ACOUSTIC CHARACTERIZATION OF UNIFORM LINEAR MICROPHONE ARRAYS

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ABSTRACT

This work aims at acoustically characterizing innovative modular uniform linear arrays (ULAs) developed by Eventide Inc. in collaboration with Politecnico di Milano (eSticks V4). Their acoustic behaviour will be evaluated by analyzing and comparing the frequency responses of different modules to an exponential frequency sweep when the source signal impinges from different directions. Moreover, a direction of arrival (DOA) estimation process based on a delay and sum (DAS) conventional beamformer will be carried out in order to evaluate the employment opportunities of the device in application contexts requiring DOA estimation and far-field source localization.

1. INTRODUCTION

Source localization, tracking and separation represent a pivotal matter in a significant number of practical applications: radar, sonar, navigation and wireless communication, for example. In this context, microphone arrays are useful devices for capturing the spatial information of an acoustic field; the array geometry is a crucial parameter [1], [2], and while a lot of array configurations are well-suited for this kind of purposes, uniform linear arrays (ULAs) are one the most popular [3]. Eventide eSticks V4 are modular ULAs: these versatile high-performance systems (*Network Based Modular Microphone Array System*, MMAS) are built to be combined together in order to generate either a linear or planar microphone element distributions by linearly combining or stacking individual modules (up to 64 microphone sensors connected to a single workstation, expandable to 512 via sub-system synchronization). The devices modular schematic can be observed in Figure 1. Each single module (eStick) consists of a 48 *cm* linear array of 16 micro-electromechanical system (MEMS) microphones equipped with an integrated Audinate Dante™ Power-over-Ethernet (PoE) interface [4]. These features grant them very high versatility in the context of DOA estimation and, in general, array signal processing.

This work aims at acoustically characterizing and comparing the modules of a set of four eSticks V4: when using multiple arrays it is important that the response of each device is similar, so that the overall system can accurately and consistently capture and analyze the acoustic environment without introducing significant variances or biases that could affect the integrity of the data and subsequent signal processing. To do so, the response of each device to an exponential frequency sine sweep was recorded in a semi-anechoic environment (Section 3), and after a brief measurement validation procedure (Section 5) and response comparison (Section 4), each module was tested in a practical DOA estimation application (Section 7); since DOA estimation for far-field source localization [5] has been a really active research field, a great variety of DOA estimation methods were developed over the years: conventional subspace-type methods such as multiple signal classification (MUSIC) [6] and estimation of signal parameters via rotational invariance techniques (ESPRIT) [7] are definitely the most popular in literature because of their high-resolution performance [8], but sparse representation methods have been catching on in recent times [9], [10], [11]. However, for the purpose of this work, a much more simple procedure, relying on a DAS beamformer employing Fourier-based spectral analysis of the spatially sampled data [12], [13], [11], [14], was deemed appropriate.

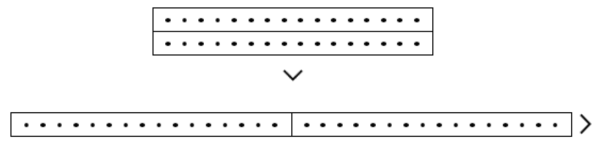

Figure 1: eStick scheme and modular expandable patterns.

Results show that Eventide are consistent devices, perfectly suitable for DOA estimation applications.

2. OPERATIONAL METHODOLOGY

2.1. Frequency Response Cross Evaluation

In order to evaluate the performance consistency of a ULA such as the eStick V4 and acoustically characterize them, the first planned steps are:

- studying the consistency of the frequency responses between different modules and between different microphone elements of the same module;
- searching for possible planar anisotropies in such frequency responses (i.e. assessing the consistency of the frequency responses across the angular spectrum in the horizontal plane).

To do so, it is sufficient to record the response of different modules to a frequency sweep - by means of a multichannel file, one channel per microphone element - for different directions of arrival of the source signal in the horizontal plane. This can be achieved, obviously, by either varying the orientation of the eStick with respect to the source or by displacing the source around the linear module. The first option was the one adopted for the present work.

