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Effects of Capsule Coincidence in FOA using MEMS: Objective Experiment

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ABSTRACT

This paper describes an experiment attempting to determine the effects of capsule coincidence in First Order Ambisonic (FOA) capture. While the spatial audio technique of ambisonics has been widely researched, it continues to grow in interest with the proliferation of AR and VR devices and services. Specifically, this paper attempts to determine whether the increased capsule coincidence afforded by Micro-Electronic Mechanical Systems (MEMS) capsules can help increase the impression of realism in spatial audio recordings via objective and subjective analysis. This is the first of a two-part paper.

1 Introduction

Ambisonics is a spherical array capture and reproduction method capable of encoding directional information of sound sources. When ambisonics was initially proposed by Gerzon in the 1970s, his mathematical theory suggested that a perfect representation of a sound field could be achieved if an infinite number of transducers could be perfectly co-located in a single point in space[1]. In practice, because this idealization is impossible, we tend towards something approximating a sphere with uniformly distributed transducers.

Michael Gerzon, from the University of Oxford, is widely credited with developing the ambisonic microphone [2]. Gerzon's inspiration indubitably stemmed from the development of the quadraphonic system[1], which was becoming popular in the 70's among audio engineers. Unfortunately, despite great efforts, these systems would never become widely adopted by consumers. Gerzon believed that part of the problem was a lack specialized recording techniques designed for such a system. This led him to design the first *native* B-format array[2], largely inspired by Blumlein's Mid-Side (M/S) recording techniques [3]. The system consisted of four cardioid microphones pointed outward, as if pointing to four corners of a room. The resulting recording could then be reproduced by four speakers located in two lower and upper corners of the room.

While this might seem today like a small feat today, audio engineers were instantly revitalized by the idea of height as a new dimension of sound. Inspired by the encoding strategies developed by Alan Blumlein, Gerzon developed his own set of mathematical operations, or decoding strategies, to optimize ambisonic recordings for different playback systems. Ambisonics, Gerzon proposed, could theoretically replace all other

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[1] Four channel reproduction systems.

[2] Original native B-format array, before double M/S.

ways in which people had been recording sound until then - essentially becoming the *swiss army knife* of audio capture and reproduction.

Much like Blumlein's M/S array, in which a figure-of-eight microphone is mixed with an omnidirectional signal, FOA encodes the output from multiple transducers to generate various alternative and related outputs. Blumlein's technique allowed engineers to control the stereo spread of a signal by adding more, or less, of a figure-of-eight microphone. Similarly, Gerzon's encoding solution mixed the outputs of four cardioid microphones, arranged in a tetrahedron, to derive three figure-of-eight responses and one omnidirectional response. Controlling the gain and phase of these, he believed, could determine the ratio of directional to diffuse sound. Gerzon also showed, mathematically, that this system could be used as a highly flexible post-production tool, since polar patterns could be changed *a posteriori*[3], allowing engineers to change the character of their recordings after these had taken place.

1.1 Focus

The focus of this particular two-part research paper is to explore how transducer capsule coincidence affects the purity of FOA recordings from an objective and subjective standpoint. The ideal ambisonic microphone, as we have said, would have an infinite number of capsules arranged precisely coincidentally such that the encoding equations will generate perfectly smooth, and infinitely narrow, directional patterns at all frequencies. Various authors have proposed the following formula to describe the degradation of polar response as a result of inner-capsule spacing in FOA:

$$f_{err} = c/2d \tag{1}$$

Equation 1, used in [4], as well as across the literature, describes the frequency point at which our array responses start to diverge from what would be considered ideal. Here c is the speed of sound and d is the inter-capsule distance.

Traditional B-format microphones feature a 1.47cm (or 14.7mm) inter-capsule separation as proposed by Gerzon in 1975, achieving error free pressure gradients up to 11.6kHz. For our research a FOA microphone with this spacing was designed. One additional design, with 6mm capsule spacing, which offers error free pressure gradients up to 28.5kHz, was also assembled and measured. An intermediate size was also assembled, but due to technical difficulties it was not measured.

