Initial design, development & calibration of MEMS based sound level meter for real-time construction monitoring

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ABSTRACT

This paper outlines the assessment and calibration of MEMS microphones, as part of the design and development process of the SiteHive Hexanode, specifically for use as a sound level meter for construction monitoring. The SiteHive Hexanode is a new type of environmental monitoring device that brings innovative new capabilities to market. The integral sound level meter function uses digital MEMS microphones. The initial verification and calibration of these is the focus of the work described herein. The current international standards for sound level meters were written for conventional instruments, not MEMS-based technologies. SiteHive has worked extensively to date with both the National Measurements Institute (NMI), and the University of Technology Sydney (UTS), to test and validate the accuracy of the MEMS microphones proposed for the Hexanode in line with relevant standards (IEC 61672). This paper will describe the conception of the device, outlining the research and development findings to date, and demonstrate how this innovative technology is adding value to construction sites across Australia and New Zealand by providing additional contextual information to construction projects, at a reduced cost.

INTRODUCTION

Major cities across the world are undergoing an unprecedented construction boom with generational infrastructure and buildings following a significant population increase. This development is being undertaken in populated urban areas, where COVID-19 amongst other factors, greatly increases the complexity of delivering construction projects surrounded by sensitive communities and stakeholders [1]-[4]. Construction noise should be continuously monitored to manage its potential impact on nearby residents.

In some cases, noise control solutions can be implemented [5]; increasingly these solutions can be *passive* [6]-[8] as well as *active* [9]-[11]. In all cases, environmental compliance is mandatory and complex. In all projects, teams are under increasing pressure to monitor environmental factors and keep clients and stakeholders informed and satisfied [12], [13]. Across the board, expectations continue to rise, and teams are having to do more with less.

SiteHive harnesses MEMS (micro-electromechanical systems) based sensors to provide innovative software and monitoring devices that are not only easy to use, but that deliver better environmental outcomes at a reduced cost. The SiteHive Hexanode is a new type of environmental monitoring device offering continuous, real-time data, all connected to cloud computing and analysis services, and combining multiple digital sensors (for noise, dust, images and audio) in one ruggedised, stand-alone Internet of Things (IoT) device. It includes innovative, edge-based software and algorithm-enabled features such as noise direction of arrival (DOA) monitoring, synchronised cameras and audio capture capabilities to identify, classify and predict sources. The significant benefit to the construction industry being that, not only is manual labour in monitoring reduced, but in the event site noise limits being exceeded, assessment of the root cause of the problem is readily possible with these enriched data, and issues can be prevented before they escalate.

The current international standards for sound level meters were written for conventional instruments, not for MEMS-based solutions. SiteHive has therefore worked extensively to date with the National Measurements Institute (NMI), to test and validate the accuracy of the SiteHive MEMS sensors in accordance with IEC 61672 [14]. The NMI's acoustic, ultrasound and vibration measurement services includes not only Australia's foremost experts in acoustic measurement standards, with a combination of unique knowledge and measurement capabilities not generally available elsewhere in the country, but represents Australia on various international forums that discuss next-generation instrumentation and measurement traceability. More recently, SiteHive has additionally engaged with University of Technology Sydney (UTS) Centre for Audio, Acoustics and Vibration (CAAV) experts to support with the creation and implementation of the development testing procedures for the Hexanode device, similarly in alignment with IEC 61672, and other tasks.

This paper will therefore outline this initial research and findings to date and the proposed future work required. In doing so, it will be demonstrated how this innovative technology is being realised, adding value to construction sites across and beyond Australia and New Zealand.

MOTIVATION AND BACKGROUND

The identified market opportunity was for a multi-sensor environmental monitoring device, combining the measurement of key environmental aspects (noise and dust) with rich contextual information (images and audio) to aid the proactive management of construction projects. By using emerging *digital* technologies, the upfront cost and maintenance associated with traditional sound level meters could be mitigated, resulting in more devices being deployed. More devices and measurements could then result in better informed decision making and proactive management of projects, reducing community impact.

Relevant Standards

Most project noise management plans refer to the international standard *IEC 61672 Electroacoustics – Sound level meters*. The standard is comprised of three parts:

Part 1: Specifications, gives electroacoustical performance specifications for sound level meters. Two performance categories, Class 1 and Class 2, are specified in this standard. Tolerance limits for Class 2 specifications are greater than, or equal to, those for Class 1. Sound level meters conforming to the requirements of this standard have a specified frequency response for sound incident on the microphone from one principal direction in an acoustic free-field or from random directions.

Part 2: Pattern evaluation tests, provides details of the tests necessary to verify conformance to all mandatory specifications given in Part 1 when seeking pattern approval. The aim is to ensure that all testing laboratories use consistent methods to perform pattern evaluation tests.

Part 3: Periodic tests, describes procedures for periodic testing for sound level meters conforming to the Class 1 or Class 2 requirements of IEC 61672-1:2002. The extent of the tests in this part of IEC 61672 is deliberately restricted to the minimum considered necessary for periodic tests. Periodic tests described in this part of IEC 61672 apply to sound level meters for which the model has been, or has not been, pattern approved by an independent testing organization responsible for pattern approvals and in accordance with the test procedures of IEC 61672-2:2003.