2.2. DOA Estimation (Application Test)

The variable impinging direction (even though limited to the horizontal plane) also allows to judge the efficiency of the eSticks when employed in an actual DOA estimation application: this can be done quite easily by employing a conventional beamformer. The idea behind the process is to sweep the azimuthal angle, perform the beamforming operation at each angle and later look for peaks in the resulting pseudospectrum. Since the actual direction of arrival is known, by contrasting the estimated value with the empirical one with appropriate statystical considerations it is possible to evaluate the performance of the module and its employability in the context of far-field source detection. The results show that the behavior of the four eSticks is consistent and provides high accuracy in a practical DOA application.

3. MEASUREMENT SETUP

The core of the characterization procedure consists in a measurement campaign carried out in a semi-anechoic chamber located in the laboratories of the Politecnico di Milano, Cremona Campus. For each one of the eSticks the response to an exponential sinusoidal frequency sweep emitted by a Genelec loudspeaker was recorded for thirty-six equally spaced angular positions of the array between $\theta = 0°$ and $\theta = 350°$ ($10°$ steps) by means of a very precise turntable. The elevation angle was kept constant ($\phi = 0°$) so that the eStick was always perpendicular to the ground and the sixteen capsules were pointed directly towards the sound source when in the initial angular position ($\theta = 0°$). The eStick was centered with respect to the tweeter of the source loudspeaker and placed at a distance $\Delta s = (2.70 \pm 0.05)\ m$ from the source itself. Both the array and the source's tweeter were set at the same height from the ground (the overall setup can be observed in Figure 2 and 3).

4. DATA ACQUISITION

The employed source signal was a $\Delta t = 10\ s$ long sinusoidal exponential frequency sweep $\left(\Delta f = \left[50 - 2 \cdot 10^4\right]\ Hz\right)$. The responses were recorded at a sample rate $f_s = 48\ kHz$ as multichannel `wav` files (sixteen channels, one per capsule). The source signal emission was sample-synchronized with the acquisition device by means of a Dante™ Virtual Soundcard in order to obtain perfectly time-aligned RIRs. A standard deconvolution technique [15] was adopted to compute accurate room impulse responses (RIRs).

5. DATA VALIDATION

Given the nature of the measurements and the limited available equipment, in order to avert glaring errors a quick validation of the acquired data was carried out. First of all, the time delay of the acquired signal was evaluated between different capsules of the same array in order to estimate the distance of the corresponding microphone from the source, therefore verifying the orientation of the eStick with respect to the source. The result of this test showed minor misalignments of the eSticks with respect to the device-source axis, but still within the confidence limit (i.e. the misalignment could not result in a substantial difference in the time response of the device). Moreover, the array frequency responses were evaluated across all angular positions to ensure that no anomalies in the

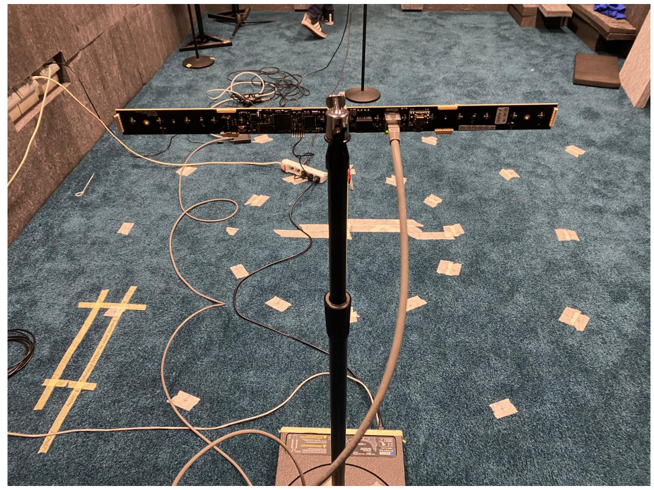

Figure 2: Measurement setup in semi-anechoic chamber.

acoustic behavior were to be found. The graphs in Figures 4-5 illustrate such frequency responses, for the first eStick when ($\theta = 0°$) and *right* ($\theta = 90°$) by way of example.

