Designing the Acoustic Camera using MATLAB with respect to different types of microphone arrays

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Abstract— In order to design an acoustic camera, it is necessary to determine the shape of the camera as well as the number of microphones and their position on the camera. Therefore, simulations were performed for linear, square, circular and spiral arrays, as well as for arrays in the shape of a hemisphere, with varying number of microphones and varying spacing between the microphones. Based on these simulations, a decision was made on the shape of the microphone array, i.e. the acoustic camera. Furthermore, an algorithm called *Hemisphere* was written in MATLAB in order to determine the number of microphones and their location on the hemisphere. Results have shown that the gain in the desired direction as well as the number of side lobes and their gain, for that type of microphone array, is very frequency dependent. Increasing the frequency at which the design of the acoustic camera was made, increases the cutoff frequency, i.e. the maximum frequency for which the camera can be used thus, enables the design of a broadband camera.

Index Terms— MEMS microphones, beamforming, microphones array, acoustic camera.

I. INTRODUCTION

This paper describes the design of an Acoustic Camera with MEMS microphones [1, 2]. MEMS microphones have an omnidirectional response, which means that they respond equally to sounds coming from any direction, see Fig. 1.
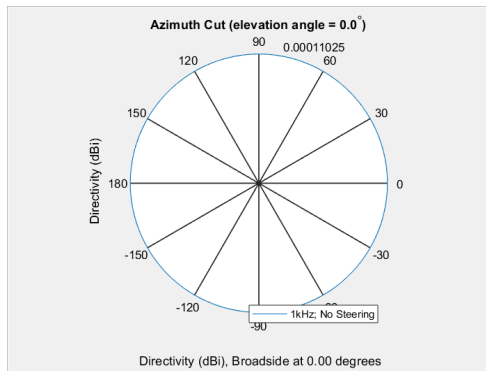

Fig. 1. MEMS Microphone Response Plot

Multiple microphones can be configured in an array to form a directional response or a beam pattern. A beamforming microphone array can be designed to be more sensitive to sound coming from one or more specific directions than sound coming from other directions [3, 4]. In order to achieve this, we have used *Sensor Array Analyzer* which is a part of MATLAB Phased Array System Toolbox.

When using the *Sensor Array Analyzer*, it is possible to obtain directivity patterns for different types of arrays. Simulations were performed for linear, square, circular and spiral arrays, as well as for arrays in the shape of a hemisphere, with varying number of microphones and varying spacing between the microphones.

The simulations were performed for the frequency $f = 1$ kHz, i.e. wavelength $\lambda = 0.343$ m. Furthermore, for each array configuration the simulations were carried out for two different microphone spacings: when all distances between adjacent microphones are less than a half of the wavelength (the maximum distance between microphones is $d_{max} = 0.1$ m) and when all distances between adjacent microphones are greater than a half of the wavelength (the minimum distance between adjacent microphones is $d_{min} = 0.2$ m).

Based on these simulations, a decision was made regarding the shape of the microphone array, i.e. the acoustic camera. Furthermore, it was necessary to determine the placement of the microphones on the camera and the number of the microphones. Thus, an algorithm called *Hemisphere* was written in MATLAB. This algorithm determines the number of microphones and their location on the hemisphere.

II. DESIGNING THE ACOUSTIC CAMERA

A. The Acoustic Camera's Shape

In this chapter the results obtained using the *Sensor Array Analyzer* for different types of arrays are discussed.

Examples of simulated linear arrays can be seen in Fig. 2 while Fig. 3 shows the directional patterns of those arrays for varying microphone spacing.
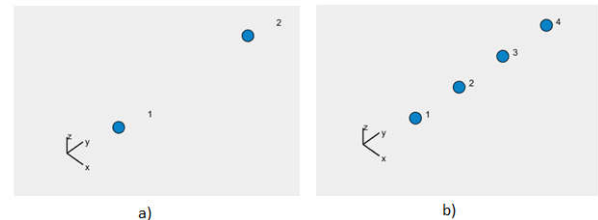