MEMS Microphones

Core to a sound level meter is the underlying microphone. A MEMS microphone is an electro-acoustic transducer housing a sensor (MEMS) and an application-specific integrated circuit (ASIC) in a single package. The sensor converts variable incoming sound pressure to capacitance variations that the ASIC transforms into analog or digital output, reducing the overall cost of the instrument. The integration of analog-to-digital circuitry directly at the chip level also eliminates electro-magnetic noise that can be coupled to the analog input line in a traditional design.

MEMS microphones are increasingly suitable for audio applications where key requirements are small size, high sound quality, reliability, and affordability. However, as MEMS microphones provide a digital signal directly at the chip level, it is not possible to separate the instrument and test the analog chain alone, as would be completed in a traditional microphone sound level meter solution. As such, there are elements of IEC 61672-2 that cannot be undertaken on MEMS microphones, e.g.: "*5.1.16 The microphone shall be removable to allow insertion of electrical test signals to the input of the preamplifier.*".

Since full pattern approval is thereby not possible, the initial design goal of the SiteHive Hexanode is to be a Class 2 equivalent device, tested with as many tests as possible as outlined in IEC 61672-2.

INITIAL TESTING AND VALIDATION

Design and Development

To test both the market and technical feasibility of the premise of a combined multi-sensor device, a proof of concept (PoC) device was developed. Since both sound level and direction of arrival of sound were primary requirements for the SiteHive Hexanode, a microphone array was selected that enabled both functions to be delivered by using a single PCB. The Seeed ReSpeaker v2 Microphone Array [15] was selected for the PoC device as shown in Figure 1. The ReSpeaker uses 4 MEMS microphones, with the output available via an XMOS microprocessor.

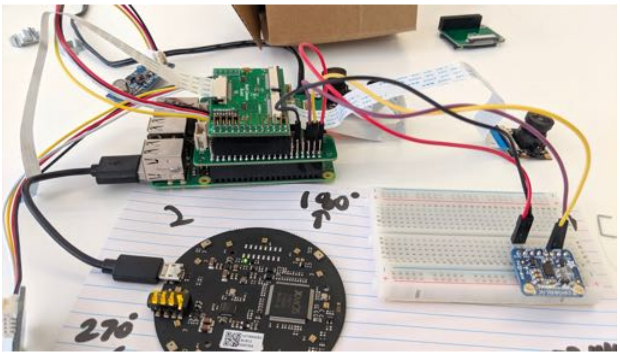

Figure 1. SiteHive PoC device using Seeed ReSpeaker v2.

Market viability, along with mechanical housing design options, was validated on a number of construction sites during early development, an example of which is shown in Figure 2.

Figure 2. SiteHive Hexanode testing on a construction site.

Testing and Calibration

The initial focus of design verification testing was on the performance of weighted frequency response of the microphone. If the microphone is capable of meeting the required weighted frequency thresholds (as per IEC 61672-1 *Table 3, 5.5 Frequency weightings*), then the other requirements of the Standard (e.g. the directional response) become primarily mechanical design challenges, building on the proven acoustic performance of the microphone.

The acoustic performance of the ST MP34DT01TR-M (mounted on the ReSpeaker) was tested by NMI in April 2020. Due to the flat geometrical profile of the ReSpeaker PCB, pressure field testing or calibration was challenging. A free-field calibration was instead undertaken as the primary method.

The initial test was to determine the free-field weighted frequency response of the ReSpeaker, in line with section *5.5 Frequency weightings* of IEC 61672-1. *Table 3 - Frequency weightings and acceptance limits* outlines the tolerances for each frequency to be tested. For a Class 2 sound level meter, it is required to perform tests from 31.5 Hz to 2000 Hz in 1/3rd octave intervals, and then from 2000 Hz to 8000 Hz in 1/6th octave intervals. This corresponds to 31 measurement points per device.

For all frequency weightings, the design goal includes a 0 dB weighting at 1 kHz. This result is also used in the calibration of the device. The free-field frequency weightings were tested first, as subsequent testing (e.g. directional response, windshield tests) would be based on the results of this test. If the free-field response could not be proven to comply with the precision requirements of IEC 61672-1, then any subsequent testing would be meaningless.

Due to limitations in the anechoic chamber at NMI, the SiteHive Hexanode was mounted perpendicular to the usual mounting position when used in the field, i.e. with the microphone array facing the sound source.

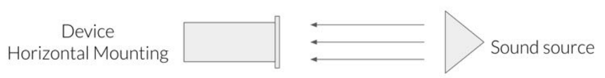

Figure 3. SiteHive Hexanode mounting schematic for acoustic performance testing at NMI.

The testing included evaluating the response across the full frequency range, at 74 dB sound pressure level (re 20 µPa), for five Hexanode devices to establish the frequency dependent performance.

