



## DESIGN AND PRELIMINARY TESTING OF A MEMS MICROPHONE PHASED ARRAY

<sup>1</sup>Stephen Orlando, <sup>2</sup>Adam Bale, <sup>3</sup>David Johnson  
Wind Energy Group, University of Waterloo  
200 University Avenue West, N2L 3G1, Waterloo, Canada

### ABSTRACT

In recent years, electret and MEMS (micro-electrical mechanical systems) microphones have been used as low-cost alternatives to more costly condenser microphones for use in phased arrays. In aeroacoustic testing, phased arrays are ideal for their ability to locate and quantify noise sources. Research into the design, fabrication, and implementation of a low-cost, electronically simple phased array will increase its potential as a common research tool. This paper discusses the design and preliminary testing of a simplified MEMS microphone array for use in aeroacoustic testing.

The primary intent of the array design was to improve the signal-to-noise ratio of aeroacoustic sources as opposed to locating them accurately, particularly in a wind tunnel with a square cross section of 152.4 mm x 152.4 mm. Using a number of beamforming algorithms, the design of the phased array was modeled numerically. The phased array was constructed on a single, two-layer PCB (printed circuit board) and composed of 27 MEMS microphones each with built-in amplification and RF protection. The Underbrink equal area aperture array layout was used in the design with 9 spirals each consisting of 3 microphones. Further design and manufacturing details are presented. The array was calibrated and used successfully in preliminary testing using the conventional beamforming technique to locate noise sources within the expected margin of error.

1. MSc Candidate, MME Department, [sorlando@uwaterloo.ca](mailto:sorlando@uwaterloo.ca)
2. MSc Candidate, MME Department, [aebale@uwaterloo.ca](mailto:aebale@uwaterloo.ca)
3. Associate Professor, MME Department, [da3johns@uwaterloo.ca](mailto:da3johns@uwaterloo.ca)

## 1 INTRODUCTION

Recent research has shown that MEMS microphones are a suitable low-cost alternative for phased arrays compared to condenser microphones [1], [2]. MEMS microphones can have built in amplification and filtering circuitry eliminating the need for costly and complex amplifiers. While the condenser microphone has a flatter frequency response over a larger range, a MEMS microphone can exhibit a flat frequency response up to 10 kHz. Additionally, since the cost of MEMS microphones can be as much as three orders of magnitude less than condenser microphones, they are an attractive choice for researchers.

The purpose of this study is to develop an electronically simple, low-cost, compact phased array for aeroacoustic testing using the Knowles Acoustics SPM0408LE5H MEMS microphone. This array will serve as a means to measure aeroacoustic sources in a closed-loop wind tunnel with a cross section of 152.4 mm x 152.4 mm. Due to the small size of the test section relative to wavelengths of audible sound the phased array's primary intention is to increase the signal-to-noise ratio rather than precisely locating sources using conventional beamforming techniques. The secondary intent of this array is to serve as a low-cost proof of concept that beamforming is possible with this type of microphone so that a larger phased array can be built in the future.

## 2 ARRAY DESIGN AND MANUFACTURING

### 2.1 Microphone Characteristics

A microphone similar to the Knowles Acoustics SPM0408LE5H MEMS microphone was successfully used in a phased array by Humphreys *et al* [1]. The microphone comes in a 3.8 mm x 4.7 mm x 1.25 mm package with surface mount pads and port hole located on one side; therefore a hole in the PCB is required to serve as an acoustic path. The SPM0408LE5H microphone was chosen based on the following [3]:

*Built-in amplification and RF protection:* These features significantly lowered the time required to design and test the microphone circuitry. Additionally, this meant having fewer components on the PCB which reduced the risk of component failure during the manufacturing process. The built in amplification circuit has an adjustable gain of 0 to 20 dB yielding a sensitivity of -38 to -18 dB and a signal-to-noise ratio of 59 dB.