6. FREQUENCY RESPONSES CROSS EVALUATION

In order to achieve the goals described in Section 2.1, the frequency responses for two selected microphone capsules (namely the first and the eighth one, one of the outermost ones and one of the innermost ones) were averaged between the four eSticks and compared with the minimum and maximum one. Such comparison is reported in Figures 6-7 for the main azimuthal angles, namely $\theta = [0\ 90\ 180\ 270]°$. The boost related to the scattering effect - due to the eStick baffle (i.e. reflections caused by the device itself) - becomes noticeable after around $3 - 4\ kHz$ and reaches its peak ($\approx +76\ dB$) at about $16\ kHz$. Such occurrence is much less apparent in the right (and left, obviously) direction, especially for outermost microphone capsules, which are clearly less subject to scattering phenomena when compared with the innermost ones, as can be plainly observed by contrasting the graphs reported in Figure 6 and 7. Results show that the frequency response of a single microphone element is consistent across different modules (eSticks), and this in turn guarantees consistency to measurements carried out by employing multiple modules.

7. DIRECTION OF ARRIVAL (DOA) ESTIMATION

The adopted measurements setup allows to test the eSticks' performance in a practical, real-world application: the detection of the direction of arrival of the source signal. As already stated in Sections 1-2, a delay and sum (DAS) beamforming technique was employed in order to estimate the DOA of the signal with respect to the array. This result was achieved by sweeping the angle of interest, executing the beamforming operation at each angle and later looking for peaks in the resulting pseudospectrum. The analytical dissertation that was referenced can be found in [16] [17].

The source signal DOA was estimated for each of the 36 angular positions and for 121 frequency bins spanning the $50 - 5600\,Hz$ range (the maximum frequency is provided by the anti-aliasing con-

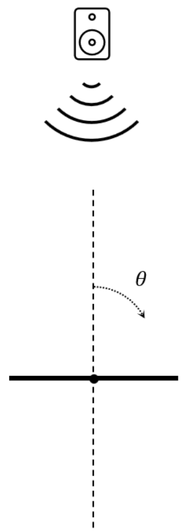

Figure 3: Measurement procedure schematic.

dition). Let us define the error parameter Δ as the difference between the DOA estimated via the aforementioned procedure and the ground truth (i.e. the known angular position of the eStick):

$$\Delta(\theta, f) = \mathrm{DOA}(\theta, f) - \theta$$

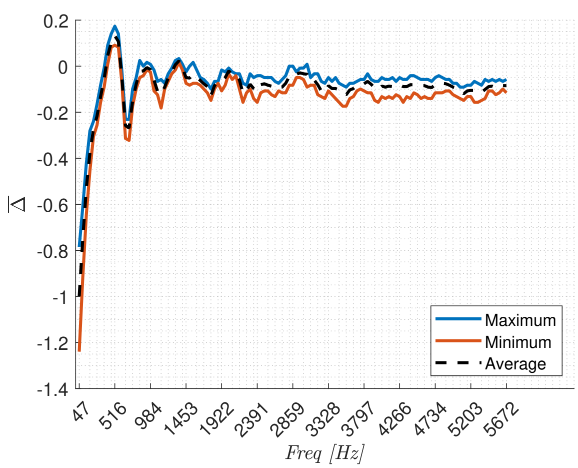

Figure 8: Error Δ averaged for azimuth angles and eSticks. The dashed line represents the actual average error, while the blue and orange lines represents the highest and lowest recorded values as a function of frequency.

The graph represented in Figure 8 is obtained by averaging $\Delta(\theta, f)$ across the 36 angular positions and the 4 eSticks. The results clearly show, as expected, that the source detection is more efficient for high-frequency signals, for which the directivity pattern of the microphone is more narrow. Notice how $\overline{\Delta}(f)$ oscillates around a value lower than zero as f grows: this is a clear indication of a systematic error of a couple of degrees, probably due to a misaligned setup of the devices in the measurement stage.