Results and Future Work

The results shown in Figure 4 from the testing highlight a number of issues with the MEMS on the ReSpeaker:

- A roll-off response characteristic above 8 kHz (Class 2 standards specify tolerance up to 10 kHz)
- Inconsistent performance across the Z weighting results (indicating that the microphone response is not flat)
- A number of results outside the tolerances of ±1.5 dB, particularly for low frequencies below 250 Hz, for A-weighted results

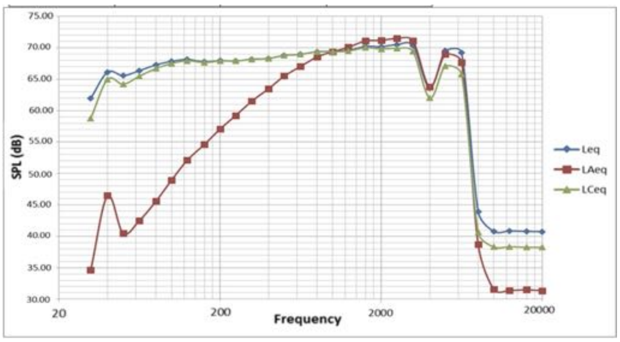

Figure 4. Results from initial NMI testing of ReSpeaker.

While the inconsistent results could have been corrected with a flattener algorithm applied to the raw microphone signals, the roll-off response above 8 kHz was more problematic. Upon further investigation, it was discovered that the XMOS microprocessor on the ReSpeaker had a fixed sampling rate of 16 kHz, causing the 8 kHz roll-off.

As such, no further testing was undertaken at this stage; a new design would be required to address the non-linear response of the microphone and the sampling rate limitation of the ReSpeaker.

MINIMUM VIABLE PRODUCT DEVELOPMENT

Design and Development

To overcome the shortcomings highlighted in the aforementioned testing, it was determined that a new approach was required, based on a bespoke printed circuit board (PCB), and potentially a different microphone. Without the XMOS processor of the ReSpeaker, a microprocessor would also be required to process the raw microphone outputs. The primary objective of the custom PCB was still to pass the weighted frequency criteria of IEC 61672-1, in a free-field environment, meeting the Class 2 requirements.

A number of iterations of PCBs were developed, with a range of MEMS microphones tested at NMI. Candidate microphones and signal processing configurations were selected based on a range of factors, to meet both the requirements of the standard but also the application of construction monitoring (e.g. requiring an acoustic overload point of over 120 dB to capture high impact works). The factors considered included:

- Sampling rate
- Microphone interface
- Sinc filter

Sampling Rate

As the ReSpeaker had a hard-coded sampling rate of 16 kHz, leading to a Nyquist frequency of 8 kHz, while the Standard requires a response up to 10 kHz for Class 2 performance, a higher sampling rate was required. Balancing the low power requirements of the end product, a sampling rate of 25 kHz was selected to provide an adequate buffer above the desired response of 10 kHz, leading to a Nyquist frequency of 12.5 kHz.

Microphone Interface

Both pulse density modulation (PDM) and inter-IC sound (I²S) provide a digital output, but offer differences that may suit applications differently. PDM is used to convert an analog signal voltage into a single-bit pulse density modulated digital stream where the bitrate is used to code the amplitude modulations in the audio signal.

PDM signals require higher sampling rates, above 3 MHz, because the digital pulses must occur much more often than the oscillation of the represented analog signal. PDM signals also need additional processing by an external Digital Signal Processing (DSP) chain or microcontroller with an appropriate codec to decimate, or downsample, the PDM signal to a lower sample rate by running it through a low-pass filter.

I²S, meanwhile, is an entirely digital signal, unlike PDM, meaning that it does not require encoding or decoding. I²S has an internal codec through its built-in filter, meaning that the data rate of the audio signal with I²S is delivered at an already acceptable level to the DSP chain.

Sinc Filter

The PDM microphones are connected to the digital filter for sigma-delta modulators (DFSDM) peripheral in the microprocessor. In this DFSDM peripheral, a sinc filter removes all frequency components above a given cutoff frequency without affecting lower frequencies, and has a linear phase response. The filter impulse response is a sinc function in the time domain, and its frequency response is a rectangular function.

As part of this process the DFSDM peripheral converts the microphone's PDM data into a pulse-code modulation (PCM) signal.

Primary Candidate Selection

Five filters were tested on the candidate microphones in an anechoic chamber to determine the best DFSDM filter for the application. The tested filters included: fastsinc, sinc1, sinc2, sinc3, sinc4 and sinc5, as summarised in Table 1. Sinc filters are idealised filters that remove all frequencies above the cutoff and while passing frequencies below without affecting them [16].

Each of the candidate filters offered compromises on frequency response, sampling rate and resolution. For each filter, an oversampling factor (FOSR) can be applied, altering the output resolution to some degree.

Table 1. Filter maximum output resolution (peak values) for some FOSR values.

FOSR	$Sinc^1$	$Sinc^2$	FastSinc	$Sinc^3$	$Sinc^4$	$Sinc^5$
x	+/- x	+/- x^2	+/- $2x^2$	+/- x^3	+/- x^4	+/- x^5
4	+/- 4	+/- 16	+/- 32	+/- 64	+/- 256	+/- 1024
8	+/- 8	+/- 64	+/- 128	+/- 512	+/- 4096	-
32	+/- 32	+/- 1024	+/- 2048	+/- 32768	+/- 1048576	+/- 33554432
64	+/- 64	+/- 4096	+/- 8192	+/- 262144	+/- 16777216	+/- 1073741824
128	+/- 128	+/- 16384	+/- 32768	+/- 2097152	+/- 268435456	
256	+/- 256	+/- 65536	+/- 131072	+/- 16777216	Result can overflow on full scale input (> 32-bit signed integer)	
1024	+/- 1024	+/- 1048576	+/- 2097152	+/- 1073741824		

The objective of testing the candidate microphones with each of the filters was to find the flattest response, within the required frequency range, using the least resources, and providing the highest area under the curve. The results of the filter tests are shown in Figure 5.

