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First steps on fan matrix condition monitoring and fault diagnosis using an array of digital MEMS microphones

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Condition monitoring and fault diagnosis of complex mechanical systems were based on vibration analysis in the last decades. The sensors which were employed in these methods needed to be in contact with the vibrant surfaces of the machines. This fact was an important limitation of the corresponding methodologies. In the last years, this problem is trying to be avoided by means of the analysis of the noise, i.e. the acoustic signals, which are directly related with the vibrant surfaces, instead of the vibrations themselves. Both, acoustic and vibrational signals can reveal information related with machinery operation conditions. Using arrays of digital MEMS (Micro-Electro-Mechanical Systems) microphones allows creating systems with a high number of sensors, without paying a high cost. This work has studied the use of acoustic images, obtained by an array with 64 MEMS microphones (8x8) inside a hemianechoic chamber, in order to detect, characterize and, eventually, identify failure conditions of a fan matrix. The acoustic images have been processed to extract different geometric parameters. Afterwards, these parameters have been used in classification algorithms, based on Support Vector Machines (SVM), in order to identify failures on the fans of the matrix.

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1. INTRODUCTION

An array is an arranged set of identical sensors. The beampattern of the array can be controlled by modifying the geometry of the array (linear, planar...), the sensor spacing and the radiation pattern, the amplitude and phase excitation, of each sensor[1]. Microphone arrays are a particular case, used in applications such as speech processing, echo cancellation, localization and sound sources separation[2]. By using beamforming techniques[3], the array beampattern can be electronically steered to different spatial positions. This steering allows spatial filtering, i.e. the discrimination of acoustic sources on the basis of their position.

The authors of this paper have experience in the design and development of acoustic ULAs (Uniform Linear Arrays). These arrays are simple, but they are limited to be able to estimate the spatial position of the sound source only one in dimension (azimuth or elevation). In order to obtain spatial information in two dimensions, working with planar arrays is needed. Planar arrays have their sensors distributed on a surface. Working with planar arrays leads to an increase in both, system complexity and space required by the acoustic sensors and the associated hardware. The extension from linear arrays to planar arrays increases exponentially the number of channels required, which are directly connected with the complexity and the cost of the system.

The acronym MEMS (Micro-Electro-Mechanical System) refers to mechanical systems with a dimension smaller than 1 mm, manufactured with tools and technology arising from the integrated circuits (ICs) field. These systems are mainly used for the miniaturization of mechanical sensors[4]. The application of MEMS technology to acoustic sensors has allowed the development of high-quality microphones with high SNR (Signal to Noise Ratio), low power consumption and high sensitivity[5].

A typical acquisition and processing system for acoustic arrays, when it is based on analog microphones, has four basic elements: sensors, signal conditioners, acquisition devices and signal processor. Digital MEMS microphones include a microphone, a signal conditioner and an acquisition device inside the same chip. For this reason, an acquisition and processing system for an acoustic array which is based on MEMS microphones is reduced to two basic elements: MEMS microphone and a processing system. The integration of the microphone preamplifier and the ADC in a single chip reduces costs and the space occupied by the system significantly.

In recent years, techniques which have been created to obtain acoustic images have been developed greatly and rapidly. At present, acoustic images are associated with a wide variety of applications, such as non-destructive testing of materials, medical imaging, underwater imaging, SONAR, geophysical exploration, etc.[6]. These techniques are based on the RADAR principles, forming an image of an object from reflected radio waves. RADAR systems require high-cost hardware and their application on people and specific materials is difficult, due to their low reflectivity. On the other hand, acoustic images represent a simple low cost alternative in such cases.

Arrays of MEMS microphones are specially designed for acoustic source localization; however, they are also used in other applications such as DOA (direction of arrival) estimation for vehicles in motion, speech processing, turbulence measurements, geometric dimensions and internal defects of concrete structures identification, or acoustic imaging. Due to the high diversity of the applications of these arrays, the authors try to widen these uses to other fields, such as the acquisition and processing of acoustic images of a fan matrix, using a planar array[7].

A fan matrix, fan array or fan wall is a system formed by several fans located on a surface, working together in order to improve the performance of one alone large fan with lower power consumption. Any type of application that requires specific temperature conditions is a candidate for a fan matrix. Fan matrices are used in very different applications, such as mine ventilation, radiator cooling in vehicles, ventilation systems, airflow control in plant factories, air handling in buildings, or wind tunnels.

