# OPTIMAL CONFIGURATION OF WIND TUNNEL ACOUSTIC BEAM-FORMING ARRAYS FOR NOISE MONITORING OF AIRCRAFT WITH COUNTER-ROTATING OPEN-ROTORS USING GENETIC ALGORITHMS

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Abstract. In this paper we present an array configuration optimization technique and the associated experimental results from wind tunnel experiments of a scaled model of a regional aircraft with counter-rotating open-rotors. A Genetic Algorithm optimization tool is developed and used during the array configuration phase in order to optimally reduce the number of elements of an acoustic array, without reducing its specific performance required for the series of experimental tests. The method is based on global multi-objective optimization of two contradictory metrics from the array response pattern, i.e., dynamic range & angular resolution. The results of the optimization tool were verified by two wind tunnel experimental campaigns using a scaled aircraft model. The wind tunnel experimental results show that the a priori selection of the optimal configuration could contribute to a significant reduction of the number of monitoring channels while, not affecting or even improving, the pattern of the beam and the overall performance.

# **1 INTRODUCTION**

Far-field phased array antennas are increasingly being used in almost any engineering and research field from aerospace to structural health and from medicine to geophysics. A large part of these are used in the acoustic field applying microphone arrays and beamforming techniques for sound/noise source localization. The microphone antenna array was introduced by Billingsley in 1974 and has since seen dramatic improvement due to the availability of better data acquisition and computing hardware [1].

Far field beamforming for sound/noise source localization, is an expanding application field today. Acoustic beamforming techniques [2] are indispensable for the localization of sound sources on moving objects, on flying aircraft, on high-speed trains, on motor cars in motion, on open rotors like helicopter and wind turbine rotors. As real applications require the ability to follow the motion of the sources, they are often replaced by static source localization experimental tests, inside the test sections of open and closed wind tunnels [3, 4].

The quality of the source detection and the direction of arrival (DOA) estimation, especially when multiple sources are present, depend highly on the response pattern of the acoustic array. A way to improve the response pattern is to design an appropriate array geometry and configuration for the application in hand. But, array construction and geometry configuration is not an easy or inexpensive task. Therefore, an early study of all possible array configurations, to achieve the desired array performance, is required before constructing an array.

Depending on the application in hand, a different design, configuration and parameterization of the acoustic arrays may be required for each case. Several restrictions and requirements are posed to the designer about the array size, geometry, number of sensors, distance, direction, positioning, etc, leading to a large number of alternative designs with comparable characteristics (figure 1). The complex configuration of a phased array antenna presents the designer with the challenge to select the best solution among a very large set of potential ones.



Figure 1. Four different array geometries using the same number of MICs and their responses (Azimuth cuts at elevation angle (0°): a) ULA, b) URA, c) UCA, d) CCA

The antenna designer needs to know at design stage the response of each acoustic array under consideration, therefore, he needs the support of a software simulation tool that will automatically calculate the corresponding antenna array pattern & characteristics for any design parameters set he compiles. Several tools may be found either from manufacturers of electronic equipment [5, 6], or, from researchers [7, 8], but most of them are bounded with specific hardware/equipment, tailored to a specific application, or, not incorporating all the features required, thus forcing often the designer to develop its own tool. The large number of candidates and the mathematical complexity of dealing with the optimization of the element positions required the use of more thorough search and detection tools applying more efficient optimization techniques such as various heuristics algorithms [9, 10, 11].

The aim of the present work is to develop a Wind Tunnel Acoustic Arrays optimization technique, design the optimal arrays and process the experimental data for Beamforming and source detection, during the experimental phase of WENEMOR project [12]. The experimental data were collected from the wind tunnel tests using the acoustic arrays already installed and functioning. The problem faced is that the existing configuration of the installed arrays is rarely the best for all cases under consideration. Each experiment may need different array layouts, additional external arrays or sub-arrays or other re-configurations of the installed equipment, leading often to a need of extra (but not available) acquisition channels to connect external equipment, or a need of extra (but not available) time & space for processing and storing the additional acquisition data sets.

In the course of this work, all alternative array designs were simulated and analyzed using the Acoustic Array Beamforming Analysis (AABA) tool [13], that was specially designed for acoustic phased-arrays and intended for supporting the design and analysis of far-field acoustic array antennas. In sequence, the selection of the fittest was performed by a specially developed Acoustic Array Design Optimization (AADO) tool that is based on Genetic Algorithms (GA) and thus robust to problems involving multiple objectives and many design parameters and also capable of efficiently searching a design space to find a global optimum [14, 15]. The tool uses a GA optimizer to calculate the best design configuration, based on the designer's criteria, requirements and goals.