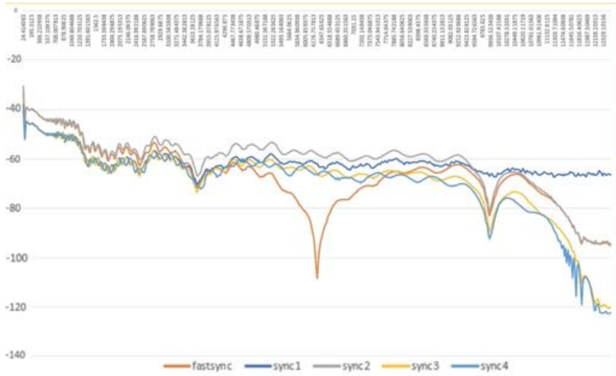

Figure 5. DFSDM Filter results.

As shown in the graph, the fastsinc filter displays a significant notch at 6.5 kHz, whereas the other filters performed consistently. Based on these results, a PDM microphone with a sinc3 filter was selected as the primary candidate.

Testing of microphone dynamic range then highlighted a shortcoming in the noise floor of the measurements. As such, the dynamic range was increased by more oversampling. The microphone was clocked at 3.2 MHz and this signal was 128 times oversampled (FOSR) to get to the 25 kHz PCM signal.

Based on the above factors, a PDM microphone, with a sinc3 filter, sampling at 25 kHz was preferred, and PCBs designed to incorporate the selected microprocessor (on a 'mainboard') and the microphone (on a 'noiseboard'), as shown in Figure 6. Employing separate boards allowed flexibility in approach if components needed to be modified or swapped, and also helped facilitate the other functions of the SiteHive Hexanode device (e.g. taking images, measuring dust, communications, etc.).

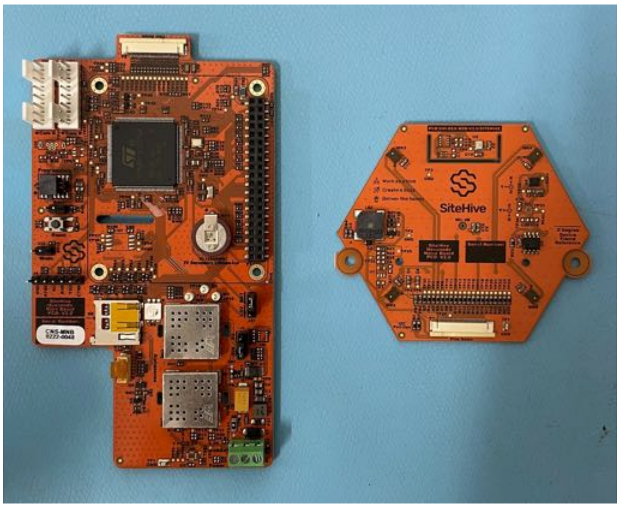

Figure 6. Hexanode mainboard (left) and noiseboard (right) with primary candidate PDM microphone (center of noiseboard), along with ring of DOA microphones.

Testing and Calibration

The primary candidate configuration was then tested by the NMI, across five different boards, to determine the raw microphone response. Firstly, each noiseboard was calibrated in a pressure field environment using a conventional pressure field calibrator at 94 dB 1 kHz as shown in Figure 7. A special adapter was engineered to provide the pressure seal around the microphone.

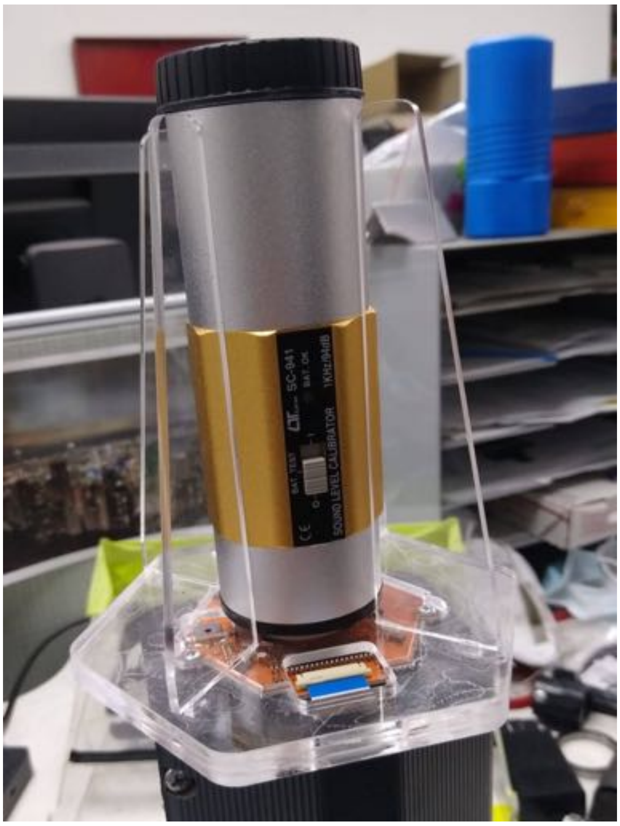

Figure 7. Pressure field calibration.