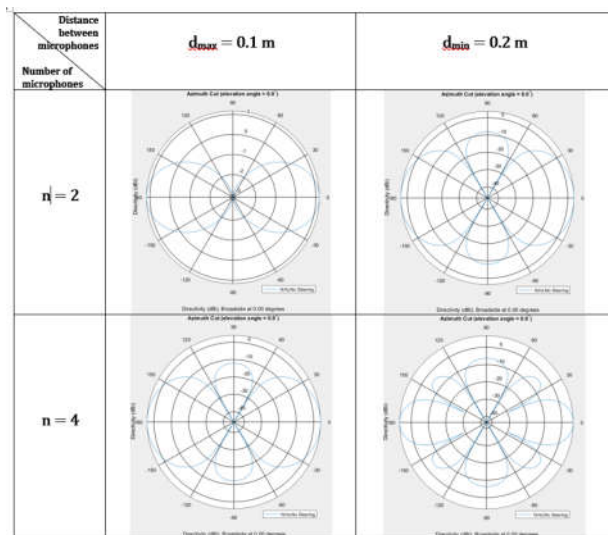Fig. 2. Linear array with a) 2 microphones and b) 4 microphones

Fig. 3.   Directivity patterns of linear arrays with 2 and 4 microphones for f = 1 kHz with a maximum distance between adjacent microphones of 0.1 m and a minimum distance between adjacent microphones of 0.2 m

Examples of simulated square arrays are shown in Fig. 4 while Fig. 5 shows the directional patterns of those arrays for varying microphone spacing.
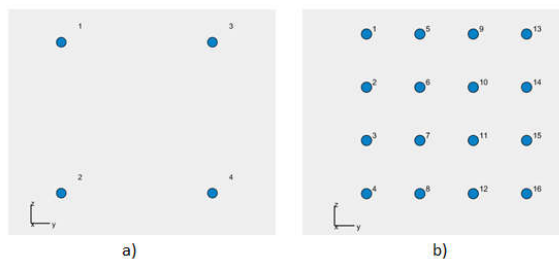

a)   b)

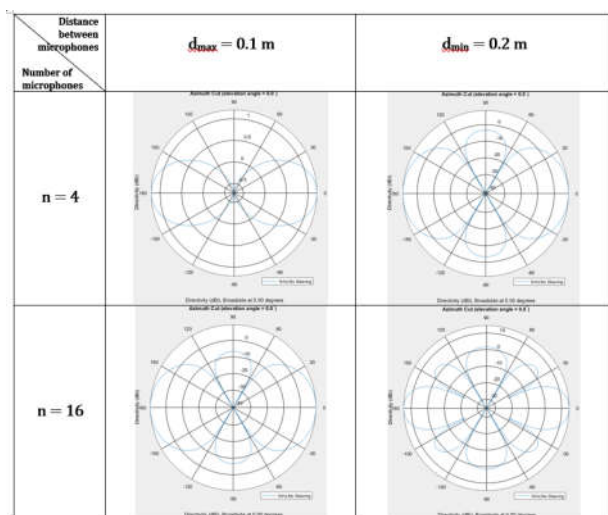Fig. 4.   Square array with a) 4 microphones and b) 16 microphones

Fig. 5.   Directivity patterns of square arrays with 4 and 16 microphones for f = 1 kHz with a maximum distance between adjacent microphones of 0.1 m and a minimum distance between adjacent microphones of 0.2 m

Examples of simulated circular arrays can be seen in Fig. 6 while Fig. 7 shows the directional patterns of those arrays for varying microphone spacing.
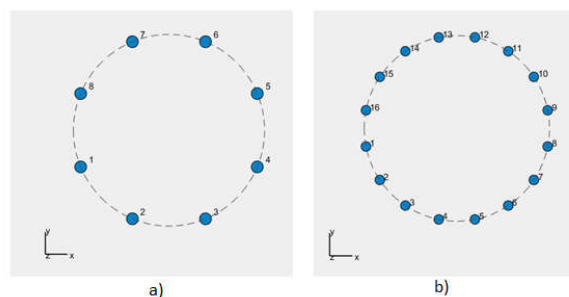

a)   b)