The objective is to find an optimal reduction of the existing arrays in order to release a number of microphones or channels, without compromising performance, i.e., keeping low side lobe level, narrow beam width and accurate source detection (DoA) and also to verify that the optimal solution is correct under the real conditions of the Wind Tunnel experiments. As the decision about the optimal solution is usually made at design stage, i.e., before constructing and using any array, the question about the correctness of the optimal solution remains, until the array is finally used in the field with real data. In our case, the final experimental data from the Wind Tunnel tests of sound emissions from an airplane model engine were used to test and verify the optimization results.

### 2 THE WIND TUNNEL EXPERIMENTAL SETUP

As presented in detail in [12] by the WENEMOR consortium, the principal goal of the WENEMOR project is to assess experimentally the noise shielding effectiveness of classic airframe components for different Open Rotor aircraft configurations. A complete 1/7<sup>th</sup> scale aircraft has been designed and built for installation in the Pininfarina Aerodynamic and Aeroacoustic Research Center Wind Tunnel (figure 2a). The model has two Open

Rotors with a contra-rotating fan at the same scale as the airframe (figure 2b). Various positions of the ORs with respect to the airframe will be tested with noise measurements being performed both in the near and the far field.



Figure 2. The aircraft model (a) and the engines (b) installed in the wind tunnel [12].



Figure 3. Pininfarina's wind tunnel: a) the 'top' and 'lateral' arrays [12], and, b) setup of the 'lateral', 'linear-polar' & Univ.PM 'front' array.



Figure 4: Topologies of the Top, Lateral & Linear-Polar Arrays, and Front array positioning.

The far field sound measurements were acquired by three (3) 2-D microphone arrays ('Top', 'Lateral' and 'Front') and one (1) 1-D/linear-polar array (figures 3 & 4) with the following details:

- Top array (78 microphones), circular in 4 concentric circles
- Lateral array (66 microphones), semi-circular
- Front array (33 microphones), circular
- Linear-Polar array (13 microphones) centered on the front blade plane covering angles from 30 to 150 about the blade side-line axis

Data were acquired simultaneously on all systems for the far field measurements at a data rate of 32,768Hz for 10s duration. A total of 16 aircraft configurations were tested consisting of 9 pusher and 7 tractor

configurations. Each aircraft configuration could in turn be modified to a take-off or approach setting. Using automated systems in the wind tunnel, each of these set-ups was then tested at a variety of angle of attack settings: 60, 80, 100, and flow speeds: 20m/s, 24m/s, 28m/s. This led to a total of 288 unique test set ups consisting of changes in model geometry, take off/approach setting, angle of attack and wind tunnel flow speed. The outputs of the WENEMOR project will form a database through which the other Green Regional Aircraft partners can validate the developed software codes.

The first test campaign of the WENEMOR project was completed in May 2013 and the second test campaign was completed in September 2013. The data analysis phase of the project followed immediately after the end of the experimental phase and the results are currently reported in the literature as they become available. The WENEMOR experiments provided, for the first time in Europe, a comprehensive database on noise effects for novel regional advanced aircraft concepts using Open-Rotor propulsion systems.

# **3** ACOUSTIC ARRAY DESIGN OPTIMIZATION TOOL

The acoustic array optimization module structure is composed of two main parts: the Acoustic Array Design Optimization (AADO) part (using GA) and the Acoustic Array Beamforming Analysis (AABA) part (using simulation). At the heart of the optimization tool is the classic GA optimizer which can use various forms of selection, cross-over, and mutation to evolve the design population. The acoustic array analysis part plays the role of a Fitness Function. It calculates the score (metrics) of each individual (array design) and it returns it to the GA for the selection process. Its functioning is based on the Acoustic Array Beamforming Analysis tool presented in [13]. Based on the above, a detailed structure of the module is shown in figure 5



Figure 5. Detailed structure of the Acoustic array design optimization tool with the GA module and the AABA module cooperation

The main design parameters that affect the performance of the acoustic array are:

- The number of array elements,
- the element characteristics (MIC pattern, orientation, freq.-range),
- the array Geometry (shape, size, distance, diameter),
- the MIC positions and any restrictions,
- the source signal characteristics (freq.-range, direction, distance, if .),
- the focus direction and the scan grid.