The intent of this research is to exploit the form factor of MEMS capsules in order to achieve error free pressure gradients up to and above 20kHz, the threshold of human hearing, and subjectively evaluate whether this reduction of spatial aliasing can improve the quality of FOA recordings. While the signal-to-noise (SNR) of MEMS capsules have kept them from being considered as suitable solutions in FOA systems, this two-paper will attempt to show that new MEMS capsules can provide suitable FOA recordings. The paper will also discuss methods of alleviating or improving the SNR deficits of these systems.

In addition, despite the omni-directionality of most MEMS capsules, our work will try to show how the physical enclosure used in this study was sufficient to induce a cardioid-like response at multiple frequencies[4]. In order to compensate for the Helmholtz resonance often found in MEMS microphones, a digital filtering system, created with MATLAB, will be employed during our subjective analysis. The results of subjective assessment will be published in an accompanying paper[5].

2 LITERATURE REVIEW

2.1 Research Involving MEMS Arrays

Research involving spatial audio and MEMS, in an ambisonic context, is limited. One of the most similar works to the one described herein was proposed by Dabin [4]. The author in that paper proposed two MEMS ambisonic microphones created using 3D printing. A single-tier and a three-tier design were analyzed for Direction of Arrival (DOA) accuracy using simulations. The single-tier microphone closely resembled the one proposed here, the three-tier microphone, in contrast, had three concentrically arranged tetrahedral arrays. Dabin's results showed that a three-tier design achieves more accurate DOA over a broad range of frequencies. It's worth pointing out that the authors used self-noise as a measure for DOA accuracy measurements but while the capsules in that experiment

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[3] After the fact.

[4] FOA microphones rely on cardioid responses

[5] Study currently pending IRB approval.

had an SNR of 59dB, the ICS-40720 used here has a 70dB SNR. It is also worthwhile to point out that while the three-tier design seems promising for audio capture it might prove difficult to integrate with 360 camera systems.

In Alexandridis et al. [5], the authors developed a MEMS system for DOA estimation, this time using digital MEMS. The authors reported obtaining positive results from their subjective experiment which compared the digital array with an analog counterpart. Their system in this case was only 2-dimensional, thus it attempted to capture and reproduce signals in only the horizontal plane. It should be noted that the subject pool in the Alexandridis et al. experiment was rather small (only 13 participants). In addition, the authors in that paper did not specify what type of capsules the analog system employed. They authors did however elucidate how digital MEMS can reduce the total cost of spatial audio systems as these replace expensive sound cards with a more affordable ASIC[6], FPGA[7] or micro-processor, a fact which should be considered in the overall design of ambisonic arrays. They also point out that MEMS feature great part-to-part consistency. For example the ICS-43432 used for their design features a +/- 1 dB sensitivity tolerance.

Kissner [6] also explored some of the limitations and benefits of MEMS systems for microphone arrays. Namely, the authors compared the static noise floor and polar patterns exhibited by single and parallel MEMS microphone configurations with a conventional electret condenser mic (ECM). Their results suggest that "direct parallel circuits" of MEMS microphones allows further reductions of the noise floor close to the theoretical value of 3dB SPL per doubling of number of microphones while maintaining omni-directionality below 5 kHz. It bears mentioning that interaural-level differences between 1kHz and 5kHz still affect localization, thus this approach might not be ideal for MEMS based FOA arrays [7]. Kissner's study did not use a physical enclosure to induce directivity or report directionality above 10kHz, thus the parallel circuit approach for improved SNR could be viable for future designs. This, naturally, would come at the expense of the array diameter, as the PCB size would have to be larger in order to fit more capsules.