The results of the subsequent raw microphone response tests undertaken by NMI in the free field environment, as shown in Figure 8, indicate a clearly consistent microphone performance, with little deviation between the minimum, maximum and average response. This was observed across each of the five boards tested.

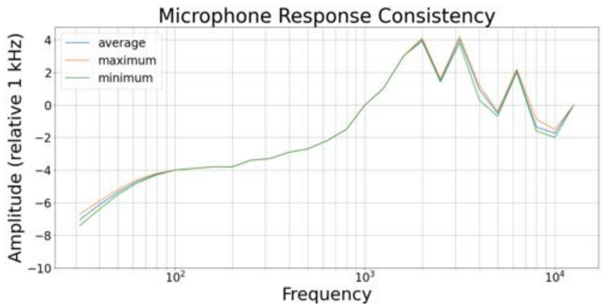

Figure 8. Raw microphone response consistency during NMI testing.

These consistent results enabled a generic signal processing response 'flattener' algorithm to be developed. For each frequency, a filter was designed in MATLAB to invert the microphone response.

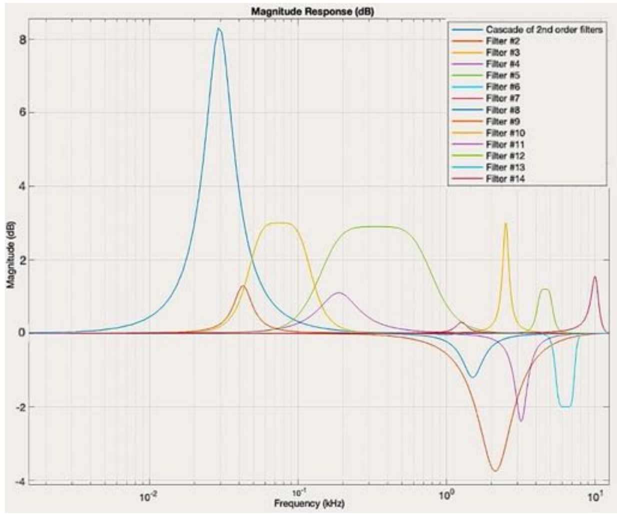

Figure 9. Filter profile.

This flattener filter was then again tested by NMI, under test conditions specified in IEC 61672-3 *Periodic Tests*.

Results and Future Work

The calibration tests performed at NMI were successful, as shown in Figure 10, proving that the weighted frequency response of the MEMS microphone, with the flattener implemented, performed within the tolerances of IEC 61672-1 in a free-field test.

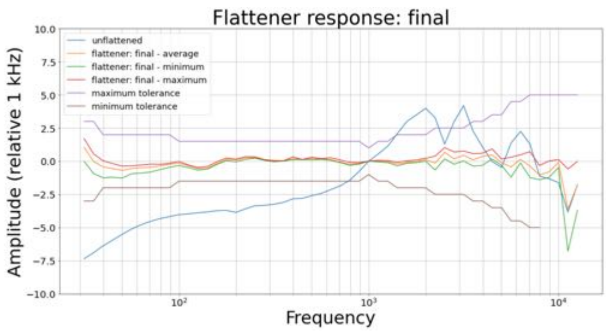

Figure 10. Weighted frequency response of flattened signal from free-field testing at NMI (unflattened response shown in blue).

As this test was conducted in line with IEC 61672-3 *Periodic Tests*, the calibration reports bear the National Association of Testing Authorities (NATA) logo. NATA accredited organisations perform testing and inspection activities for their products and services. NATA certification is often a key requirement for sound level meters used for construction monitoring in Australia and New Zealand; achieving this enables the SiteHive Hexanode with MEMS microphones to be used for these applications.

The testing at NMI however was just the weighted frequency response aspect of IEC 61672. A much broader set of tests can now be designed and undertaken, to ascertain the performance of MEMS microphones.

BROADER TESTING DESIGN

The next phase the product development to design and implement a free-field testing process to determine performance in relation to further aspects of IEC 61672, specifically:

- Directional response
- Level linearity
- Windscreen impact

To complete the necessary work, SiteHive is collaborating with the University of Technology Sydney (UTS) Centre for Audio, Acoustics and Vibration (CAAV). The CAAV, primarily based at UTS Tech Lab, offers the world-class equipment, facilities and expertise to enable the effective and precise testing required to inform the research, design and development of such precision instrumentation.

Directional Response

The directional response is the performance of the previously tested weighted frequency response, but with plane progressive sound waves arriving from a range of sound-incidence angles, rather than directly into the microphone (0°).

As the SiteHive Hexanode is a multi-sensor device, and is required to be deployed in the harsh environment of construction sites, the housing of the device is non-typical compared to traditional sound level meters. Also the main microphone of the sound level meter is located in the centre of a flat PCB (the noiseboard), which may impact performance and require design iterations to resolve this.

The requirements are outlined in IEC 61672-1 section *5.4 Directional Response*. IEC 61672-1 states "*the directional-response design goal is equal response to sounds from all directions of sound incidence*" (5.4.2) and outlines the acceptable limits for deviations of directional response from the design goal (Table 2, 5.4.4).