The main performance indicators/metrics are:

- The Spatial resolution, the ability to separate two sound sources. It is expressed in centimeters. It represents the closest distance between two sources, where they still appear separately and do not merge into a single source. The lower the spatial resolution, the better the source localization. In this work the Angular Resolution is used instead, in order to remove the dependency from the unknown source distance.
- The Dynamic range, expresses sound level differences in dB between real sound sources and surrounding mathematical artifacts inherent to the sound source localization techniques. The higher the dynamic range, the better the source localization. (In beamforming techniques, the dynamic range is also linked

to frequency – the lower the frequency, the higher the dynamic range). In this work it is measured as the difference between the mainlobe and the highest sidelobe.

• The Number of Microphones, that require acquisition channels & infrastructure that in not always available, so the lower the number the better as long as they meet acquisition requirements.



Figure 6. The Genetic Algorithm optimizer flowchart and the parameters setup GUI

The GA optimization cycle and the user defined parameters are shown in figure 6. Depending on the specific array design under consideration, the goals of the user may be different. For example:

- When there are multiple sources in the area that need to be separated, the designer must improve the spatial resolution of the array, i.e., the designed array should have as small as possible Angular Resolution (AR) in its main lobe.
- When the array is in a noisy environment with reflections and interference, the designer must increase the difference between the main-lobe and the highest of all side-lobes i.e. increase the Dynamic Range (DR) of the array.
- When in a shortage of acquisition channels or time, the designer must reduce the number of connected/sampled microphones to the minimum acceptable without reducing performance.

The problem with the above goals is that they are contradictory (when AR is improved, DR is decreased, when using less microphones SNR is reduced, etc.) and that they are always posed in combination. This constitutes a Multi Optimization Problem and an advance optimization tool like the one proposed above was required.

## 4 OPTIMIZATION OF THE WIND TUNNEL ACOUSTIC ARRAYS

### 4.1 Optimal Design using Experimental data from a white noise Speaker Source

As the decision about the optimal array configuration is usually made at design stage, i.e., before constructing and using any array, the question about the correctness of the optimal solution remains, until the array is finally used in the field with real data.

In the WENEMOR case, experimental data from Wind Tunnel tests using white noise sound emitted from a speaker were acquired in order to be used for the optimization of the arrays. The speaker was placed at the direction of the expected noise source, i.e., the airplane engine.

The objective of this task is to find for each Wind Tunnel Array a reduced version with fewer MICs without altering the array geometry and by simply deactivating the redundant MICs. So, the aim is to define the best subset of the existing MIC elements that could be used for the monitoring of the experiments with equivalent or better performance. This would reduce significantly the total amount of recorded data while freeing up a substantial number of acquisition channels for other data acquisition needs.

### **TOP** Array

After considering a series of reductions (from 70 to 25 microphones) it was found that a reduction of almost 50% of the original channels could be achieved, without reducing the performance of the array. More precisely, starting with an initial population of 20-30 members and after 20-30 generations, the averaged results over a



frequency range of 2 - 8 kHz showed that an array with 40 elements (figure 7 - table) could perform better than the original one, and would also save 38 acquisition channels for additional measurements. The proposed reduced array geometry layout with only 40 elements (microphones) is shown in figure 7.

Figure 7. The optimally reduced TOP arrays (70-25mic), and the selected one with 40mic

An initial verification step followed every optimal design phase by comparing the response of the original (full) array to the one of the optimally reduced array demonstrating the improved antenna pattern (figure 8).



Figure 8: Responses from a speaker noise source: a) the original (78mic) TOP array, and, b) the 40mic optimal (GA best fit) array.

### LATERAL Array

For the 'Lateral' acoustic array design case, the initial population members have their microphones randomly selected among the originally available 66 positions. Following the same procedure described earlier the resulting array is the following:



Figure 9: The optimally reduced Lateral arrays (50-12mic), and the selected one with 26mic.

## FRONT Array

For the 'Front' acoustic array design case, the initial population members have their microphones randomly selected among the originally available 33 positions. Following the same procedure described earlier the resulting array is the following:



Figure 10: The optimally reduced Front arrays (30-12mic), and the selected one with 15mic.

