Array microphones are cost-effective free-field acoustic sensors designed to be mounted on large or small arrays for the analysis of sound fields, sound power and transients. These types of microphones are typically used for measuring and locating sound sources using techniques like Beamforming, Nearfield Acoustic Holography (NAH) and Acoustic Cameras. For those applications, it is important to consider not only frequency response and sensitivity but also the phase-matching between microphones on the array. Close phase-matching between microphones will lead to good accuracy in the measurements and a better implementation of the algorithms for source localization. Due to this, researchers working with array microphones are pushing manufacturers to provide tighter specifications regarding microphone phase-matching. If those requests are not followed by accurate system calibration and improved accuracy on microphone array positioning before measurements, it will not be possible to take advantage of the microphones’ improved phase-matching.

Two small experiments were carried out using measurement and array microphones, a rotary motor with 1-degree accuracy and a sound source with adjustable distance to the microphones. With these configurations, it was possible to show how very small positioning changes of the microphones (like the ones produced by inaccurate mounting), sometimes imperceptible to the naked eye, can affect the phase response of the measurement to a greater extent than the microphones’ specified phase-matching tolerance for a given frequency range. In other words, not only must the phase responses specified for the array microphones be considered, but also the phase changes that inaccurate microphone positioning or array calibration introduces to the measurement. Source location algorithms rely, among other things, on phase differences of measured signals to perform an accurate localization of the sound source. Therefore, inaccurate microphone positioning in the array and inexact position calibration of the microphones will potentially affect the precision of a source locating system.

1. Introduction

Close manufacturing tolerances provide array microphones with a high degree of interchangeability, a major advantage when used in multiples forming arrays and matrices. These tolerances include not only sensitivity and frequency response measurements, but also phase-matching between the units.

Multiple techniques are used nowadays to locate noise sources, find the direction of firearms, planes, in surveillance applications or conference rooms. These techniques include different types of Beamforming methods, like delay and sum (DSB) or filter and sum and Nearfield Acoustic Holography (NAH). There are also other techniques which combine these methods with pictures or video like the Acoustic Camera.

All the approaches mentioned above typically rely on a great number of microphones mounted in an array to capture acoustic signals in the field for processing. The more microphones the array uses, the better the reduction of non-directional noises will be [1]. Wider arrays also tend to extend the lower frequency range of use and improve the general performance of the beamforming, since
the beam will be narrower for a given frequency [1]. Furthermore, the distance between the microphones in the array must be small to reduce aliasing when processing the signals [1].

The need to use many microphones generates the necessity of using low-cost sensors. If these sensors are not provided by a reliable source, they might have phase and frequency offsets that, if not considered, will deteriorate the result of the beamforming [2]. Therefore, it is important to select microphones that have very similar sensitivity, frequency and PHASE response between each other. Having a better phase-matching between microphones, makes it easier for the user to measure more accurately the phase differences between the source and every microphone in the array and, in the end, achieve better results with source location algorithms.

Another important thing to consider, besides microphone phase-matching, is the accuracy of microphone positioning in the array. Algorithms for sound source location must take into consideration the precise position of every microphone, given that even small uncertainties in microphone location can lead to large errors related to overall localization of the source [3].

The purpose of this paper is not to get into details of beamforming or NAH algorithms but to focus on the first line of the measurement chain, which are the microphones, and on how inaccurate microphone positioning, such as the one produced due to inaccurate mounting, affects the phase response of every microphone in the array.

2. Beamforming basics

There are multiple beamforming techniques available and appropriate for different ambient noise conditions [4] [5]. This section describes the fundamentals of the delay and sum (DSB) beamforming method. Recognising its principles will help understand the importance of phase-matching all the microphones forming the array.

If a group of microphones is aligned in a straight line and placed in a field with a sound source, the microphone closest to the source will capture the signal from it first. After that, all the other microphones will receive the signal at a different combination of phases in ascending order of distance to the source [6]. If in the next step the microphones are aligned in a straight line perpendicular to the sound source, all the microphones will capture the signal coming from the source at the same time. When all the signals recorded by the microphones are added up, the ones arriving at the same time will be reinforced, while those coming from different directions and arriving at other times, will not. The result is an array with a listening beam oriented to the direction of the array. It is also possible to manually move the array or delay the measured signals using digital signal processing to orient the beam to a different direction in the sound field. This electronic steering of the array’s beam will allow a piece of software to “listen” to different points in a grid and create an acoustic representation of the field with frequency and sound pressure level data.

The chart in Figure 1 shows a basic overview of the delay and sum beamforming method:

![Figure 1 – Overview of the delay and sum beamforming method. Courtesy of © GfaI (www.gfaitech.com). [7]](image-url)
For the calculation of beamforming maps in aero-acoustical application, the delay and sum algorithm require the following input data [1]:

- Time Series/tracks of all microphones.
- A grid of focus points that includes the region of interest.
- Parameters of the flow.
- The accurate position of all microphones.