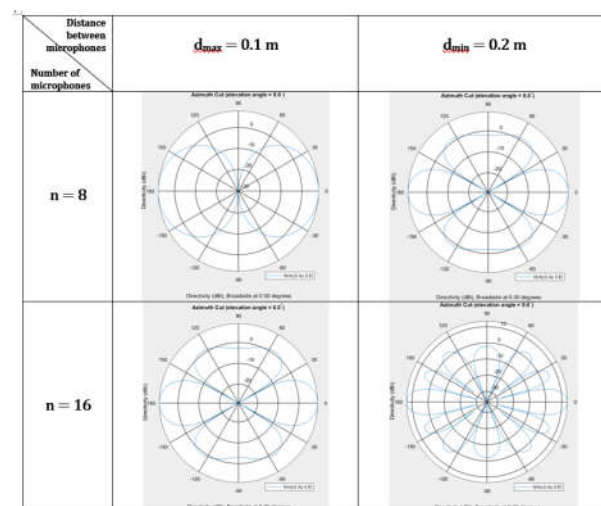Fig. 6.   Circular array with a) 8 microphones and b) 16 microphones

Fig. 7.   Directivity patterns of circular arrays with 8 and 16 microphones for f = 1 kHz with a maximum distance between adjacent microphones of 0.1 m and a minimum distance between adjacent microphones of 0.2 m

Examples of simulated spiral arrays with one turn can be seen in Fig. 8 while Fig. 9 shows the directional patterns of those arrays for varying microphone spacing.

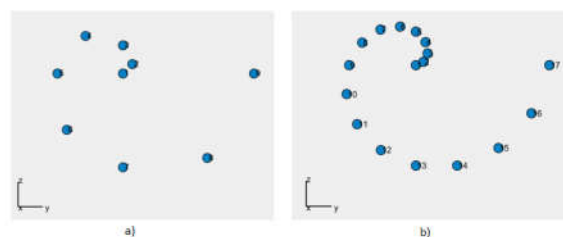a)   b)

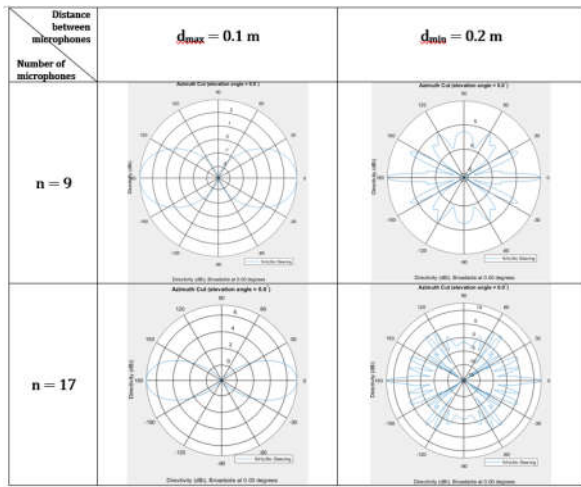Fig. 8.   Spiral array with one turn with a) 9 microphones and b) 17 microphones

Fig. 9. Directivity patterns of spiral arrays with one turn with 9 and 17 microphones for f = 1 kHz with a maximum distance between adjacent microphones of 0.1 m and a minimum distance between asdjacent microphones of 0.2 m

Examples of simulated spiral arrays with two turns can be seen in Fig. 10 while Fig. 11 shows the directional patterns of those arrays for varying microphone spacing.
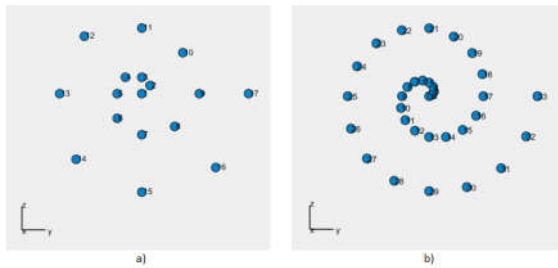