#### 4.2 Verification using Realistic Experimental data from Open Rotors in Pusher & Tractor Configuration

All the optimally reduced array configurations that were produced using the white noise speaker data, were subsequently used with the realistic experimental datasets produced on May (pusher) & September (tractor) in order to compare and verify the results.

The comparison & verification of the Acoustic Array Optimization results on the optimal acoustic array topologies of each Wind Tunnel array is shown next. A couple of sample datasets is shown first and then the overall results over all pusher & tractor recorded datasets (over 340).

#### TOP Array Comparison (78 vs. 40mic)

The sample Responses from two datasets are shown in figure 11. In the left is the original array response and in the right the optimally reduced array response. The figures also show the azimuth and elevation cuts used to calculate the performance metrics.

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Figure 11: TOP Array Comparison (78 vs. 40mic) for 2 datasets.

The Overall performance metrics results from all datasets from Pusher (May) and Tractor (September) experiments are shown in figure 12. The diagonal indicates equal performance. The original array performs better in cases below the diagonal, and, the reduced array performs better in cases above the diagonal.



Figure 12: Overall TOP Array Comparison (78 vs. 40mic).

# LATERAL Array Comparison (66 vs. 24 mic)

The sample Responses from two datasets are shown in figure 13. In the left is the original array response and in the right the optimally reduced array response. The figures also show the azimuth and elevation cuts used to calculate the performance metrics.



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Figure 13: LATERAL Array Comparison (66 vs. 24mic) for 2 datasets.

The Overall performance metrics results from all datasets from Pusher (May) and Tractor (September) experiments are shown in figure 14.



Figure 14: Overall LATERAL Array Comparison (66 vs. 24mic).

# FRONT Array Comparison (33 vs. 15 mic)

The sample Responses from two datasets are shown in figure 15.



Figure 15: FRONT Array Comparison (33 vs. 15mic) for 2 datasets.

The Overall performance metrics results from all datasets from Pusher (May) and Tractor (September) experiments are shown in figure 16.



Figure 16: Overall FRONT Array Comparison (33 vs. 15mic).

## 4.3 Optimal Design using the Realistic Experimental data

A part of the realistic experimental dataset was also used to select an optimally reduced configuration of the Top array with fewer (40) microphones. Following the same method presented earlier and starting with an initial population of 30 arrays and after 30 generations, an optimal array configuration was achieved is shown in figure 17.



Figure 17: An optimally reduced Top array using a realistic experimental dataset.

The resulting array was used on the rest of the dataset over the frequency range of 400-8000Hz and the results are shown in figure 18 where the pattern of the reduced array (b) demonstrates a higher dynamic range and better angular resolution than the response pattern of the original array (a).



Figure 18: Response pattern of (a) the original and (b) the optimally reduced array.

# CONCLUSIONS

The Acoustic Array Design Optimization tool was successfully applied to reduce the number of elements of acoustic arrays without reducing their specific performance, as well as, their ability to detect the correct Direction-of-Arrival (DoA). The results show that the a priori selection of the optimal configuration using this GA based tool substantially reduces the number of microphones needed, while keeping or improving the pattern of the beam and its overall performance. From the experimental runs, either the preliminary ones with a white noise speaker or the later realistic ones with the airplane model in pusher & tractor configuration (May-September 2013), it is shown that, the optimal array configurations proposed by the GA tool, while using fewer microphones, e.g., 40 out of 78 or 15 out of 33 mics, could even outperform the original array configuration.

From the presented results it becomes clear that the beamforming tool for the reduced (40 mic) Top array

detects successfully the origins of the noise signal received. The beamforming tool for both the original & the reduced array detects accurately the area where the noise signals are produced and it also detects correctly the Direction-of-Arrival (DoA) of the highest noise source which is the engine rotor.

Moreover, these results based on realistic experimental data also verify that, there are significant possibilities to modify the configuration of the Wind Tunnel arrays to achieve better performance for specific cases. The response patterns of the optimized Top array exhibits better characteristics than those of the original Top array while using almost one half of the microphones. The two patterns may have their peak values at the same direction (figure 29), but, the sidelobes of the optimized (40 mic) array response are much lower providing a better Dynamic Range (DR), and also, its lobe width is much narrower providing a better Angular Resolution (AR) that is required for better source separation.

These latest results indicate the possibilities to further optimize the acoustic array if one takes into account more precise data, conditions, expected directions, etc. This constitutes a research action that will follow the main WENEMOR results on array optimization.

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