*Frequency Response:* According to the manufacturer, these microphones have a smooth frequency response between 100 Hz to 10 kHz. This frequency response is due to the fact that the MEMS sensor is located directly below the port hole. A flat frequency response above 10 kHz is possible depending on the geometry of the port hole in the PCB.

*Cost:* The unit cost of the microphones is approximately \$3 CAD making them very practical for building low-cost microphone phased arrays.

### 2.2 Array Layout

The two main constraints for the phased array layout were the number of channels available in the data acquisition hardware (32 channels) and the geometry of the intended wind tunnel test section (152.4 mm width).

Potential board layouts were assessed using beamforming on simulated data to investigate various microphone geometries, including a circular array, a random array, and various spiral

geometries. The results of these tests indicated that the Underbrink equal aperture array achieved the best array performance while also lending itself to a concise, organized layout [4]. Efforts were made to maximize the microphone count within the limits of the 32 channels while maintaining an odd number of elements, to eliminate redundancy between sensors and achieve a range of sensor spacings [4]. The optimal layout was determined to be composed of 9 arms containing 3-element spirals for a total of 27 microphones. The spiral parameters were selected to have an inner radius of 13 mm, an outer radius of 68 mm, and a spiral angle of 70°.

### 2.3 Microphone Circuit

The overall dimensions of the PCB are 203.2 mm x 152.4 mm. Each microphone section consists of the microphone and an additional 4 passive components, while the circuit also includes additional parts such as power supply filtering capacitors and connectors for signals and power distribution. The gain of the amplifier was set to the maximum 20 dB yielding a nominal sensitivity of -18 dB and the high-pass corner frequency was set to 141 Hz. A two-layer PCB was used with the lower layer reserved for the ground plane and the upper layer for all power and signal traces, with ground traces inserted between all others to minimize cross-talk. The board layout was sent out for fabrication and returned for population in-house using surface mount components. Furthermore, six 50 mm x 50 mm single microphone test PCBs were designed and fabricated for testing the reflow soldering process and circuit optimization.

### 2.4 Manufacturing Process

The phased array was constructed on a conventional 1.5 mm thick FR4 PCB. The SPM0408LE5H microphones are surface mount components with 8 concealed solder pads. All other passive components were chosen as surface mount for a compact layout. The passive components and microphones were populated in a custom reflow oven. An acoustic seal between the microphone and board is provided by a solder ring around the port hole. The completed phased array is shown below in Fig. 1.