Fig. 10. Spiral array with two turns with a) 17 microphones and b) 33 microphones
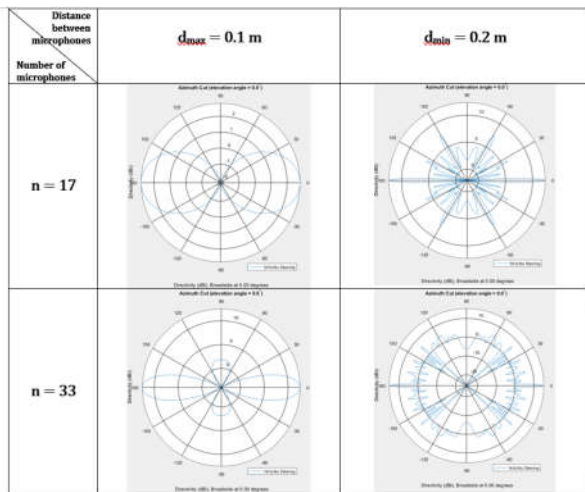

Fig. 11. Directivity patterns of spiral arrays with two turns with 17 and 33 microphones for f = 1 kHz with a maximum distance between adjacent microphones of 0.1 m and a minimum distance between adjacent microphones of 0.2 m

Examples of simulated arrays in the shape of a hemisphere are shown in Fig. 12 and Fig. 13. Furthermore, Fig. 14 shows the directional patterns of those arrays for varying microphone spacing.
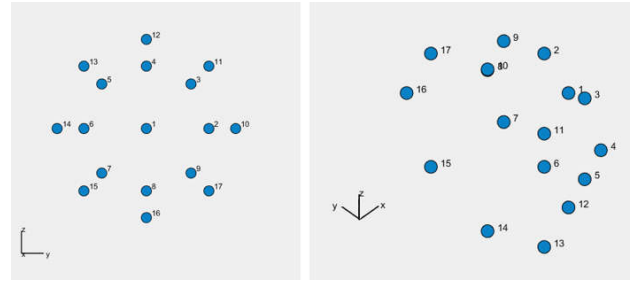

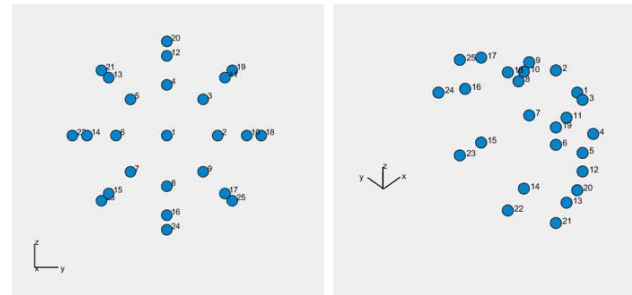Fig. 12. Array in the shape of a hemisphere with 17 microphones

Fig. 13. Array in the shape of a hemisphere with 25 microphones
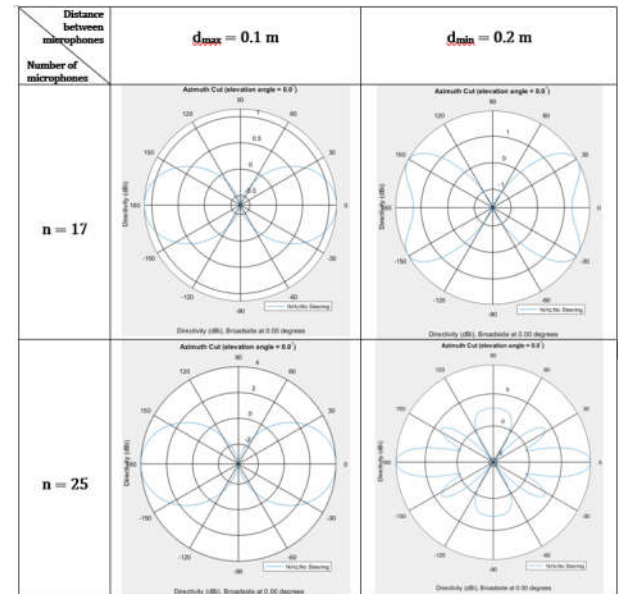

Fig. 14. Directivity patterns of arrays in the shape of a hemisphere with 17 and 25 microphones for f = 1 kHz with a maximum distance between adjacent microphones of 0.1 m and a minimum distance between adjacent microphones of 0.2 m

B. The Selected Array's Shape

Results gathered in simulations for linear, square, circular and spiral arrays and the arrays in the shape of a hemisphere show that increasing the number of microphones produces a larger and narrower main lobe, i.e. a higher gain of the signal in the desired direction (0° on the directivity pattern). Moreover, it is obvious that increasing the spacing between adjacent microphones will result in an increase of the side lobes. Therefore, it can be concluded that the spacing between adjacent microphones should be less than a half of the wavelength. Table I. shows signal gains for each simulated array configuration, as well as the length or surface area required for positioning the microphones in a particular configuration.

