailing edge and leading-edge noise sources, is lost.

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 number of segments [4]. Therefore, the Segmented ROSI method overcomes the shortcomings of the original ROSI method mentioned above. The Segmented ROSI method applies the same steps as the original method up until the de-Dopplerization step. Following this step, the Segmented ROSI method applies a segmentation process, from which it has received its name. In this step, the time-domain signal is separated into revolutions, and each revolution is further divided into segments. The Discrete Fourier Transform step then converts these segments into the frequency domain in order to calculate the cross-spectral density matrices. By doing so, a beamforming map can be obtained for each segment within a revolution. How many segments a revolution is divided into depends on the application and the user. The advantages of the Segmented ROSI method are commonly 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, we are able to investigate the radiation characteristics of the noise sources along the various segments. The Segmented ROSI beamforming method therefore allows for the examination of details that are associated with various segments of a rotation and could not be seen with the original ROSI method. Further details regarding the Segmented ROSI beamforming method can be found [4].

5. Acoustically transparent duct

In the case of ducted fans, acoustic investigations should be carried out in a ducted environment in order to guarantee the flow conditions experienced under operating conditions. The literature has provided methods for using microphone arrays in the investigation of ducted systems [7-11]. The methods range from mounting microphones on the inner surfaces of the ducts [8,10] to investigating the turbomachinery from beyond the ends of the duct upstream or downstream of the investigated turbomachinery [7,11]. If mounting the microphones in the duct, there are many difficulties associated with the measurements, including the disturbing effects of duct modes and flow-induced microphone self-noise. While the latter can be dealt with to some extent with the use of an appropriate surface treatment [12], the acoustic duct modes resulting from the ducted environment [13] greatly influence the results of the beamforming investigations, making it difficult to separate the various components of the noise in the measured microphone signals and trace them back to their source regions [8,14-15]. If one places the array of microphones upstream or downstream of the duct, where there is no longer flow, as in [7,11], the microphone self-noise can be avoided, but the duct modes will still be present. While applying such methods can be useful in some investigations, in order to gain direct access to the noise radiating from a ducted source, and in order to eliminate the effects of duct modes, one needs to use an Acoustically Transparent Duct (ATD) [16]. An ATD is a hydrodynamically impenetrable duct section that can be used for transporting fluids, and which is designed to be acoustically transparent. Such an ATD has been designed and built by our research team and has been shown to sufficiently transmit acoustic signals, making it possible to carry out beamforming investigations on ducted low-speed fans for a wide frequency range, while providing a hydrodynamically impenetrable duct surface for the flow [16]. In our design, which is detailed in [16], a perforated 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 fan systems. The ATD technology described herein has been used in this investigation, replacing the access window of the centrifugal fan located at KIT. The KIT test rig with an access window made with ATD technology and the phased array used to carry out the investigation can be seen in figure 5. The access window can be seen from a better angle in an enlarged view in the top right corner of the figure.

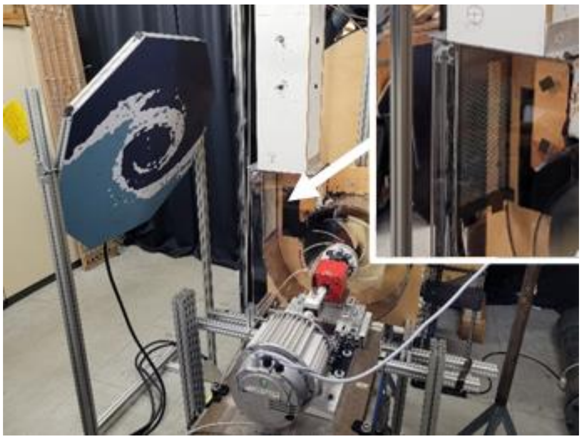

Figure 5. KIT centrifugal test rig and BME phased microphone array as used during the investigation.

6. Phased microphone array

The phased microphone array used in the investigation has been developed and built in-house at BME. This phased microphone array has been the first array developed in-house at BME, and therefore the geometry has been based on a phased microphone array system that is available at the department, the OptiNAV Inc. Array24 [17]. This has provided the authors with an opportunity to test the system side by side with an existing array. The comparison results have encouraged the authors to develop further arrays for specialized applications. The applied phased microphone array has a diameter of 0.74 m and consists of 24 microphones, arranged in the shape of logarithmic spirals. Affordability has been a key design aspect. Therefore, the array has been built of low-cost, general-purpose miniature condenser microphones. While this admittedly results in the signals from the individual microphones being of questionable quality, the large number of microphones has provided a statistical guarantee that the processed phased microphone array output will be of acceptable quality. This has encouraged many in the industry to construct phased microphone arrays from such microphones [17]. The microphone signals are pre-amplified with a printed circuit board designed specifically for this phased microphone array. The microphones are 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 are sent to a 24-channel audio interface manufactured by MOTU, where the signal conditioning and the A/D conversion take place. The audio interface is capable of sampling the microphone signals with a maximum frequency of 96 kHz. The analog signals are converted to 24-bit digital signals. The digital signals then go on to a laptop and are recorded using Boom Recorder software.