Section *9.3 Directional Response* of IEC 61672-2 describes the test conditions required to fulfil these requirements. As set out before, a Class 2 sound level meter must be tested with sound signals from 500 Hz to 2 kHz at 1/3rd octave intervals and then from greater than 2 kHz to 8 kHz at 1/6th octave intervals. Each of these frequencies must be tested at angular intervals of no more than 10°.

Level Linearity

The SiteHive Hexanode will also be tested for level linearity. This testing will indicate that the microphone under test will respond proportionately to sounds at any frequency and sound pressure level in its operating range.

IEC 61672-2 section "*9.8 Level linearity*" asserts that a Class 2 sound level meter must demonstrate level linearity across its total operating range at three different frequencies: 31.5 Hz, 1 kHz, and 8 kHz (9.8.1.1, IEC 61672-2).

Windscreen Impact

The windscreen of a traditional sound level meter reduces the noise caused by wind. As the SiteHive Hexanode noiseboard contains multiple sensors and circuits, the windshield must also be integrated with structural support that protects the PCB from both the rigours of life on a construction site, and meteorological conditions (e.g. wind, rain) that may damage the otherwise exposed PCB.

The weighted frequency responses were performed at NMI without a windscreen, as the focus was on the electrical performance of the MEMS microphone, as opposed to the mechanical impact of a windscreen. The end goal of this research and testing is, however, to design a windscreen that offers the required structural support, weather protection, and minimal acoustic impact in line with the requirements of IEC 61672.

Design candidate windscreens, developed for field testing, will be used in these tests to inform windscreen design. Design candidate 1 shown in Figure 11 was developed primarily to provide structural support and weather proofing and consists of a nylon top cap over the noiseboard, with a two-layer steel mesh surrounding the board, then covered in 10 mm of acoustic foam.

Figure 11. Design candidate windscreen 1, noiseboard for scale reference (deployed as horizontal plane).

Design candidate 2 shown in Figure 12 provides a more minimal supporting structure, consisting of a laser cut top cap with an open hexagonal pattern, a machined bottom piece, then with both a hydrophobic mesh and foam providing weather resistance for the exposed areas.

Figure 12. Design candidate windscreen 2.

Free Field Test Setup

SiteHive and UTS collaborated to design a free-field test setup that allowed the above elements of IEC 61672 to be tested, providing design input and verification, before undertaking certification testing at NMI. NMI was engaged to support and validate the test setup by providing advice and supervision to the test design and execution.

The tests were all designed to be undertaken in the primary anechoic chamber at UTS Tech Lab, Botany, NSW as shown in Figure 13. The UTS anechoic room is a precision acoustical measurement facility, providing a free-field environment without noise interference and sound reflection.

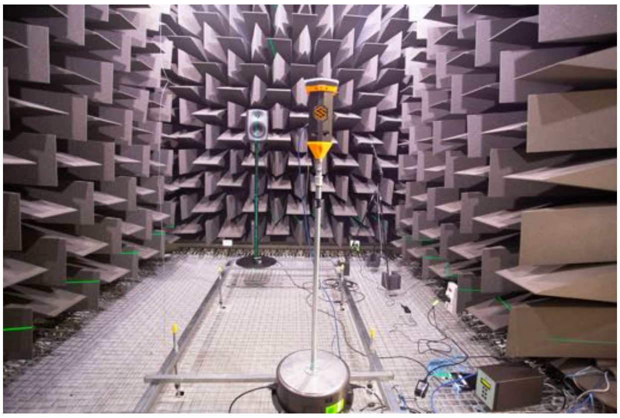

Figure 13. UTS Tech Lab anechoic chamber used for testing (including the green laser level lines used for alignment).

The overall background noise level inside the room was 16.9 dBA, measured by a Brüel & Kjær Type 4189 microphone with inherent noise of 14.6 dBA, over 1/3rd octave bands centered between 12.5 Hz and 20 kHz. This background noise is sufficiently low and permits accurate and precise measurements for most ordinary tests in the anechoic room.

The cut-off frequency is 89 Hz, which was the lower frequency of the 100 Hz 1/3rd octave band. The free-field condition was met over all five microphone traverses. The size of the bare room (without wedges) is approximately 6.46 × 4.66 × 7.00 m with a volume of 211 m^3. The usable space between the wedges and above the wire trampoline is 4.46 × 2.66 × 4.60 m, giving a usable volume of 55 m^3.

The free-field testing process consisted of undertaking reference measurements from a Class 1 Brüel & Kjær Type 4191 microphone coupled with a Type 2669 preamplifier, positioning the microphone in as close proximity to the microphone position of the SiteHive Hexanode as possible. Reference measurements across the full test suite would then be taken, before repeating the process with the SiteHive Hexanode. Figure 14 shows the equipment setup.

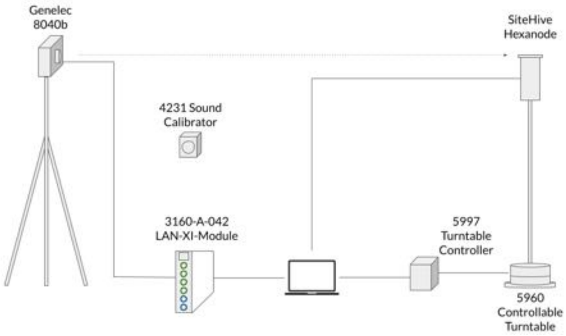

Figure 14. Test setup diagram - Hexanode vertical mount.