TABLE I.   SIGNAL GAINS FOR EACH ARRAY CONFIGURATION

Array Configuration	$d_{max} = 0.1$ m	$d_{min} = 0.2$ m	Size (given d = 0.1 m)
a) Linear, 2 microphones	1.17 dBi	3.65 dBi	D = 0.1 m
b) Linear, 4 microphones	4.01 dBi	6.63 dBi	D = 0.3 m
c) Square, 4 microphones	1.21 dBi	4.98 dBi	P = 0.01 m²
d) Square, 16 microphones	5.69 dBi	11.48 dBi	P = 0.09 m²
e) Circular, 8 microphones	7.93 dBi	9.09 dBi	P = 0.05 m²
f) Circular, 16 microphones	9.09 dBi	13.28 dBi	P = 0.20 m²
g) Spiral, 1 turn, 9 microphones	2.94 dBi	9.89 dBi	P = 0.06 m²
h) Spiral, 1 turn, 17 microphones	7.20 dBi	12.55 dBi	P = 0.21 m²
i) Spiral, 2 turns, 17 microphones	2.81 dBi	12.33 dBi	P = 0.05 m²
j) Spiral, 2 turns, 33 microphones	12.51 dBi	15.21 dBi	P = 1.13 m²
k) Hemisphere, 17 microphones	1.14 dBi	1.29 dBi	P = 0.02 m²
l) Hemisphere, 25 microphones	4.01 dBi	9.52 dBi	P = 0.05 m²

From results shown in Table I. it is apparent that the best signal gains are obtained for array configuration marked *j)*, however, the surface area required for the construction of that type of array is much larger than the surface area required for other configurations. From the results shown in chapter *II.A*, it is noticeable that the increase in the number of microphones results in a higher appearance of the side lobes for all configurations except *h)* and *l)*. Although, the gain obtained for configuration *h)* is greater than for configuration *l)*, we have decided that the acoustic camera would have the shape of a hemisphere respectively to the surface area required for the construction. However, if the chosen configuration was configuration marked *h)* with the increase in the number of microphones we would have a large increase of the surface area.

C. Placement of Microphones

After choosing the shape of acoustic camera, we needed to determine the optimal number of microphones and the position of microphones on the camera. In order to achieve this goal, we have developed an algorithm called *Hemisphere* which was written in MATLAB. The algorithm determines the number of microphones and their location on the hemisphere. This algorithm is envisaged as a broadside microphone array in which a line of microphones is arranged perpendicular to the preferred direction of the sound waves, see Fig. 15 [5]. In Fig. 15 *d* is the spacing between the two microphones in the array. Broadside arrays are implemented with basic processing which means that the microphones in the array are simply summed together [5].
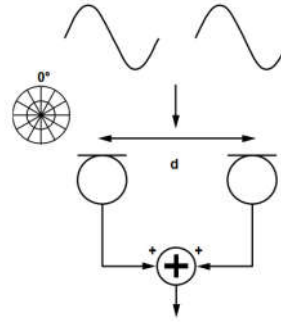

Fig. 15. Broadside Array with 2 microphones

Broadside arrays with more than two elements can also be constructed by simply adding additional microphones in line with the original two, as is shown in Fig. 16 [5]. As we have already concluded, it is obvious that higher numbers of microphones in broadside arrays can achieve greater attenuation of sound coming from the sides of the array.
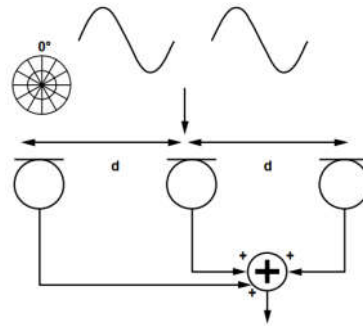