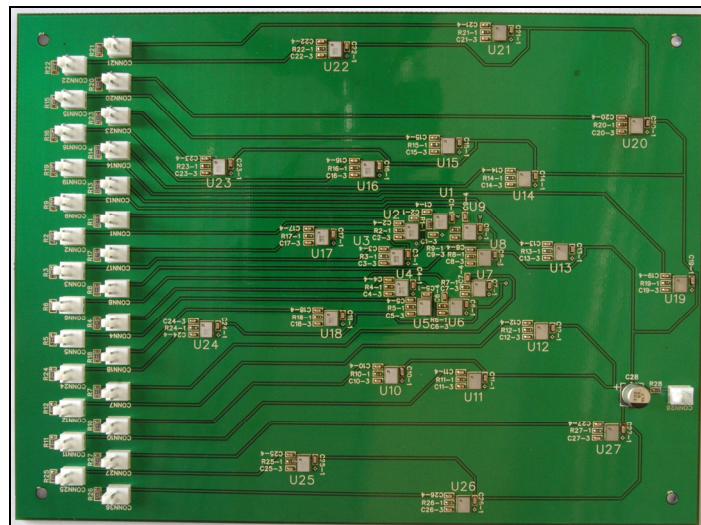


Fig. 1. Top view of the completed phased array, 203.2 mm x 152.4 mm

### 3 MICROPHONE CALIBRATION

It was necessary to calibrate the microphones in terms of amplitude response to determine the maximum sound pressure level at which the microphones could be used. Details regarding the frequency response were also required to quantify the variations in sensitivity in the desired frequency range. Due to the board geometry it was unfeasible to simultaneously test the frequency response of the MEMS microphones mounted to the PCB with a reference microphone in a normal incidence plane wave tube [2]. However, the single microphone test PCBs allowed the use of a plane wave tube, enabling simultaneous measurements from a reference microphone. It was therefore assumed that the frequency response of the microphones on the single microphone test PCBs was the same as those on the completed phased array. Since the frequency response results are referenced to the sensitivity of the microphone at 1 kHz, it was also necessary to measure the 1 kHz sensitivity of each microphone on the phased array.

#### 3.1 Calibration Process

An amplitude response test was performed between 80 dB and 130 dB, in 0.5 dB steps by providing a 1 kHz tone referenced to the B&K 4192 microphone, to ensure that the MEMS microphones had no deviation in sensitivity in the intended amplitude range. The tests were performed using a software control system which supplied an analog output to an amplified B&C DE10 25.4 mm compression driver coupled to a plane wave tube with 22 mm inner diameter and 112 mm length. The amplitude of the analog output was controlled by the output of the B&K 4192 microphone, and once stabilized, measurements were made from the output of the MEMS microphones. A total of 10 consecutive samples within 1% convergence were required at each test point.

Following these tests, frequency testing of the six single microphone test PCBs was performed, again using the B&K 4192 as the reference microphone. The control system was configured to output a constant 104 dB signal referenced to the B&K 4192 microphone, and each MEMS microphone was tested from 500 Hz to 20 kHz in 1/12 octave intervals.

Under the assumption that the frequency response of each microphone is the same as those measured on the single microphone test PCBs, it was necessary to find the sensitivity of the microphones on the phased array. The final calibration method involved measuring the 1 kHz sensitivity of the microphones on the completed phased array in a method similar to Marcolini *et al* [5]. The compression driver was coupled to the B&K 4192 reference microphone through an opening in an aluminum disc to determine the required input to the compression driver to provide a 104 dB signal at 1 kHz as shown in Fig. 2 a). The B&K microphone was then removed and the calibrated 104 dB signal was applied to each microphone by positioning the coupling disc over each microphone's port hole as in Fig. 2 b). A seal between the PCB and coupling disc was provided by an O-ring on the coupling disc. The sensitivity of each microphone was determined by measuring the output voltage from each microphone at 104 dB.

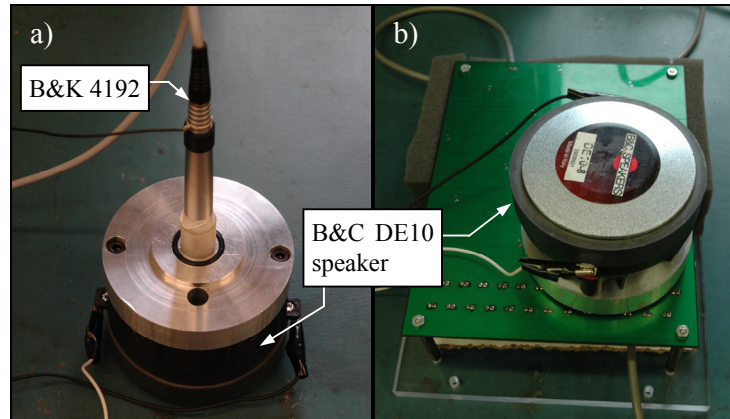


Fig. 2 1 kHz sensitivity testing with a) reference microphone and b) phased array microphones

### 3.2 Microphone Calibration Results

The results from the amplitude response tests are presented below in Fig. 3. With a gain of 20 dB the sensitivity of the microphones at 1 kHz does not vary appreciably until 113 dB. A test was also performed with a gain of 0 dB which yielded a flat amplitude response until 124 dB. However it should be noted that the manufacturer states a total harmonic distortion of less than 1% at 100 dB and less than 10% at 115 dB [3] so these microphones would not be a suitable choice at these amplitudes.