2. PROCESSING AND ACQUISITION SYSTEM

This section shows the acquisition and processing system[7], based on a 2D array of MEMS microphones and the 2D positioning system used in this study.

The system to acquire acoustic images used in this paper is based on a Uniform Planar Array (UPA) of MEMS microphones. This array, which has been entirely developed by the authors, is a square array of 64 (8 × 8) MEMS microphones that are uniformly spaced, every 2.125 cm, in a rectangular Printed Circuit Board (PCB), as shown in Figure 1.

This array was designed to work in an acoustic frequency range between 4 and 16 kHz. The 2.125 cm spacing corresponds to $\lambda/2$ for the 8 kHz frequency. This spacing allows a good resolution for low frequencies, while avoiding grating lobes for high frequencies in the angular exploration zone of interest.

For the implementation of this array, MP34DT01 microphones of STMicroelectronics, - digital MEMS microphones with PDM interface - were chosen with the following features: low-power, omnidirectional response, 63 dB SNR, high sensitivity (-26 dBFS) and a nearly flat frequency response (± 6 dB in the range of 20 Hz to 20 kHz).

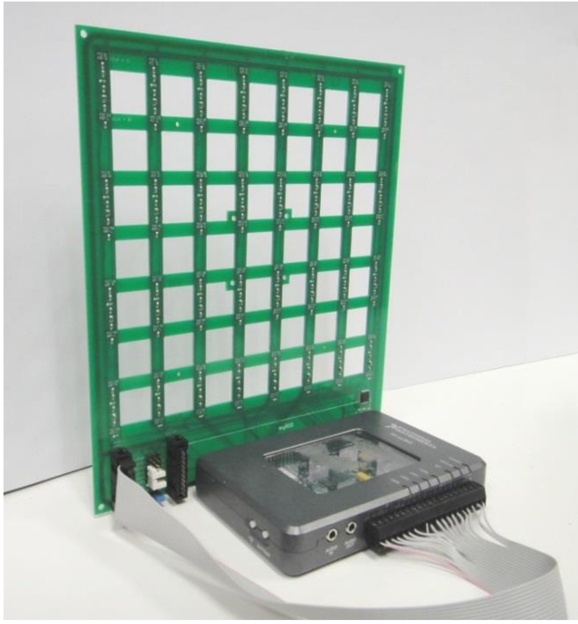


Figure 1. Array module with myRIO and MEMS array board.

A MyRIO platform[8] is the base unit for this system. This platform belongs to the Reconfigurable Input-Output (RIO) family of devices from National Instruments, which are oriented to sensors with nonstandard acquisition procedures. The embedded processor included in myRIO is capable of running all the software algorithms to generate acoustic images, so it can be used as a standalone array module formed by a myRIO connected to a MEMS array board as shown in Figure 1. Although myRIO can work as a standalone system, the lack of display means that it is usually controlled from a PC connected using a Wi-Fi interface. In a global hardware setup, as shown in Figure 2, the system includes a PC and one or more array modules.

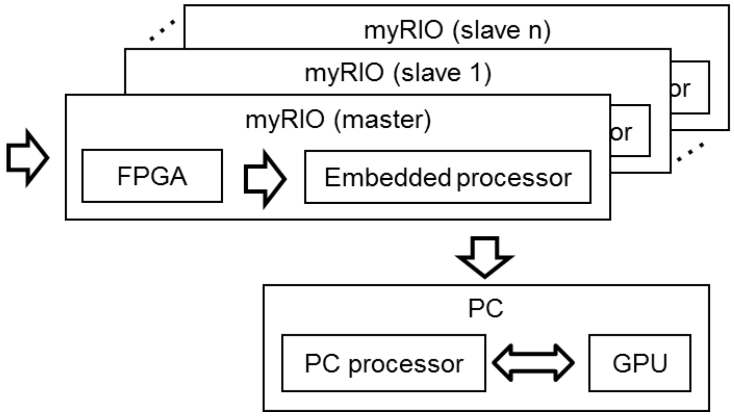


Figure 2. Global hardware setup.