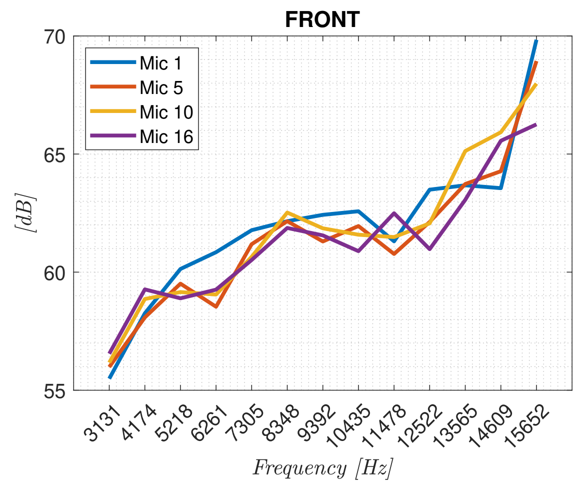

Figure 4: Frequency Response - 1^{st} eStick, FRONT.

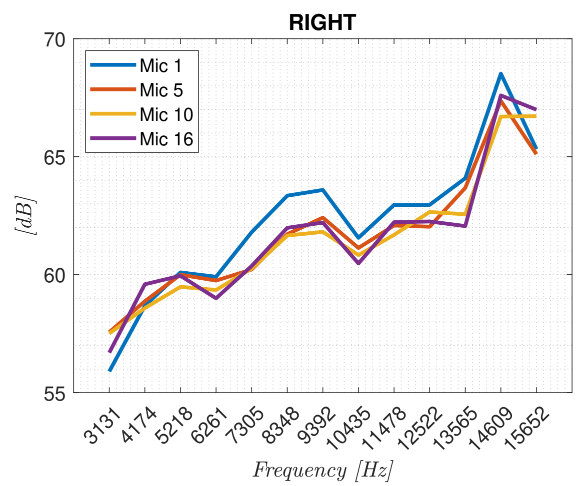

Figure 5: Frequency Response - 1^{st} eStick, RIGHT.

8. CONCLUSIONS

The present study showed that Eventide Inc. eSticks V4 are an effective and consistent tool to be employed in source tracking applications. A lot of their qualities come from the ease of use that characterizes them and from their modularity. A possible further in-depth study may consider the evaluation of the devices' performance in a tridimensional context (e.g. by varying also the inclination angle of the device), or may focus on different modular configurations to evaluate how different microphone distributions (alongside an extension of the device's baffle) may influence the overall frequency response and the efficiency of the direction of arrival estimation for critical directions. In addition to that, more accurate and elaborate DOA estimation methods (e.g MUSIC or ESPRIT, see Section 1) may be implemented in order to further evaluate the eSticks acoustic performance.