7. Preliminary measurements

As can be seen in figure 5, the access window of the test rig is relatively small. In anticipation of the potential difficulties associated with the small window size, the limited viewing angle, as well as reflections off of the housing, and in order to acquire data that can be used during the development of the measuring and processing methodologies for centrifugal turbomachinery, preliminary investigations have been carried out on a centrifugal fan located at BME. The fan has been described in the second half of section 2 and depicted in figure 3 - 4.

The preliminary measurements have included the investigation of 6 cases with various distances and angles. The distances used in the setup have been 0.35, 0.5, and 0.75 m. The two viewing angles have been 0 ° and 90 °, with 0 ° corresponding to the normal to the face of the phased microphone array being parallel to the axis of the impeller. This abundance of arrangements has been examined in order to observe how the processing behaves at various distances and angles. The setup consists of a centrifugal fan with its housing removed, as depicted in figure 4. Removing the housing of the centrifugal fan provides for a simplified test case that provides an unobstructed path for the acoustic signals to propagate toward the phased microphone array. It has been anticipated that this would result in more accurate beamforming maps, as the phased microphone array has been provided with an unobstructed view of the noise sources, and the reflections off of the housing walls do not influence the processing of the data. A tachometer has been used to measure the rpm of the impeller.

An abundance of cases have been investigated in order to better understand the behavior of the processing method as a function of viewing distance and viewing angle. Ultimately, the goal has been to extract useful information from measurement data collected in a similar manner to what can be attained through the access window on the KIT test rig. The test case which best resembles the KIT test case is presented herein. Refer to figure 5 for a better understanding of the setup. The viewing angle, in this case, has been 90 °, or in other words, the normal to the face of the phased microphone array has been perpendicular to the axis of the impeller. The center of the microphone array has been positioned at a distance of 0.35 m from the axis of the impeller. The main difference between the BME and the KIT cases is that the BME setup does not have a housing.