The algorithms implemented in the system, shown in Figure 3, can be divided into three blocks: MEMS acquisition, signal processing, and image generation (wideband beamforming and image storage). The programming language used is LabVIEW 2015, along with its Real Time, FPGA, and GPU modules, which allows developing applications on different hardware platforms like those used in the system: FPGA, Embedded Processor (EP), PC, and GPU.

- In the acquisition block, each MEMS microphone with a PDM interface performs signal acquisition.
- In the signal processing block, two routines are implemented: deinterlacing and decimate & filtering, obtaining 64 independent signals (one of each MEMS of the array).
- Finally, in the image generation block, based on wideband beamforming, a set of N × N steering directions is defined, and the beamformer output is assessed for each of these steering directions. Then, the images generated are displayed and stored in the system.

A processing platform enables to work at a low level -to acquire signals- and at a high level -to implement spatial processing algorithms-, using low cost commercial systems was defined. The processing algorithms are shared between the FPGA and the PC, excluding beamforming, which is implemented on the GPU, as shown in Figure 3. The embedded processor is used to control and transfer data between the PC and FPGA.

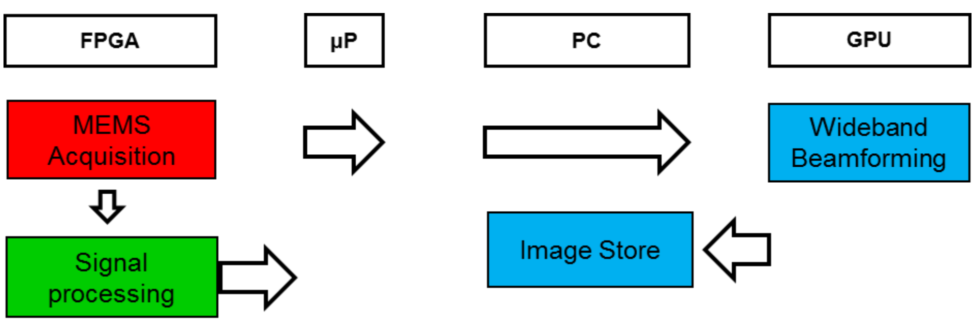


Figure 3. System framework

3. FAULT DIAGNOSIS OF A FAN MATRIX

The system shown in previous sections has multiple applications: localization and characterization of noise or vibration sources, spatial filtering and elimination of acoustic interference, etc. This paper is focused on obtaining acoustic images of a fan matrix.

A. TEST FAN MATRIX

A case study has been carried out with a 3x3 fan matrix, specifically built for these tests with 9 coherent axial PC fans, which move the air in the direction of the fan axis. Each of the fans used to build the fan matrix is a Foxconn D90SM- 12 3-Pin with 7 blades, with a size of 92x92mm. The size of the used fans allows them to move a great amount of air without rotating at a high speed -related with a high noise level- and to use a reduced-sized engine – so that the turbulence noise will be controlled. One of these fans is shown in Figure 4 (a), and Figure 4 (b) shows the fan matrix implemented for the tests.

(a) ***(b)***

Figure 4. (a) Foxconn D90SM- 12 fan. (b) Fan matrix built for the test

As it can be observed in Figure 4 (b), the fans of the matrix are controlled by a Kkmoon 8-channel relay interface board, controlled by the ARM microcontroller of a MyRIO platform. The interface board of the control system allows turning on and off the fans of the matrix independently, in order to simulate faulty fans in fault diagnosis tests.

B. ACOUSTIC IMAGES

The tests developed to obtained acoustic images of a fan matrix have been carried out inside an anechoic chamber, using a system developed previously by the research group[7]. The fan matrix has been placed 30 cm opposite the MEMS array. These tests have allowed the authors to obtain acoustic images of the fan matrix with only one of the fans working, as well as acoustic images of the whole fan matrix, i.e. with the nine fans working at the same time.

Before showing the obtained acoustic images, the acoustic signals received by the microphones of the array have been analyzed in order to understand better the noise generated by the fans. It was observed that fan noise isn’t stationary or periodic and it shows a high harmonic around 1100Hz. Working with non-stationary signals is not ideal, so they decided to capture 1000 signals for each specific test, in order to obtain the averaged signal in each case and analyzed it to obtain the averaged behavior of the fans.

The acoustic images of each one of the 9 fans of the matrix running alone were obtained by using the array of MEMS microphones together with wideband beamforming techniques, using a work frequency of 1100Hz. For each fan, 1000 acoustic images were generated, in order to obtain 9 consistent averaged acoustic images, which are shown in Figure 5.