Backman [8] has also presented work on the subject of "utilizing multiple transducers for improving signal-to-noise ratio over minimum transducer configurations" to "provide precise polar pattern control over the entire audio bandwidth". While Backman's first paper focused on two-dimensional arrays, the author later presented a theoretical system for gradient microphones [9]. Unfortunately, no actual microphone appears to have been constructed, or if it was, no public record could be found. In another paper, by Lecomte and Gauthier [10], the authors revealed a Higher Order Ambisonics (HOA) microphone with 200 MEMS capsules and 50 channels. Unfortunately, once again, little information regarding the system seems to be publicly available. The hope of this project is to openly release each MEMS array design in order to help others build their own arrays and collaboratively optimize the system.

More recently[8], Gonzalez et al. [11] proposed a modular design approach to MEMS ambisonic arrays which seems extremely promising. The design offers various models created using openSCAD, a script based Computer Assisted Design (CAD) software, and a modular design which enables the user to change the diameter of the HOA system by swapping detachable parts. The author of that paper does provide some information regarding the implementation of the system[9]. One of the possible criticisms of their design, however, might be the use of analog capsules, instead of digital MEMS, which despite having worse SNR, could substantially lower to total cost of the system. Additionally, the SNR of the selected capsules in that project do not appear to be suitable for good music recordings.

While not falling under the category of MEMS arrays, the work by Lopez-Lezcano [12] certainly warrants mentioning here. The designs proposed by Lopez-Lezcano, similarly to Gonzalez's [11], are not only modular in nature but similarly designed with OpenSCAD and specifically created for low-budget 3D printers[10]. Much like Lopez-Lezcano's 2018 paper, the measurements for this project were done using an automated process, albeit a much less sophisticated one, in an attempt to acquire the greatest amount of high quality data. Unfortunately, the designs shared here are not optimized for low-quality printers although these were ultimately possible with enough patience. It is

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[6] Application Specific Integrated Circuit

[7] Field Programmable Gate Array

[8] In 2018.

[9] www.appropedia.org/Modular_Spherical_Microphone_Array

[10] Much like Gonzalez's

Fig. 1: 6.35mm diameter PCBs with mounted MEMS

the hope of this project that designs of a similar quality as those accomplished by Lopez-Lezcano might be accomplished using MEMS capsules and that these designs be available to the public.

2.2 Prior Work by Author

In [13], a FOA microphone was constructed, quantitatively analyzed and subjectively evaluated. In this research, the author's involved with the work constructed a microphone using CAD 3D printed models and analog MEMS capsules. The dimensions of the tetrahedral array for that experiment were a function of the radius of our custom PCB, which had a larger radius than our new design (the PCB size was reduced from 12.5mm to 6.35mm diameter). The initial radius of the PCB was mostly a function of ease of assembly. These dimensions were also loosely based on the dimensions the Sennheiser Ambeo, our point of comparison in that experiment. Figure 1 depicts the new panelized PCBs with ICS-40720's mounted. This particular batch was surface mounted using the Manncorp reflow oven at NYU's Tandon School of Engineering.

The quantitative measurements for that first iteration of our project were done under anechoic conditions at Cooper Union. A rotating platform, dubbed Automatic Rotating Microphone Mount, or *ARM*[2], integrated with ScanIR ([14]), was modified and employed in the measurement process. In a similar fashion to previous research ([15]), a comparative evaluation of a professional and amateur microphone was performed.

In our case the experiment was conducted via an online survey and took advantage of Omnitone, a web-based ambisonic binaural decoder and rotator[11] by Google, which gave the authors the ability to deploy the assessment globally via the internet. While this was an effective solution, it restricted our ability to dictate experimental conditions such as noise-levels and reproduction methods. The findings were reported based on the type of binaural reproduction method used by subjects (headphones or earbuds) and any subject who had not used either was discarded.

Preliminary findings showed that while MEMS capsules were capable of quite aptly reproducing the sound field, their omnidirectional response, over multiple frequency bands, had a negative effect on accurate sound field reproduction. It should be pointed out that in contrast to our old design, the new CAD models printed for this work have a closed-back design which block sound arriving from the back of the capsule, alleviating this problem.