Since the floor of the chamber is steel wire mesh, two steel rails were installed running the length of the chamber, providing a stable mounting platform for testing equipment and preventing disturbance from people walking in the chamber. Figures 15 and 16 show the setup. The loudspeaker is positioned 2 meters away from the device under test to allow progressive plane waves being received.

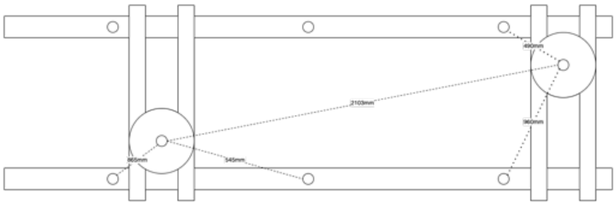

Figure 15. Diagram of test layout, showing placement of microphone and speaker.

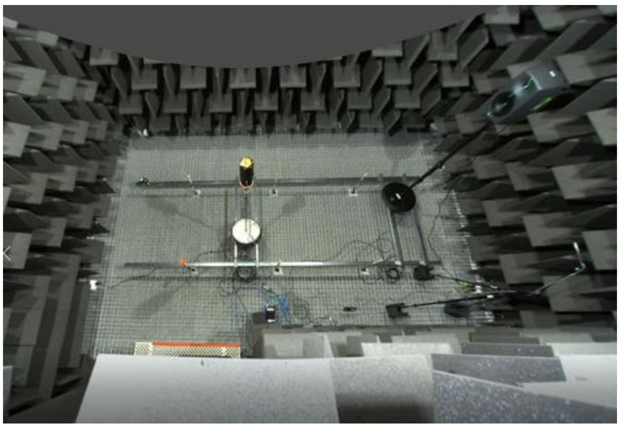

Figure 16. Aerial view of test setup.

The equipment used in the testing process is listed in Table 2.

Table 2. The equipment used in the measurements

Equipment Name	Description
Controllable Turntable	Brüel & Kjær Type 5960
Turntable Controller	Brüel & Kjær Type 5997
Loudspeaker	Genelec 8040B
Pulse Generator Module	Brüel & Kjær Type 3160-A-042
Free-field ½" Microphone	Brüel & Kjær Type 4191
Microphone Preamplifier	Brüel & Kjær Type 2669
Sound Level Meter	Brüel & Kjær Type 2250
Microphone Calibrator	Brüel & Kjær Type 4231
Thermo / Hygro / Barometer	RS PRO 1160
Pulse LabShop Software	Brüel & Kjær Version 23

Considerations of the test design included, but are not limited to:

- Repeatability across tests,
- Avoiding impact from test environment (e.g. stands and brackets),
- Accurate and programmable turntable and data acquisition to allow automated test processing,
- Suitable calibrated reference system,
- Suitable calibrated sound source,
- Strict requirement on positioning and alignment of the source loudspeakers, the device under test and the reference microphone.

Some steps have been made to account for these considerations in the design of the test setup, but need to continue to be researched and mitigated against. Most notably, early test setup validation demonstrated the effect of misalignment on measured sound pressure level at the reference microphone. Integrating a laser based leveling tool into the test setup significantly aided both initial alignment and monitoring throughout testing.

The impact of the 3D printed mounting brackets must also be accounted for (see figure 19). Different brackets will be designed and tested to identify any significant impact from reflections.

Test Process Development

Directionality Test

The normal mode of operation of the SiteHive Hexanode is in a vertical position, as shown in Figure 17, with the PCB sitting flat towards the top of the device.

Figure 17. SiteHive Hexanode in normal operating position when deployed on a construction site.

Since the microphone (on the noiseboard PCB) is not symmetrical about the principal axis in normal use, the directional response must be measured in two planes perpendicular to each other. As such, the test configuration includes mounting the device in three distinct orientations, one vertically, and two horizontally (one rotated by 90° with respect to the other). These are shown schematically in Figure 18.

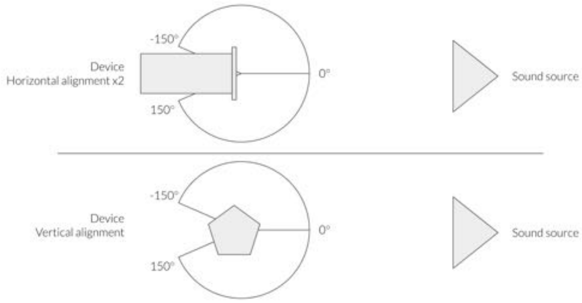

Figure 18. Test setup configurations to determine Hexanode directional response.

A bespoke mounting setup, shown in orange in Figure 19, was 3D printed to ensure the microphone at the centre of the noiseboard was always in the same position during each test position/orientation as the device was rotated on the turntable.

Figure 19. 3D printed mounting device to ensure microphone position when mounted horizontally (shown with windscreen on).

The measurement is then conducted by playing a tone at each of the test frequencies for 25 seconds. data will be recorded during only the latter 20 seconds to allow the signal and pressure in the room to stabilise. A balance must be found between allowing plenty of settling time to minimise any possible frequency band to frequency band variability, while maintaining a practically reasonable total test duration.