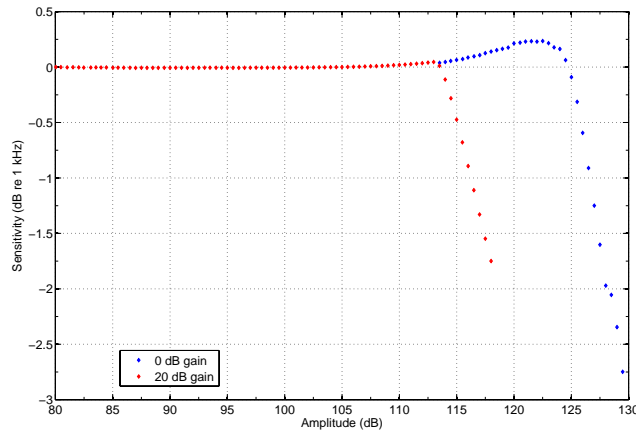


Fig. 3. Amplitude response results from 80 dB to 130 dB at 1 kHz

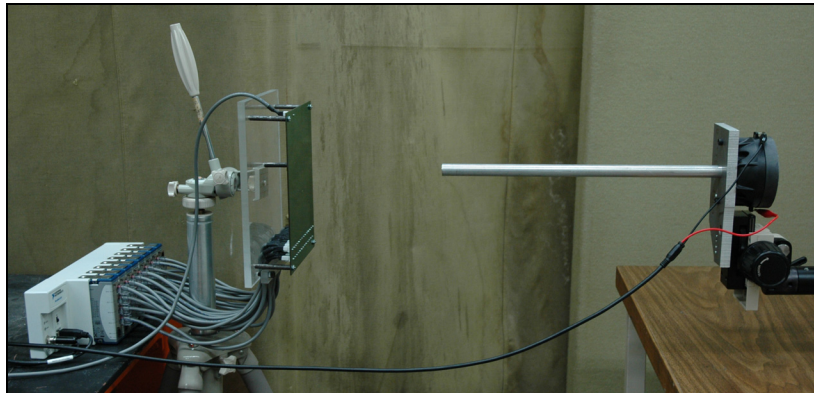
The frequency response results deviate from the expected behaviour especially at frequencies above approximately 8 kHz, which can be attributed to limitations of the normal incidence plane wave tube. The upper cutoff frequency for plane waves to be present in the 22 mm tube, such that  $\lambda < 2D$ , is approximately 7.7 kHz, so these deviations from the manufacturer's results are expected [6]. Further investigation into plane wave tube design is required to have better confidence in the frequency response tests. Based on these findings, the manufacturer's frequency response has been assumed for the entire frequency range. This frequency response remains to be independently verified.

The sensitivity calibration results for the 27 microphones reveal an average microphone sensitivity of 118.37 mV/Pa (-18.54 dB) with a standard deviation of 3.79 mV (0.29 dB).

## 4 PRELIMINARY BEAMFORMING TESTS

### 4.1 Experimental Setup

Preliminary beamforming tests were conducted with the array and a single acoustic source outputting a pure sinusoidal tone. These tests were conducted in a non-anechoic room with a 40 dB background noise floor. A 370 mm tube with a 12.7 mm inner diameter was attached to the B&C DE10 speaker to create a monopole source as shown below in Fig. 4. The source was positioned normal to the array with the centres of the source and array aligned. Two different separations between array and source of 164 mm and 385 mm were tested, representing solid collection angles [7] of 45° and 10° respectively. For the 45° case the speaker was driven by a 0.5 V peak-to-peak signal and for the 10° case the speaker was driven by a 1.5 V peak-to-peak signal. Using a laser, the centre of the tube was aligned to the centre of the array to an accuracy of  $\pm 1$  mm.