Furthermore, the achievable frequency range and quality of results may depend on [1]:

- Characteristics of microphones.
- Array properties (Number of mics. spacing and aperture).
- Channel to channel phase difference (or phase-matching).

This paper will only put the attention on microphones’ phase-matching, position accuracy and characteristics.

3. **Microphone phase-matching**

As mentioned above, using phase-matched microphone arrays is important to achieve better results with source location applications. However, how can the phase-matching process be explained?

The process of phase-matching microphones usually consists in using a reference signal like a sine sweep emitted by an electrostatic actuator mounted on top of the microphone’s diaphragm or by a sound source inside an anechoic chamber. Once the signal is emitted, the output of the microphone is compared to the signal generator output that acts like the reference signal for the phase calculation. Once this process is finished, it is possible to compare the phase plots of multiple microphones and select the ones with similar results. Another possibility would be to compare the phase plots of the microphones under test to a reference curve with the desired response. As with today’s technology it is not possible to manufacture two sensors with the same phase response, it is common to find tolerances like the ones shown in Table 1:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Hz – 100 Hz</td>
<td>+/- 5º</td>
</tr>
<tr>
<td>100 Hz – 3 kHz</td>
<td>+/- 3º</td>
</tr>
<tr>
<td>3 kHz – 5 kHz</td>
<td>+/- 5º</td>
</tr>
<tr>
<td>5 kHz – 10 kHz</td>
<td>+/- 10º</td>
</tr>
</tbody>
</table>

Table 1 – Example of array microphone phase tolerances.

As the frequency increases and the wavelength of the acoustic signal gets shorter, the phase-matching will be harder to achieve and therefore the tolerances will get bigger.

4. **Test Description**

The following section describes the two different test performed using array and measurement microphones and test equipment used.

4.1. **Test Equipment**

- 4x GRAS 40PL CCP Free-field Array Microphone.
- 1x GRAS 46BE ¼” CCP Free-field Measurement Microphone.
- GRAS 44AA Sound Source.
- GRAS PR0001-2 Array Module mounted in rotary servo base with 1-degree precision.
- GRAS 12AQ 2-channel power module.
- National Instruments PXI-1002 DAQ with LabView Software.
4.2. Microphone Characteristics

![Image of microphones](image_url)

Figure 2 – Left: GRAS 40PL. Right: GRAS 46BE (Right).

Table 2 – Specs. comparison between GRAS 40PL and GRAS 46BE microphones.

<table>
<thead>
<tr>
<th></th>
<th>GRAS 40PL CCP Free-field Array Microphone</th>
<th>GRAS 46BE ¼” CCP Free-field Measurement Microphone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong></td>
<td>50 Hz - 20 kHz</td>
<td>4 Hz - 100 kHz</td>
</tr>
<tr>
<td>±1 dB</td>
<td>100 Hz - 5 kHz</td>
<td>10 Hz - 40 kHz</td>
</tr>
<tr>
<td>±2 dB</td>
<td>10 Hz - 20 kHz</td>
<td>4 Hz - 80 kHz</td>
</tr>
<tr>
<td>±3 dB</td>
<td>10 Hz – 50 Hz</td>
<td>4 Hz - 100 kHz</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td>32 dB(A) to 150 dB</td>
<td>35 dB(A) to 160 dB</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>10 mV/Pa (+/- 3 dB)</td>
<td>3.6 mV/Pa (+/- 3dB)</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Array</td>
<td>Measurement Mic.</td>
</tr>
</tbody>
</table>

4.3. Description

The tests were carried out in an anechoic chamber and were divided in two different parts: Test 1 and Test 2.

4.3.1. Test 1

For the first test, four array microphones (GRAS 40PL) with very close phase-match specifications were selected (See Figure 3) and installed in an array fixture mounted on the rotary servo base. The rotary servo base had the possibility to be rotated with 1-degree steps and was facing a fixed loudspeaker (GRAS 44AA) at a 5 cm distance, that acted as a sound source for the test. Pictures from Test 1 and layout are shown in Figure 4 and 5.

![Graph showing phase responses](image_url)

Figure 3 - Selected GRAS 40PL phase responses. The red dotted lines represent the phase tolerances for this type of microphone.

![Image of test setup](image_url)

Figure 4 – Pictures from Test setup 1 inside the anechoic chamber.
The array was rotated three times in one direction only and with 1-degree steps, as shown in Figure 5. For every step, a logarithmic sine sweep from 100 Hz to 20 kHz was reproduced through the loudspeaker, acting as a reference signal. The signal emitted was captured by the four microphones in the array and sent to a computer where Magnitude and Phase charts were plotted.

### 4.3.2. Test 2

For the second test, one ¼” free-field measurement microphone (GRAS 46BE) was placed at an initial distance of 32.50 mm from the sound source. The phase response between the microphone output and the reference signal sent to the source was measured. Next, the distance between the source and the microphone was incremented to -1, -2 and -3 mm compared to the initial position (See Figure 6 Left). For every distance, the phase response was measured and compared to the initial position to see how small distance changes in between the microphone and the source affect the phase response of the system. The difference between the phase response from the initial position and positions -1, -2 and – 3 was calculated.