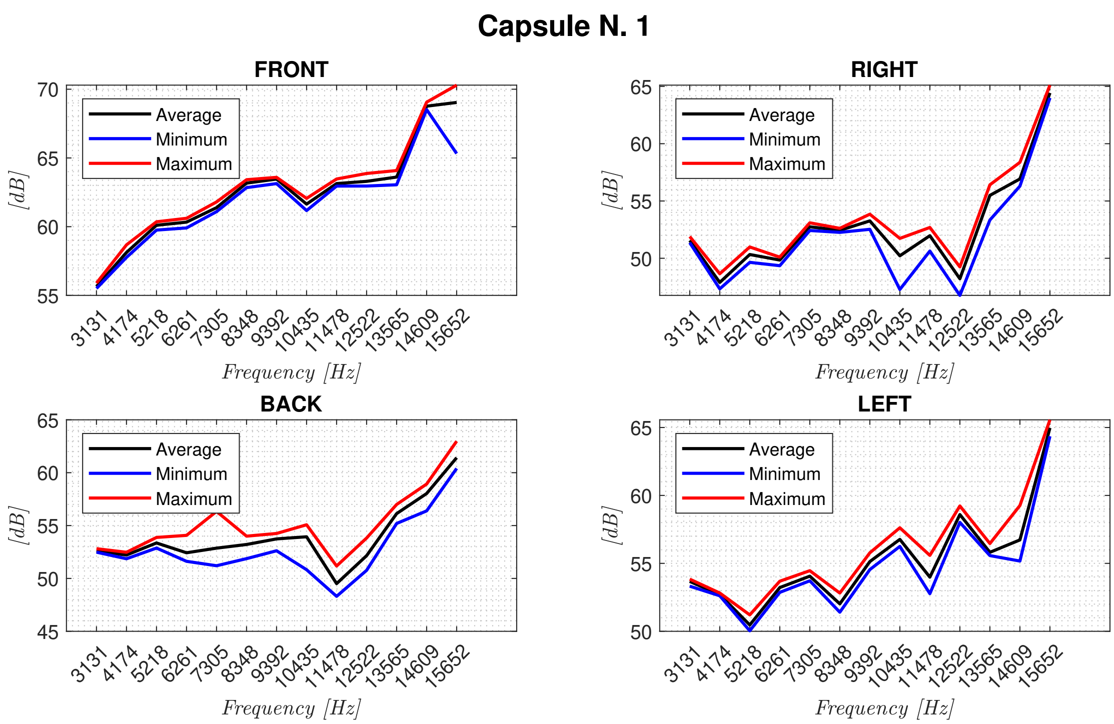

Figure 6: Average (black) and min/max (blue/red) frequency responses relative to the 1^{st} capsule of the four modules.

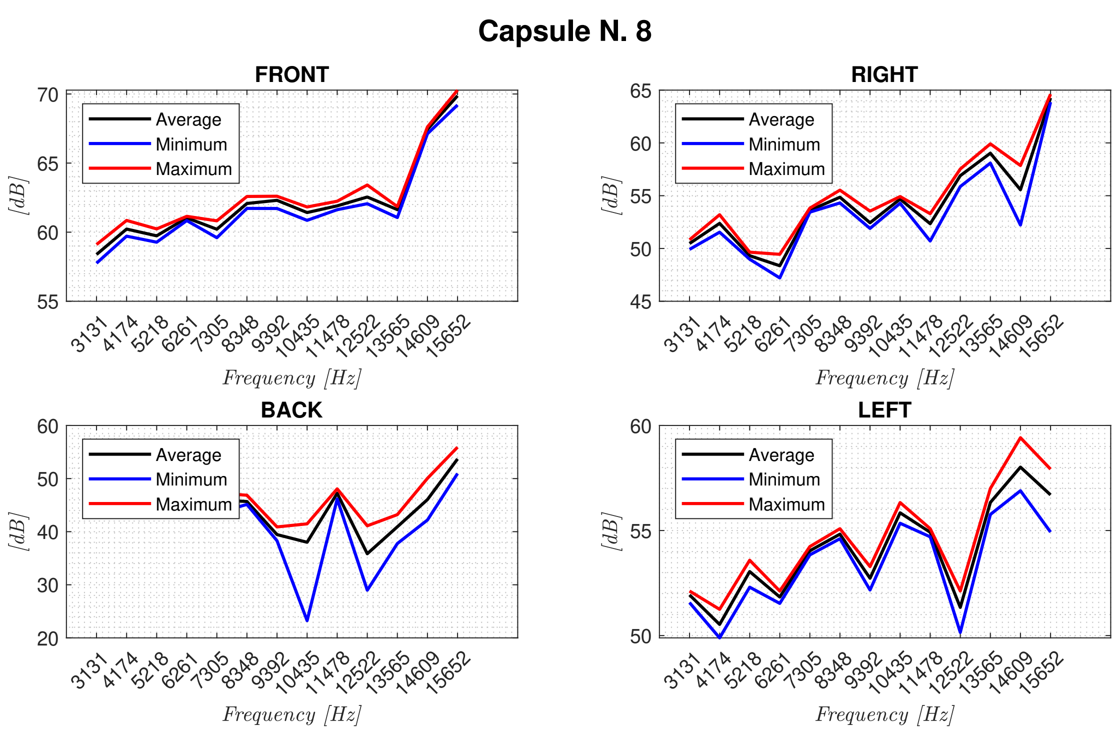

Figure 7: Average (black) and min/max (blue/red) frequency responses relative to the 8^{th} capsule of the four modules.