*Fig. 4. Preliminary phased array experimental setup*

A simultaneous sampling data acquisition system with a resolution of 24 bits over a range of  $\pm 250$  mV was used. Each channel's data set consisted of 50 blocks with 8192 data points per block collected at 50 kHz. The measured sensitivity of each microphone was applied to the corresponding data set to convert the raw voltages to pressure. A Hamming window was applied to the data and a standard diagonal removal beamforming method [8] was used to create the beamformed maps.

### 4.2 Results

Tests were conducted with source tones of 3, 5, and 7 kHz. The scanning plane for the 45° solid collecting angle case was 400 mm x 400 mm with a grid spacing of 2.5 mm and the scanning plane for the 10° solid collecting angle case was 800 mm x 800 mm with a grid spacing of 5 mm. The 1/3 octave band beamformed maps for 3, 5, and 7 kHz at a solid collecting angle of 45° and 10° are presented in Fig. 5 and Fig. 6 respectively. Each figure shows the decibel level contours of the beamformed map referenced by the respective peak decibel level.

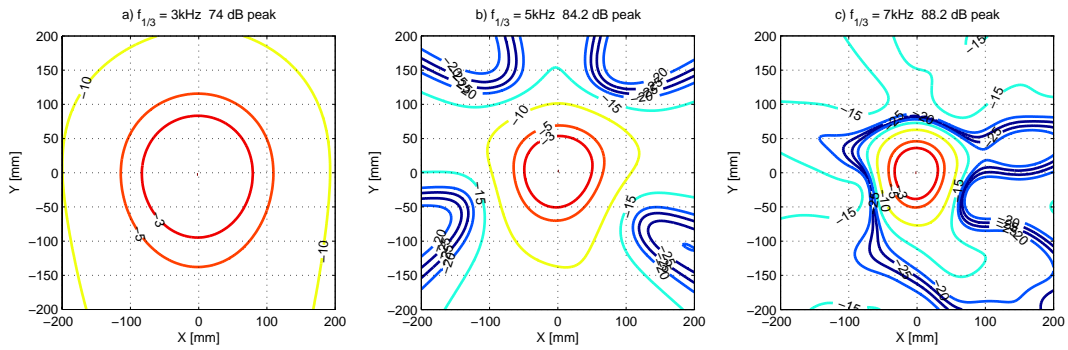


Fig. 5. Beamformed maps at a solid collecting angle of 45° for a) 3 kHz, b) 5 kHz, c) 7 kHz

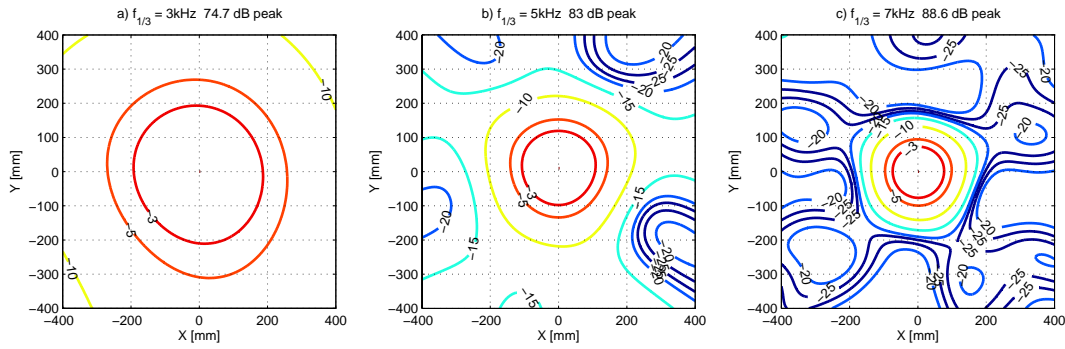


Fig. 6. Beamformed maps at a solid collecting angle of 10° for a) 3 kHz, b) 5 kHz, c) 7 kHz

In all cases the beamformed map predicts the location of the speaker within the ±1 mm margin of error that it could be positioned. For both 3 kHz cases the main lobe is quite large and no side lobes are visible within the scanning plane. However the 5 kHz and 7 kHz cases have sidelobes at approximately 20 dB below the peak. As expected due to inter-microphone spacing the beamwidths are large relative to the array size especially for the 3 kHz cases. The beamwidths for all cases are presented in Table 1, and are calculated as the diameter of a circle equal in area to the area inside the -3 dB contour.