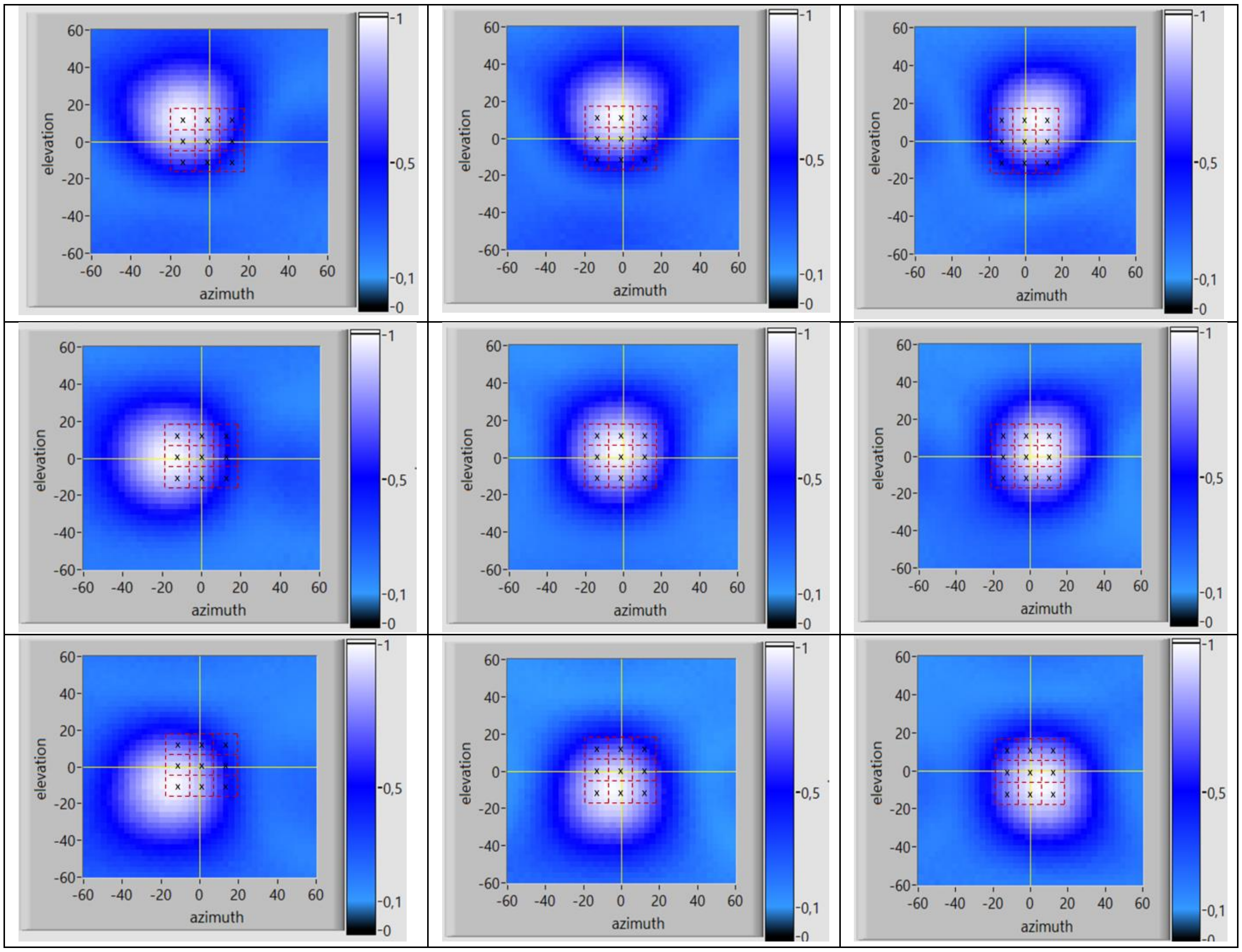
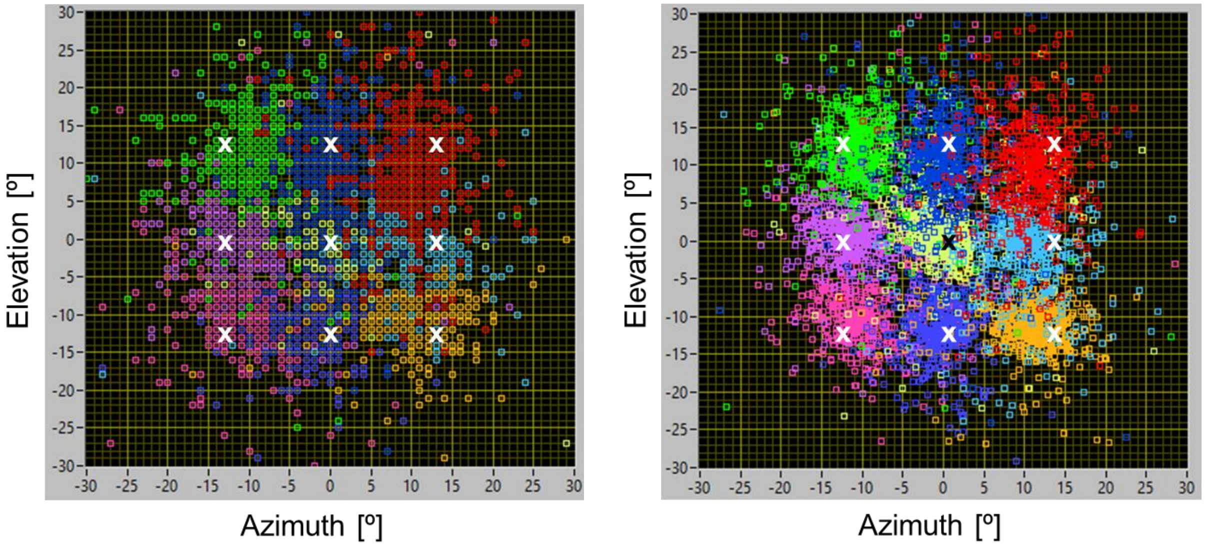