Fig. 16. Broadside Arrays with More Elements

Therefore, it is possible to state that the main parameters for beamforming are the distance between microphones and the number of microphones. Furthermore, we have decided to analyze the directivity patterns for frequencies other than *f* = 1 kHz while maintaining the same number of microphones

and their positions on the hemisphere. In Table II. parameters of an acoustic camera with 14 microphones, one on top of the hemisphere, and the others positioned equidistantly in 2 different circles on the hemisphere can be seen. In Table II. r_{max} is the radius of the hemisphere, while d represents the distance between adjacent microphones in the two circles. Parameter α_1 determines the radius r_1 of the first circle, as well as the height of the first circle, while n_1 represents the number of microphones in the first circle. Analogously, α_2 determines the radius r_2 and height of the second circle, while n_2 represents the number of microphones in the second circle. The total number of microphones used is equal to the sum of the microphones in both circles and the one on top of the hemisphere, i.e. $n = n_1 + n_2 + 1$. The parameter A in Table II. is the minimal attenuation of the side lobes, i.e. the difference in the gain G in the desired direction and the gain of the most prominent side lobe.

TABLE II.   PARAMETARS OF ACOUSTIC CAMERA

r_{max}	0.200 m
d	0.170 m
α_1	20°
r_1	0.188 m
n_1	7
α_2	35°
r_2	0.164 m
n_2	6
G	13.2 dBi
A	16.3 dBi
n	14

Fig. 17 shows the directivity pattern for the camera on a frequency $f = 1$ kHz. If we increase the frequency for that type of an acoustic camera to 2 kHz and then to 4 kHz, we get directivity patterns shown in Fig. 18. When comparing the directivity patterns in Fig. 17 and Fig. 18 it is noticeable that the gain G in the desired direction (0°) as well as the number of side lobes and their gain is very frequency dependent. It is obvious that the geometry of a camera obtained with optimization for $f = 1$ kHz lacks in desirable characteristics on higher frequencies. Considering our goal, which is to design an acoustic camera which could be used for higher frequencies as well, i.e. a broadband camera, we have decided to increase the camera's optimization frequency to $f = 4$ kHz.
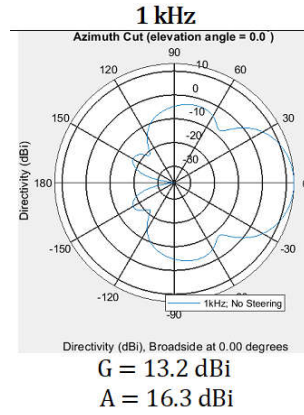

1 kHz

G = 13.2 dBi
A = 16.3 dBi

Fig. 17. Directivity pattern for $f = 1$ kHz

2 kHz   **4 kHz**

G = 11.4 dBi   G = -5.7 dBi
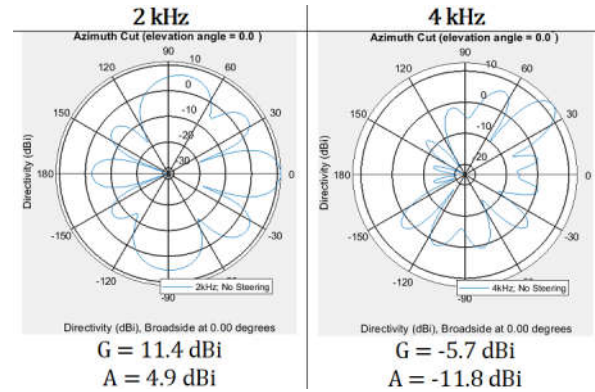A = 4.9 dBi   A = -11.8 dBi