46BE measurement microphone has a wider frequency range than the 40PL used in Test 1. Due to this, a logarithmic sine sweep up to 30 kHz was reproduced through the sound source (GRAS 44AA) to be able to measure the phase response changes at higher frequencies. Figure 6 shows the setup layout and a picture from the measurement.

### 5. Test Results

The following section shows the obtained results for Test 1 and 2.

#### 5.1. Test 1

Figures 7, 8, 9 and 10 show the phase differences measured for microphones 1, 3, 4 and 6 respectively at the different angles. For every angle 1º, 2º and 3º the measured phase was compared against the reference phase response at 0º. The difference between every angle and the reference was obtained.

Figure 11 shows the phase differences between the microphones in the outer extremes of the array (Mic 1 and 6).
Figure 7 – Mic 1 Phase Difference Referenced to 0º.

Figure 8 - Mic 3 Phase Difference Referenced to 0º.

Figure 9 - Mic 4 Phase Difference Referenced to 0º.

Figure 10 - Mic 6 Phase Difference Referenced to 0º.

Figure 11 - Phase difference between Mic 1 and 6 when the array has been rotated 1º, 2° and 3°.
5.2. Test 2

Figure 12 shows the results for Test 2:

![Figure 12 - 46BE Phase Difference Referenced to X = 0.](image)

6. Results Analysis

6.1. Test 1

The first thing worth noticing after looking at results from Test 1 is that microphones 1 and 3 have positive phase response results while microphones 4 and 6, negative. This can be explained by the fact that the first two microphones (1 and 3) are moving away from the sound source, while the latter (4 and 6) are getting closer with every rotation.

As it was expected, the microphones positioned in the extremes of the array (1 and 6) show a greater phase deviation compared to the microphones in the middle (3 and 4) due to higher range of displacement that these units experience.

In every case, 1000 Hz is the frequency were the phase difference starts being greater than 5°. Between 100 Hz and 1000 Hz the phase differences compared to the reference are close to 0° and that is why they were of no interest for this research.

With the setup used on this test, an array variation in angle of 1° lead to a phase difference range going from approx. 7° and up to 80° compared to the reference. A 2° angle of the array the phase difference compared the reference goes from 18° to 130°. And for 3° angle, the phase variations are from 30° and up to 140°.

The phase difference results between the microphones in the outer extremes of the array (See Figure 11) show that, for a 1-degree displacement of the array, the phase differences are around 40° at 10 kHz and larger for higher frequencies.

The highest measured phase differences between Mic 1 and 6 are approx. between 130° and 300° at 20 kHz depending on the angle of the array.

Figure 3 shows the phase-matching between the four microphones chosen for Test 1. At 10 kHz the highest phase difference between the units is approx. 4°. While Figure 11 shows that with an array rotation of 1° the phase difference between the microphones in both extremes of the array will be approx. 13° at the same frequency (or even greater are higher frequencies / rotation angle).

6.2. Test 2

A 1mm displacement from the reference will cause, according to the results, phase differences going from 0° to approx. 40° depending on the frequency of interest. The phase difference range for 2mm distance from the initial position goes from 0° to approx. 60°. In addition, for 3mm is 0° to approx. 100°.

With the minimum displacement (X=−1mm), for frequencies equal and above 8 kHz, the phase displacement is already greater than 10° which is greater than the phase-matching tolerances typically established array microphones and even phase matched measurement microphones.
Focusing at the frequency range starting at 10 kHz and up to 30 kHz, the smallest phase difference is approx. 30º (X=1mm @10 kHz), while the biggest is around 100º (X=3mm @30kHz).

7. Conclusions

This paper presented two different tests to identify how small changes in the angle and distance of a microphone or array of microphones in relation to a sound source affect their phase response. This was made to simulate inaccurate positioning of the microphones in the field.

All the results shown in section 5 clearly prove that small changes in angle or distance of an array of microphones or a single microphone in the field will lead to phase differences referred to the sound source of interest. If these phase differences are not considered in the context of sound source location using methods like beamforming, it can potentially lead to poor performance of the algorithms. The last word on how these issues can affect the performance of sound source location algorithms is out of the scope of this paper and is the software developer’s job to find out.

Methods for array position calibration have been presented in the past [7][8][9][10], yet they require complex setups that can only be made in laboratory conditions, their precision is less than 1 mm (between 1 and 6 mm) and are not suitable for portable microphone array available in the market that can be mounted with different array spacing and aperture.

Even with the smallest change in distance from the source (X=1mm) the phase differences compared to the reference at frequencies equal or higher than 8 kHz are greater than the typical tolerances established for these type of sensors (+/- 10º). This means that no matter how close the phase-matching is achieved for the microphones, an inaccurate positioning in the field will cause a phase difference greater than the mentioned tolerance.

Acknowledgments

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8. References