Figure 5. Acoustic images of the fan matrix with only each one of the fans running

With the analysis of these images, it can be observed that the center of each image seems to be placed near the real position of the matrix where the working fan is located (x). So, the averaged acoustic images of the fans could be used to estimate their positions in the matrix, in order to guess which fan is running in case they would not be visible, like in a certain refrigeration system of a car, for example.

It is clear that the geometry of the acoustic images is related with the real position of the working fan. On the basis of this relation, the positions of the maxima and the centers of mass of the acoustic obtained images were assessed. For each fan, both geometric parameters and its averaged value are shown in Figure 6.

In this Figure 6, it can be observed that the assessed geometric parameters of each acoustic image are scattered around the "real position" (x) of the corresponding fan. So, the information obtained from these geometric parameters could be used to identify the working fan in the matrix using classification algorithms based on machine learning techniques.



(a) ***(b)***

Figure 6. Acoustic images of each working fan: (a) Sampled and averaged (x) positions of the maximum. (b) Sampled and averaged positions (x) of the centers of mass

C. SVM CLASSIFICATION

On the basis of the acoustic images of the individually working fans and the geometric parameters that have been extracted from them, classification tests were carried out. In these tests, a Support Vector Machine (SVM), based on a Radial Basic Function Kernel, was used. The objective of these tests is to detect which fan is working by means of the information obtained from the whole acoustic image and/or the extracted geometric parameters. The obtained classification results are shown in Table 1.

Table 1. SVM classification error rates

Information	**Dimension**	**Error Rate**
Whole acoustic images	1681	75.30%
Parameters of acoustic images		
Maximum positions	2	34.78%
Center of mass positions	2	32.84%
Maximum + centers m. positions	4	21.44%

Analyzing these results it can be observed that using the whole acoustic images to detect the running fan is not suitable. The classification error rate in this case is too high (75.30%). The whole acoustic images include too much information and the SVM classifier does not analyze them correctly in order to extract the useful information.

If only one of the geometric parameters is used, it can be observed that the obtained classification results are better than the one obtained with the whole acoustic images. Using only one geometric parameter, the maximum positions or the center of mass positions, the obtained classification error rate is half the one previously obtained. Using the maxima, the error rate is 34.78%, and using the centers of mass, the error rate is 32.84%. Here, it is shown that the geometric parameters are useful in the classification task, and that the whole image provides too much information that misleads the classifier.