The most salient quality of the capsules resulting in decreased performance, however[12], was the high-frequency boost above 10 kHz. This behavior is a commonly reported characteristic of MEMS capsules which occurs due to the Helmholtz resonance of the "semi-open system" and is a function of "inner dimensions of the capsule" ([16]). In addition to evaluating how capsule coincidence could be used as a means of improving realism, our aim during the course of this new experiment was to modify the proposed microphone's output based on these former findings.

In the evaluation of our new microphones, for part two of this paper, we opt against using the web-based decoder and survey. This was in part due to due to our desire to use a head-tracker[13], enabling subjects to have a more natural testing experience, as well as to limit the number of independent variables, such as external noise levels and headphone model. The objective measures presented in this paper are supposed to inform the results of our future subjective assessments.

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[11] Written in JavaScript.

[12] According to subjects comments.

[13] Gyroscope unit mounted on a listener's head which sends rotational data to the ambisonic binaural decoder.

3 Methods

3.1 Microphone Design

In contrast to former research conducted by the author on the subject of MEMS-based ambisonic systems, this paper outlines a direct comparison between two different MEMS arrays of different sizes. No professional arrays, such as an Ambeo or TetraMic, were used to compare our systems. This was mostly due to their unavailability under present conditions but also since this allows us to isolate our independent variable during subjective tests. Future work will attempt to compare our ideal MEMS system with professional ambisonic solutions.

In order to create our microphone enclosures our former microphone CAD models were re-purposed and modified. The majority of this work was done in an easy-to-use online CAD platform[14]. During the printing of our two microphones multiple different printers, including a PRUSA I3 MK3, a LulzBot Taz 5, and a FormLabs Form 2, were used. Many of our initial attempts failed due to the fragility of the material/design and the quality of the prints. In the future we hope to adopt and adapt the models proposed by Lopez-Lezcano [12] for our own array. This should allow one to print these microphones with lower quality printers and replace any parts the may break with greater ease.

In order to power the MEMS arrays a new battery circuit was assembled. The circuit uses an Adafruit Coin Cell Breakout Board. This together with a small number of additional electronic components allowed us to connect and disconnect each of our arrays from the power supply, instead of having multiple power-supply systems for each array. For the interested reader an entire assembly manual was written and published at github.com/gzalles/ambisonics-z-array[15]. The manual describes how to approach the surface-mounting of the MEMS capsules, how to acquire the PCBs designed for this project and how to assemble the power-supply. The repository also has MATLAB code for filtering the output to compensate for the Helmholtz resonance, plotting the ScanIR ([14]) measurements and encoding to B-format[16]. Figure 2 depicts one of the microphones assembled for this project.