The turntable will then be rotated in 10° increments between 180° and - 180° (36 angular orientations), across a frequency spectrum of 1/3rd octave bands from 250 Hz to 2 kHz, then 1/6th octave bands to 8 kHz (22 frequencies). This resulted in 792 measurements per configuration. Completing full rotations per frequency allows for easier monitoring of the test setup, especially as it tests over low frequencies.

With the full set of frequencies and angle increments tested, the setup will be reconfigured to test the other mounting orientations as shown in Figure 18. As in Figure 20, this then creates a domed point mesh of results that show the frequency response at a total of 93 different angles of incidence.

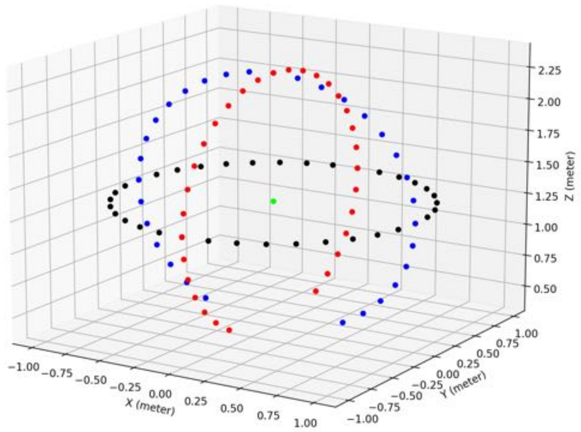

Figure 20. Domed frequency responses from Directionality Tests

A Brüel & Kjær LAN-XI module is used to interface with the free-field ½” microphone and Genelec loudspeaker. The Genelec 8040B loudspeaker features two separate cones at different heights for the tweeter and woofer. The acoustic axis suggested by its manual is applied to account for the orientation of the sound source from 2 meters away. Different loudspeakers, i.e. coaxial loudspeakers, and mounting systems will also be considered and trialled.

The test process was automated by controlling the LAN-XI module and the Brüel & Kjær controllable turntable from a computer using a bespoke python implementation. The test operator could then concurrently record results from the sound level meter under test. Automating the test system has reduced human input in the test process, which has mitigated the risk of human error, reduced test time and centralised measurement recording.

Level Linearity Test

The level linearity test is designed to be conducted in the free-field, with the Hexanode setup in the vertical mounting orientation on the controllable turntable.

For each test of the three frequencies (31.5 Hz, 1 kHz, 8 kHz), the level linearity test begins with the loudspeaker input signal adjusted such that the test microphone displays the required sound level at the starting point on the reference level range (IEC 61672-2 9.8.1.4). The input signal from the speaker is then increased in 1 dB increments until the first indication of overload. The input signal is then reduced in 1dB steps to the first indication of under-range, and then increased again in 1 dB steps back to the reference level.

For each increment, as for the directional response test, the source is live for 25 s. The A-weighted time-averaged sound level for the latter 20 s was recorded. The key measurement in this test is recorded level deviation from the expected sound level as determined by the reference microphone and preamplifier. The test microphone is compliant with Class 2 if the extent of the linear operating range is at least 60dB at 1 kHz (5.6.4), the measured level linearity deviations do not exceed +/-1.1 dB (5.6.5), and if measured deviations from the design goal of any 1-10 dB changes in input signal level do not exceed +/-0.5 dB (5.6.6).

Windscreen Test

Each of the above tests will then be repeated for each windscreen design, to determine the impact on the acoustic performance of each windscreen. It is expected that elements of each design will have performance impacts on the weighted frequency and directional responses. Specific items to test include:

- Material testing - how does the hydrophobic membrane perform vs the steel mesh?,
- Height of windscreen - how does the height of the windscreen impact acoustic performance?
- Windscreen supporting structures - consistent by less porous form in design candidate 1, vs. structural pillars with open space in design candidate 2,
- Top lid - solid nylon cap in design candidate 1, vs. open hexagonal structure in design candidate 2.

Following this ongoing testing, further iterations of each of the above factors will be designed and developed, eventuating in a windscreen design that provides a practical solution to the environmental requirements while also delivering a uniform acoustical impact, within the tolerances of the standard, for each frequency and directional response.

SUMMARY AND NEXT STEPS

Through the tests performed to date, it has been shown that, with appropriate signal processing, MEMS microphones can meet the precision requirements of the IEC 61672-1 frequency weighted response. It has also been found that, in the free field, the design and execution of tests to determine the performance of such a microphone in line with the directional, level linearity and windscreen impacts aspects of the standards is challenging.

The primary challenges arise due to both the rigours of ensuring the repeatability of tests in the test setup design, and also the placement of reference vs. candidate microphones.

This latter element is exacerbated by the current design of the SiteHive noiseboard, placing the microphone in the center of a non-symmetrical hexagon, requiring additional directional testing to be undertaken. Further work will include the testing of the validity of the various test setups employed including determining repeatability and the influence of the sound sources and mounting accessories.

Following feedback from the presentation of this paper at Acoustics 2022 in Wellington, New Zealand, the proposed testing setup and process may be refined before being executed. Based upon the results of the tests when they are executed, the design of the SiteHive Hexanode noiseboard and windscreen will be iterated, and further testing conducted, towards the overall design goal of passing all tests possible to be undertaken as outlined in IEC 61672.

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