Fig. 18. Directivity patterns for $f = 2$ kHz and $f = 4$ kHz

Our assumption was that increasing the frequency at which we optimize the camera would result in a camera which could be used in a broader frequency range. Fig. 19 shows the array geometry obtained with optimization at $f = 4$ kHz and the directivity pattern of that camera at $f = 4$ kHz. In Fig. 20 the directivity patterns of the same camera are shown for frequencies $f = 1$ kHz and $f = 2$ kHz. It is evident that the assumption was valid and that the increase of the frequency results in a greater gain in a broader frequency range. Increasing the frequency at which we design the acoustic camera increases the cutoff frequency, i.e. the maximum frequency for which the camera can be used.
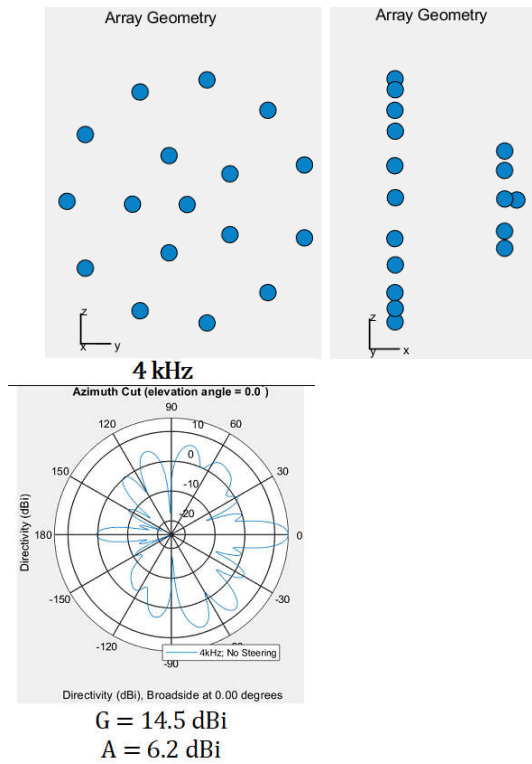
Fig. 19. Example of a hemispherical acoustic camera and the directivity pattern for f = 4 kHz
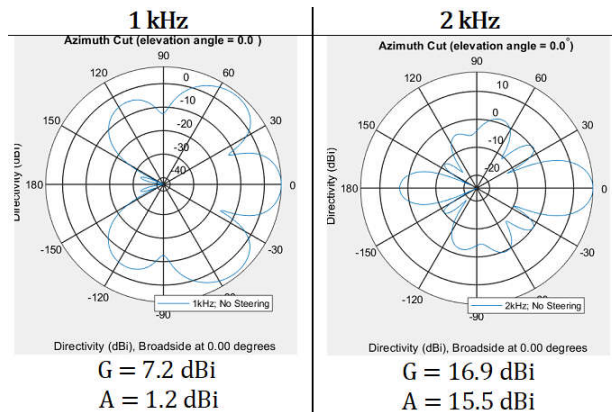

Fig. 20. Directivity patterns for f = 1 kHz and f = 2 kHz

It can be seen that by changing the optimization parameters we can obtain significantly better results, however, there are too many parameters which can be changed. Therefore, if we want to design an optimal broadband acoustic camera we need to develop and use a more powerful algorithm to get the best acoustic camera with an optimal number of microphones in optimal positions. Therefore, in future work we will use a Genetic Algorithm *GA*. This algorithm can take into consideration multiple parameter changes simultaneously and can optimize the number and the positions of microphones on the hemisphere,

in order to obtain an optimal acoustic camera which could be used for a broader frequency range.

III. CONCLUSION

After conducting numerous simulations using MATLAB's *Sensor Array Analyzer* for various shapes of MEMS microphone arrays, with varying number of microphones and varying spacing between the microphones we have concluded that the acoustic camera should have a shape of a hemisphere. The main reason for this is the reduction of the surface area required for the construction of the microphone array while the gain in the desired direction and the attenuation of side lobes is maximized. A logical conclusion is that higher numbers of microphones in broadside arrays can achieve greater attenuation of sound coming from the sides of the array. Thus, we can conclude that the main parameters for beamforming are the number of microphones and the distance between them. Both of these parameters have a significant influence on the obtained results which are very frequency dependent. It is evident that the geometry of a camera obtained with optimization for f = 1 kHz lacks in desirable characteristics on higher frequencies. Considering our primary goal, which is to design an acoustic camera which could be used for higher frequencies as well, i.e. a broadband camera, we decided to increase the frequency for which we optimize the acoustic camera to f = 4 kHz. Increasing the frequency at which we design the acoustic camera increases the cutoff frequency, i.e. the maximum frequency for which the camera can be used.

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