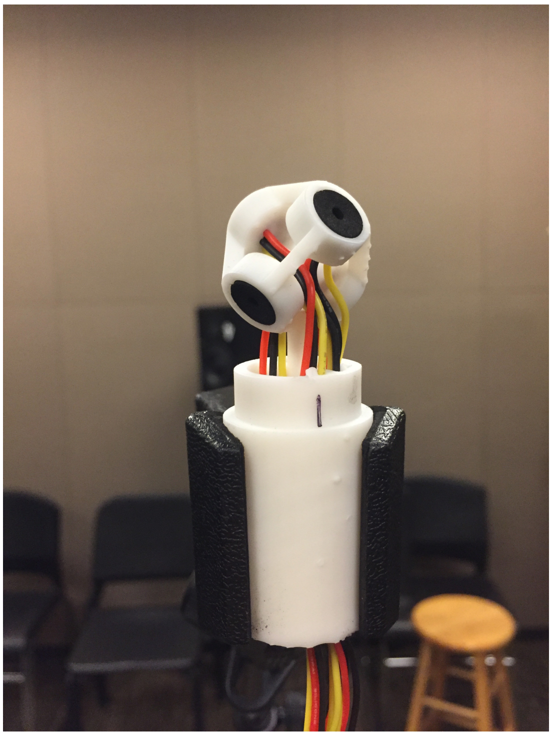

Fig. 2: FOA MEMS Microphone Prototype

3.2 Measurement & Plotting Process

Much like the work done in 2017 by this author, the ScanIR MATLAB system was used in order to measure our microphone's polar response. Unfortunately, these measurements were not done in anechoic conditions due to the unavailability of such a space. In contrast the author's previous research, this paper presents the results of two B-format polar plot measurements. These measurements, as opposed to single capsule measurements, show the B-format response also described as the encoded output of the tetrahedral array.

In order to accomplish these measurements the multichannel input feature of ScanIR was employed. The code had to be modified for stepper motor functionality as this new feature has only recently been added to the system [17]. Our measurement process, as before, records the response of the system using 100 steps over 180 degrees (the other half of the system is assumed to be symmetric). In order to record our 4 channels a U-Phoria UMC404HD USB Audio Interface was used. This sound card was selected due to

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[14] TinkerCAD

[15] Due to a change of institutions the NYU repository is no longer supported.

[16] Without impulse responses. Just a simple matrix operation.

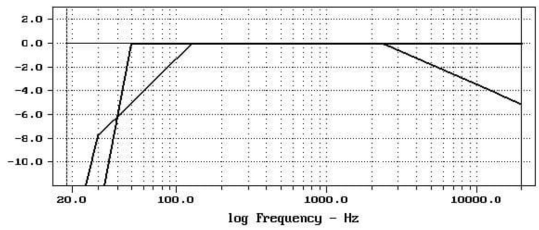

Fig. 3: BM6A Trim Control Response

its low cost. Unfortunately, the gain controls on this interface are not digital which means there could be very slight variations between microphone levels. The impulse measurements were done at Conrad Preby's Music Center[17] using a Dynaudio BM6A near-field monitor which offers -/+ 3dB frequency response from 43Hz to 20kHz. The level switch on the back of the unit, which sets the unit's input sensitivity, was set to +4 for all measurements. The high frequency and low frequency trim controls were set to 0. Figure 3, from the operation manual, shows the theoretical response based on the trim controls settings[18]. The "flatter" curve in the image represents the response of the speaker.

No calibration process was attempted for this experiment. We assume that specification sheets from manufacturers are accurate in each case for both the response of the capsules and speaker. In future work we would like to implement the calibration process described by Lopez-Lezcano. Fortunately, the MEMS capsules used in this project offer very good sensitivity tolerance (+/- 2dB). In the future we are also considering moving measurements to a larger space to compare the results.

In order to acquire our different plots it was necessary to align the desired capsule or sets of capsules with the center of gravity of our rotating microphone mount. The array was placed 15 inches away from the speaker[19]. Two single capsule measurements were performed in order to test the effect of the closed back design. In addition, four sets of measurements were performed with the array aligned along its center of gravity. Two of these measurements were performed in order to acquire spherical harmonics X and Y, two additional measurement with the array lying horizontally were performed in order to acquire the Z harmonic. The reader should be informed at this point that the bottom of our microphone is currently open; while this might aid with the clarity of the Z harmonic it will unlikely remain this way in future iterations since circuits will need to be embedded and contained in the enclosure. Figure 4 shows one of our arrays arranged horizontally in preparation for the Z harmonic measurement. [13] shows a complete image of the microphone mount.

Fig. 4: FOA MEMS Microphone Z-axis Measurement

4 Results

Given the natural symmetry of our system on the horizontal plane only one of the two horizontal harmonics is presented here. The other harmonic is assumed to be identical. For all the measurements in this experiment a sampling rate of 96kHz, and resolution of 24 bits, was used. Due to the difficulty of representing all frequency bands clearly in a document format a select number of target bands is presented here. For all of the plots presented here an FFT size of 2^{16} is used, giving us a resolution of around 1.5Hz. For the single capsule plots a tukey window is used to try to abate the room

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[17] Room 365.