9. REFERENCES

[1] H. L. Van Trees, *Optimum array processing: Part IV of detection, estimation, and modulation theory*. John Wiley & Sons, 2002.

[2] S. Makino, *Audio source separation*. Springer, 2018, vol. 433.

[3] H. Huang, B. Liao, X. Guo, and J. Huang, "Doa estimation of rectilinear signals with a partly calibrated uniform linear array," *Signal Processing*, vol. 147, pp. 203–207, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0165168418300409

[4] M. Pezzoli, L. Comanducci, L. Bondi, A. Canclini, and A. Sarti, "A dante™ powered modular microphone array system," *IRIS Re.Public@polimi.it Pubblicazioni di ricerca del Politecnico di Milano*, 2018. [Online]. Available: https://hdl.handle.net/11311/1146068

[5] J. Benesty, J. Chen, and Y. Huang, *Microphone array signal processing*. Springer Science & Business Media, 2008, vol. 1.

[6] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE transactions on antennas and propagation*, vol. 34, no. 3, pp. 276–280, 1986.

[7] R. Roy and T. Kailath, "Esprit-estimation of signal parameters via rotational invariance techniques," *IEEE Transactions on acoustics, speech, and signal processing*, vol. 37, no. 7, pp. 984–995, 1989.

[8] J. Dai, W. Xu, and D. Zhao, "Real-valued doa estimation for uniform linear array with unknown mutual coupling," *Signal Processing*, vol. 92, no. 9, pp. 2056–2065, 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S016516841200031X

[9] Y. Liu, M. Wu, and S. Wu, "Fast omp algorithm for 2d angle estimation in mimo radar," *Electronics letters*, vol. 46, no. 6, pp. 444–445, 2010.

[10] D. Malioutov, M. Cetin, and A. S. Willsky, "A sparse signal reconstruction perspective for source localization with sensor arrays," *IEEE transactions on signal processing*, vol. 53, no. 8, pp. 3010–3022, 2005.

[11] Z. Yang, J. Li, P. Stoica, and L. Xie, "Sparse methods for direction-of-arrival estimation," 09 2016.

[12] V. Giurgiutiu, "11 - in-situ phased arrays with piezoelectric wafer active sensors," in *Structural Health Monitoring*, V. Giurgiutiu, Ed. Burlington: Academic Press, 2008, pp. 503–588. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B978012088760650012X

[13] A. Canclini and A. Sarti, "Microphone arrays: spatial methods for doa estimation," *Sound Analysis, Synthesis and Processing Course - Module 2: Sound Synthesis and Spatial Processing*, 2024.

[14] M. S. Bartlett, "Periodogram Analysis and Continuous Spectra," *Biometrika*, vol. 37, no. 1-2, pp. 1–16, 06 1950. [Online]. Available: https://doi.org/10.1093/biomet/37.1-2.1

[15] A. Farina, "Advancements in impulse response measurements by sine sweeps," *Audio Engineering Society Convention Paper*, May 2007.

[16] D. Marković, K. Kowalczyk, F. Antonacci, C. Hofmann, A. Sarti, and W. Kellermann, "Estimation of acoustic reflection coefficients through pseudospectrum matching," *IEEE Transactions on Audio, Speech and Language Processing*, vol. 22, no. 1, p. 125 – 137, 2014, cited by: 12; All Open Access, Green Open Access. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84897944209&doi=10.1109%2fTASLP.2013.2285483&partnerID=40&md5=2ef79c626673181fa37485a9ee6f3636

[17] D. Mirabili and E. A. P. Habets, "Pseudo-spectrum based methods for estimating the wind speed and direction based on closely spaced microphone signals," *184th Meeting of the Acoustical Society of America*, 2023. [Online]. Available: https://doi.org/10.1121/2.0001737