Table 1. Beamwidths for each test case measured at 3 dB below the peak

	3 kHz	5 kHz	7 kHz
45° solid collecting angle	170 mm	102 mm	69 mm
10° solid collecting angle	390 mm	216 mm	150 mm

## 5 CONCLUSIONS AND FUTURE WORK

The work presented here reinforces past work showing that MEMS microphones are an acceptable low-cost alternative to costly condenser microphones. The built in amplification and RF protection of these microphones allows the array designer to spend less time on circuit design. Sensitivity results measured at 1 kHz showed that a set of microphones have a small, acceptable standard deviation of 3.79 mV (0.29 dB). Preliminary beamforming tests showed that these microphones in particular are suitable for low-cost phased arrays. The array was successful at accurately locating a monopole source at two distances in preliminary testing using the conventional beamforming technique. Future efforts will include

improvements to the calibration technique to verify the manufacturer's published frequency response. Further testing of the array is required, particularly, in its intended wind tunnel application. Additionally, a larger array, for better resolution of low frequencies will be considered as a future project.

**ACKNOWLEDGEMENTS:** The authors would like to thank Knowles Acoustics for their gracious donation of MEMS microphones. The authors would like to acknowledge the support of the Natural Sciences and Engineering Research Council of Canada. Special thanks also go to Nevin McCallum, Ryan Grant, and Adam McPhee for their valuable insight and assistance with the circuit design and fabrication.

## REFERENCES

- [1] Humphreys, W. M., Jr, Shams, Q. A., Graves, S. S., Sealey, B. S., Bartram, S. M., Comeaux, T., "Application of MEMS Microphone Array Technology to Airframe Noise Measurements", *11<sup>th</sup> AIAA/CEAS Aeroacoustics Conference*, Monterey, CA, May 2005.
- [2] Arnold, D. P., Nishida, T., Cattafesta, L. N., and Sheplak, M., "MEMS-Based Acoustic Array Technology," *AIAA Aerospace Sciences Meeting and Exhibit*, Paper No. 2002-0253, January 2002.
- [3] "SPM0408LE5H," *Knowles Acoustics*, Product Literature, Revision B, April 2009, [http://www.knowles.com/search/prods\\_pdf/SPM0408LE5H.pdf](http://www.knowles.com/search/prods_pdf/SPM0408LE5H.pdf)
- [4] Mueller, T. J., *Aeroacoustic Measurements*, ed. 2002, Springer-Verlag: Berlin. 114-128.
- [5] Marcolini, M. A., Lorber, P. F., Miller, W. T., Jr., and Covino, A. F., Jr., "Frequency Response Calibration of Recess-Mounted Pressure Transducers", *NASA Technical Memorandum 104031*, Hampton, VA, March 1991.
- [6] Arnold, D. P., Bhardwaj, S., Gururaj S., Nishida, T., and Sheplak, M., "A piezoresistive microphone for aeroacoustic measurements," *Proceedings of ASME IMECE 2001*, New York, NY, November 2001.
- [7] Brooks, T. F., and Humphreys, W. M., Jr., "Effect of Directional Array Size on the Measurement of Airframe Noise Components", *5<sup>th</sup> AIAA/CEAS Aeroacoustics Conference*, Bellevue, WA, May 1999.
- [8] Brooks, T. F., and Humphreys, W. M., Jr., "A Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) Determined from Phased Microphone Arrays", *10<sup>th</sup> AIAA/CEAS Aeroacoustics Conference*, Manchester, UK, May 2004.