[18] https://www.dynaudio.com/professional-audio/classic-bm-range/bm6a/support/manual/en/operation

[19] In the future we might opt for a standard distance of one meter.

effects in our measurements. For the multi-channel measurements the IR length of 1024 samples was selected. For all these plots the data is normalized along steps which simulates the polar response for a system with flat frequency. In a future paper, we will try to integrate our FIR Helmholtz compensation filter in lieu of normalization to observe a more realistic behavior.

4.1 Single Capsule Measurements

The results from our single capsule measurement under these new conditions are vastly different than what we had expected. Specifically, for the small array, the response depicted in Figure 5 appears extremely erratic. It's worth mentioning that the response of all these systems vary widely across frequency bands and that one large contributing factor to the success, or failure, of these measurements relies on how closely we can simulate free-field conditions. The presented plots in this section correspond directly to the same frequency bands targeted in our B-format measurements. An additional single capsule plot (Figure 11) was added to the appendix showing a more promising measurement of the directivity of the small array. Our current theory, based on observations from measurements, suggests that the additional volume around the capsules greatly aid in inducing directivity, specially at higher frequencies. In regards to the null point at 0 degrees in the 5kHz band, our best hypothesis is that this was a result of room reflections. Interestingly enough, the same effect is less pronounced in the smaller array. This might suggests that the effect might also be caused by diffraction. In future experiments we are hoping to gain access to a larger, quieter space, and use more sophisticated processing techniques[20] for semi-anechoic impulse response measurements in order to resolve this quandary.

4.2 Multi Capsule Measurements

Figure 7 shows one of the horizontal harmonics of our larger array. Here, again the measurements become extremely difficult to analyze. Notice that while 700 and 5000Hz are relatively good a butterfly pattern occurs at 12 and 17 kHz. This is not consistent with our single capsule measurement which suggests that 17kHz is closer to our ideal response than 5kHz. This might be explained by phase differences between capsules.

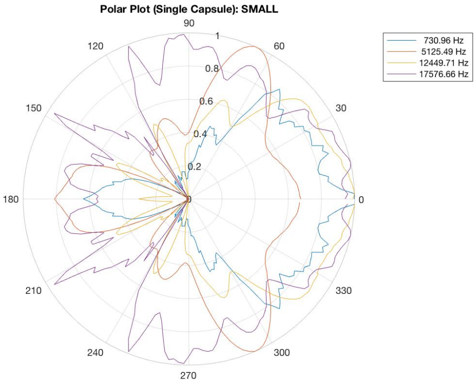

Fig. 5: Single Capsule Polar Plot of Small Array

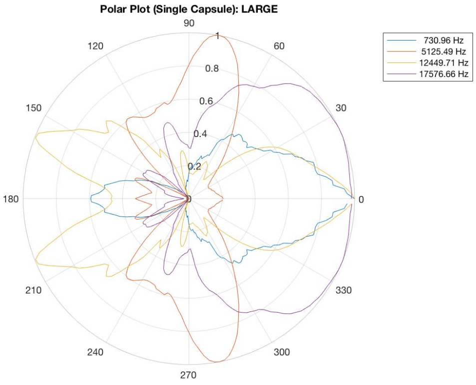

Fig. 6: Single Capsule Polar Plot of Large Array

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[20] ie. Kirkeby Inverse-Filtering.