If both geometric parameters, maximum and center of mass positions, are used, the classification error rate decreases. This decrement shows a better behavior of the classifier. So, these results show that the geometric parameters seem to reveal useful information for the classification.

4. CONCLUSIONS

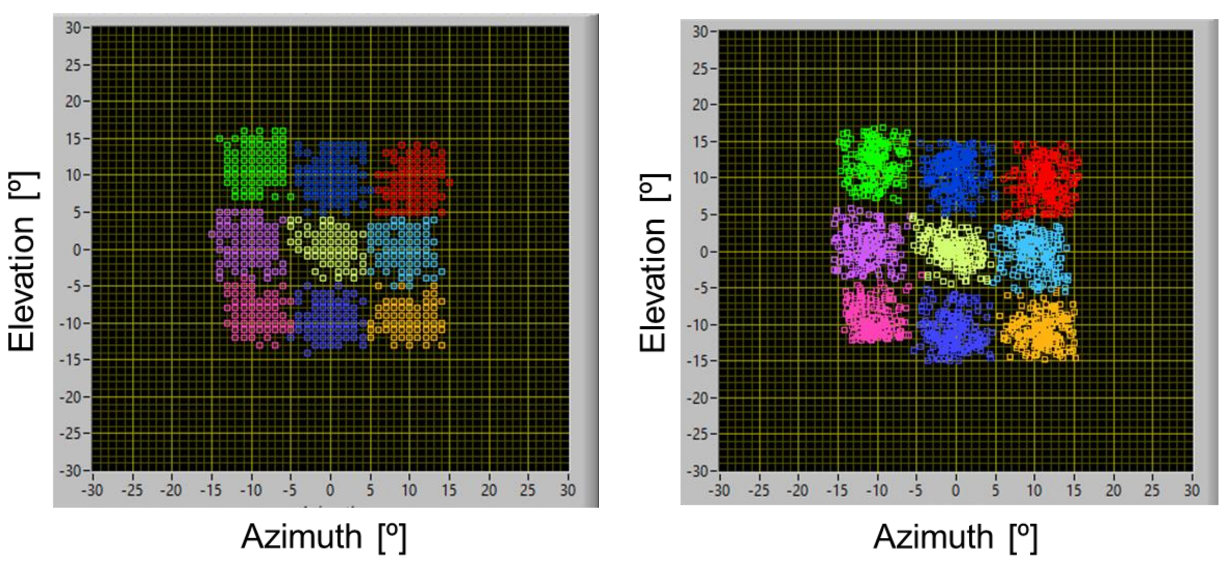
This work is a first step of a bigger study based on fault diagnosis of a fan matrix by means of the analysis of the acoustic images obtained with a MEMS microphone array, using classification techniques based on machine learning. The final objective is to detect faulty fans in the fan matrix.

The analysis of the acoustic images of the individually working fans reveals that the average of these images could be used to estimate their real positon of the working fan inside the matrix. Also it reveals that the geometry of the images is directly related to this estimation.

On the basis of these observations, some geometric parameters, such as the positions of the maximum of the acoustic images and the positions of their center of mass have been assessed and used as classification parameters in some classification tests based on Support Vector Machines (SVM). These SVM classification tests have revealed that:

- The whole acoustic images include too much information which does not allow the classifier to interpret correctly this information.
- The geometric parameters reveal more useful information with the objective of detecting the working fan in the matrix.

For future work, it could be pointed that it would be very useful to improve or preprocess the obtained acoustic images by filtering them or by using averaging techniques, for example. The objective of these enhanced acoustic images is to obtain less dispersion of the “extracted geometric parameters positions” around the “real positions” of the fans, as it is shown in Figure 7.



(a) *(b)*

Figure 7. Acoustic images: (a) filtered positions of the maxima, (b) filtered positions of the centers of mass

More work must be done related to the SVM classification. To improve these tests, more geometric parameters from the acoustic images should be extracted; not only from the azimuth versus elevation images shown in this work, but also from the information included in the range and frequency dimensions that the acquisition system is able to obtain. In this work, range and frequency dimensions were fixed to certain values.

The tests shown in this work could be repeated considering the opposed test scenario, that is, considering that all the fans are working except one. These test cases are more realistic, are adapted to a real situation of a faulty fan matrix. The objectives of these new tests are: first, to detect if there is any failure in the fan matrix, and, secondly, to identify which fan does not work properly

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