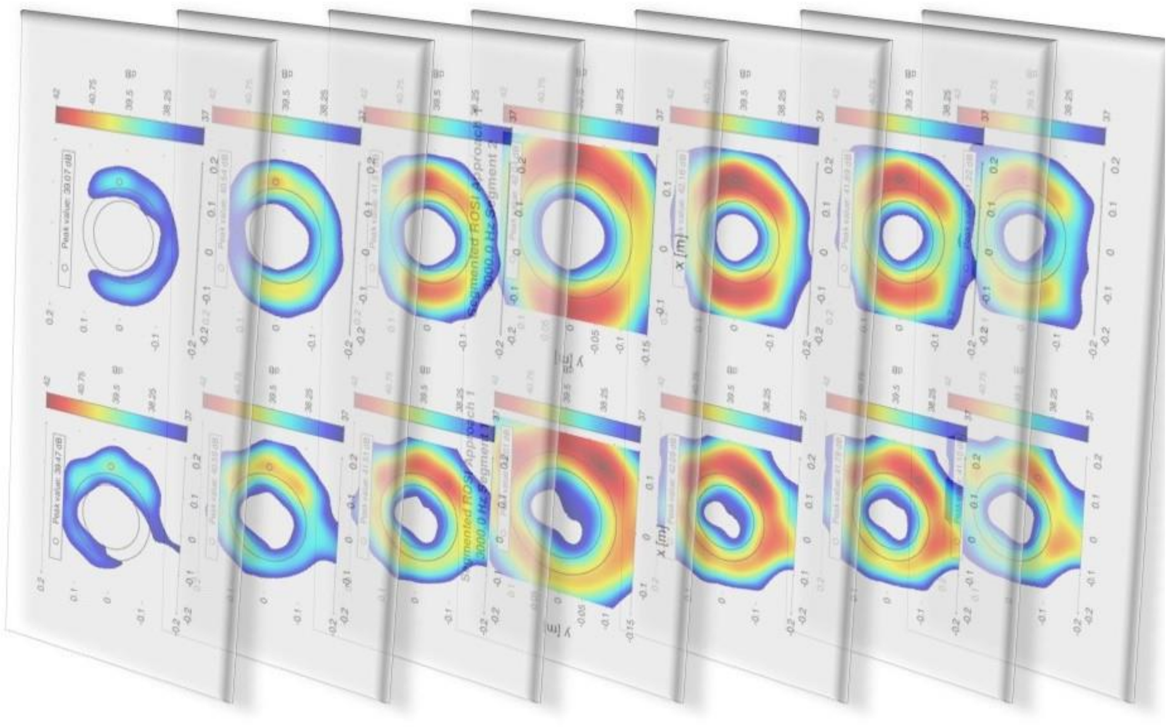

Figure 6. KIT centrifugal test rig and BME phased microphone array as used during the investigation.

The collected data has been processed by dividing each revolution into 2 segments. The planes under investigation have been the ones that are perpendicular to the axis of the centrifugal fan, with the axis passing through the midpoint of each investigated plane. Multiple planes have been examined along the axis of the centrifugal fan. This provides insight regarding the resolution that can be achieved. It has been anticipated that the investigation of this plane would be rather difficult from the given viewing angle, as the beamforming methods have difficulties in resolving noise sources at various depths. On the other hand, such results would be the most logical and useful in evaluating the noise sources. It has been found that the Segmented ROSI method could extract such slices very nicely, providing an almost 3D rendition of the noise sources. Beamforming maps for the various slices of the 2 segments can be seen in figure 6 [18]. The individual beamforming maps in the figure are too small to read and investigate in detail, but the details are irrelevant at this point in time. The semi-transparent slices have been layered on top of one another in order to depict how the various layers align. The top and bottom rows of beamforming maps depict the two segments under investigation. Moving from the left end of the figure toward the right end, we transition across the span of the airfoils from one endwall to the other. The figure depicts the beamforming levels of the various segments for the given planes. The dynamic range has been kept at a constant value of 5 dB and the peak value has been set to 42 dB on each plane. The highest values are red and the lowest values are blue, as can be seen on the scales in the figure. The reason behind fixing the peak value to a given value has been to qualitatively show how the beamforming levels of the noise sources change from one plane to the next. It can be seen that the noise sources are highly velocity dependent, as the slower flow velocities near the endwalls result in weaker noise sources. The resolution across the span is surprisingly very good, as described above. Unfortunately, the depth resolution is less ideal, as the beamforming methods are unable to localize the noise sources that are located between the tightly spaced impeller blades (see figure 4).

8. KIT measurements

The KIT measurements have all been carried out from the same distance and angle, resulting from the geometric constraints of the environment. The distance between the plane of the phased array and the axis of the impeller has been 0.903 m. The viewing angle has been 90 °, which means that the normal to the face of the phased microphone array has been perpendicular to the axis of the impeller, as can be seen in figure 5, and as has also been implemented during the preliminary measurements. The rpm of the centrifugal fan has been measured using a tachometer. As compared to the preliminary measurements, each revolution has been split into 5 segments instead of 2 in order to account for the limited area that can be simultaneously viewed through the access window. This change influences the FFT block size, which has been set to 256.

The collected data has been processed and assessed. It has been concluded, based on the outcomes of the preliminary measurements, that the currently used access window and the reflective surface of the housing have made the currently available data difficult to process and evaluate by simply applying the Segmented ROSI beamforming method. In order to make it possible to evaluate the data in greater detail, instead of just the access window, the complete housing will be changed to one made of ATD material. This will allow for the examination of the test rig in a similar manner to what has been carried out on the test rig at BME. It is expected that the alteration of the test rig will result in measurement data of high quality which can be evaluated as desired.

9. Conclusions and outlooks

This investigation has presented advances that have been made in the area of noise source localization for centrifugal turbomachinery applications. The paper has presented the technology that is needed in order to overcome the two hardships associated with such measurements. First, an acoustically transparent yet hydrodynamically sealed material has been applied to the access window of a centrifugal turbomachinery investigation in order to allow direct access to the noise sources under investigation. Second, the Segmented ROSI beamforming method has been applied in a preliminary assessment of its capabilities with regard to localizing noise sources from a difficult viewing angle and in a difficult measurement environment.

The achievements that have been made show that if a centrifugal impeller is investigated without its housing, then the noise sources at the outlet plane of the impeller can be localized. The outcomes also suggest that the use of an acoustically transparent, yet hydrodynamically sealed complete housing would allow for the investigation of centrifugal turbomachinery under working conditions. In the following, steps will be taken in order to manufacture a complete centrifugal fan housing out of ATD material and carry out a new series of measurements.

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