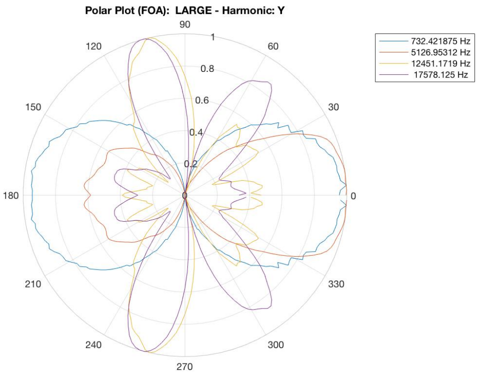

Fig. 7: B-Format Polar Plot of Large Array Y-harmonic

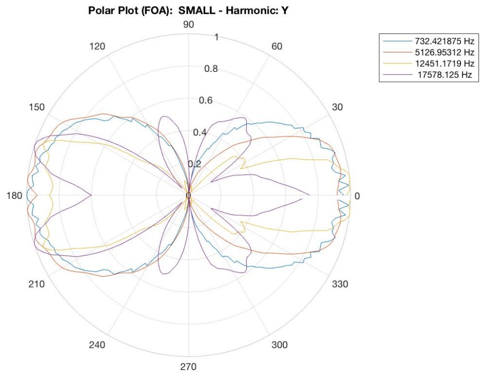

Fig. 8: B-Format Polar Plot of Small Array Y-harmonic

The author attempted to implement the Gerzon's compensation filters described in [1] but this produced no visible change. Despite these deviations, we can clearly see that it is possible to obtain figure-8 response, for some frequencies, using these omnidirectional capsules. This is likely possible due to the enclosure around the individual capsules. In a future version of this project we intend to revisit Gerzon's compensation filters [1] to examine if this can improve our results without compromising sound quality.

Figure 8 shows one of the horizontal harmonics of our smaller array. As we can clearly see, despite the obvious distortions, this version of the microphone behaves much better in the spherical domain than it's larger counterpart. Of particular note are the 12 and 17kHz bands, which, despite revealing clear irregularities, subtly approximate a figure-8 response. This result is particularly striking considering that the single capsule response of the smaller system, depicted in Figure 5, is vastly more erratic than that of its larger counterpart. We believe this might be the result of capsule coincidence. The 5kHz band also shows a better front/back balance than the larger array. We believe this be due to microphone placement.

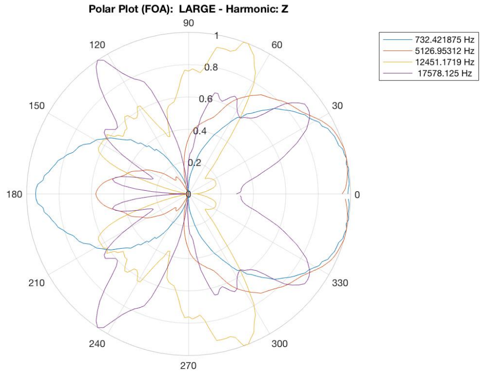

Fig. 9: B-Format Polar Plot of Large Array Z-harmonic

Figure 9 shows the vertical harmonic of our large array. As we can see, the polar response of the system approximates a figure-8 pattern for 700Hz and slightly for 5kHz. We believe this particular measurement suffered from inaccurate centering around the axis of symmetry which had to be done manually. This is supported by our 700Hz response which tends towards the front of the microphone. In the future we would like to design an attachment for the microphone mount to alleviate this problem. The measurement does show however that at certain frequencies the vertical harmonic exhibits the desired directivity. At 12 and 17kHz reveal similar responses to Figure 7, where a butterfly-like pattern emerges for higher frequencies. Again, these values might potentially be explained by phase differences between capsules. This vertical harmonic will also likely change in future designs which will attempt to embed circuits inside the enclosure (currently our circuits lie outside the enclosure).

Figure 10 shows the vertical harmonic of our small array. In contrast to our larger array, the response of this measurements seems to more closely approximate what one might like to see. The resulting measurement

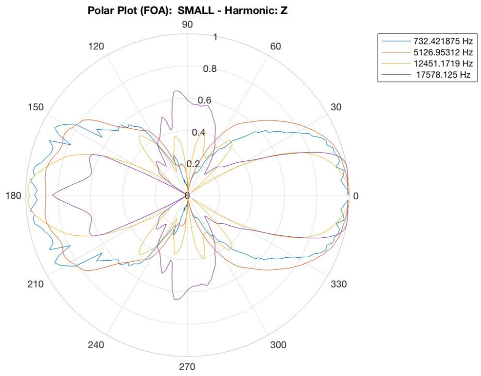

Fig. 10: B-Format Polar Plot of Small Array Z-harmonic

agrees with that of our horizontal measurement for the small array. The 12kHz band shows more directivity than the lower frequency bands and some bleed from the sides. The latter could be explained by reflections off the hard enclosure while the former might be explained by the aperture of the black foam ring above the PCB which creates a short resonant tube. The 17kHz band contains even more side bleed, this again we believe is caused by reflections off the enclosure.

5 Conclusion

This paper has attempted to present the effect of capsule coincidence in FOA using MEMS capsules. These objective measurements reveal that despite their omnidirectionality it is possible to produce figure-8 polar responses from MEMS capsules, likely because of the enclosure used here, which induced directivity at multiple frequencies. One might notice that no W measurement was provided. Despite our best effort no suitable W measurement could be produced. We believe that was due in part to the difficulty of accurately centering the system along the fulcrum and because of the lack of pure cardioid response from our system. This means that greater attention should be paid for inducing pure cardioid response prior to adopting this design for FOA capture. In the second part of this research subjective testing with human subjects will be used in order to determine if capsule coincidence had an effect on perception. The measurements here are intended to inform the results of that paper.

While interest in MEMS capsules as a possible solution for hi-fi microphone array designs is increasing, due to the increase in performance of these devices over the last years, work remains to be done in order to validate these systems for FOA. On the one hand, while the SNR of these capsules has improved considerably over the years, they are still not as good in this respect as high quality ECMs[21]. The benefits of MEMS over ECMs primarily include price and uniformity, the latter of which is a result of the highly reproducible micro-machining process used to manufacture them. ECMs offer other advantages, such as proper cardioid response and wider operating voltages.

Despite MEMS having their fair share of deficits, perhaps one of the most important benefits of these systems, over ECMs, are integrated ADCs[22] (for digital packages). MEMS capsules with integrated ADCs can easily replace expensive multi-channel interfaces generally required for this type of system. The SNR of these devices tends to be slightly poorer than that of their analog counterparts, however, this problem can easily be mitigated by using multiple capsules in series or parallel. Other authors have discussed how higher order MEMS arrays are possible but require understanding the encoding process employed. Another possible approach might be using analog MEMS, or even lower cost ECMs, with a small multi-channel embedded ADC to maintain performance while delivering convenience and cost.

6 Appendix

One additional plot of the small array single capsule measurement shown here. Linearly spaced frequency bands from 100 to 16000 Hz. Some of the differences observed between this plot and figure 5 are the result of a longer Tukey window and a different tapper setting.

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[21] Electret Condenser Microphones

[22] Analog-to-Digital Converter

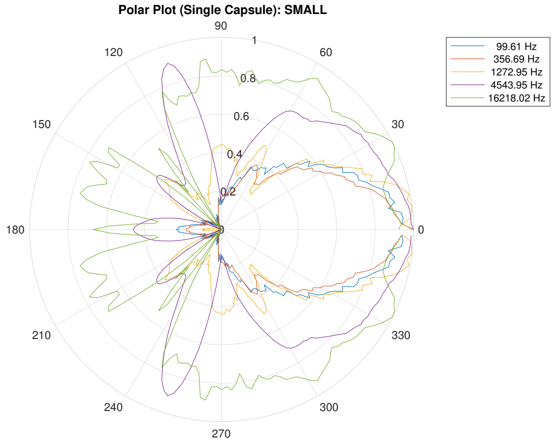

Fig. 11: Single Capsule Polar Plot of Small Array (Extra)

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