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Smartphone-based sound level measurement apps: Evaluation of compliance with international sound level meter standards☆

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ABSTRACT

Smartphones have evolved into powerful devices with computing capabilities that rival the power of personal computers. Any smartphone can now be turned into a sound-measuring device because of its built-in microphone. The ubiquity of these devices allows the noise measuring apps to expand the base of people being able to measure noise.

Many sound measuring apps exist on the market for various mobile platforms, but only a fraction of these apps achieve sufficient accuracy for assessing noise levels, let alone be used as a replacement for professional sound level measuring instruments.

In this paper, we present methods and results of calibrating our in-house developed NoiSee sound level meter app according to relevant ANSI (American National Standards Institute) and IEC (International Electrotechnical Commission) sound level meter standards. The results show that the sound level meter app and an external microphone can achieve compliance with most of the requirements for Class 2 of IEC 61672/ANSI S1.4-2014 standard.

1. Introduction

Excessive noise is a public health problem and can cause a range of health issues: noise exposure can induce hearing impairment, cardiovascular disease, hypertension, sleep disturbance, and psychological, social and behavior problems. The World Health Organization (WHO) estimates that 466 million people have disabling hearing loss [1]. Occupational hearing loss is the most common work-related illness in the United States; the National Institute for Occupational Safety and Health (NIOSH) estimates that approximately 22 million U.S. workers are exposed to hazardous noise [2].

The number of smartphone users will reach 2.87 billion by 2020 [3]. The power of modern mobile devices is comparable to the power of desktop computers. Performance results obtained by Geekbench [4], which is a popular cross-platform performance benchmark tool, show that iPhone 7 performs about as well as Intel Core i5 processor.

Android and iOS are the two major platforms for mobile operating systems worldwide and account for almost 99.7% of the mobile smartphone market today [5], with 85% and 14.7% market share respectively, and are thus the two natural choices for mobile applications development. Using a mobile device, which has a built-in audio input as a sound measuring device is not new. Mobile applications (apps) such as NoiseTube [6], SoundPrint [7], and iHEARu [8] are some of the examples of apps where users can use their smartphones to report the noise levels and geolocation using the devices' audio and GPS (global positioning system) capabilities for mapping noise levels in cities or rating restaurants and entertainment venues based on their ambient noise environment.

Although Android smartphones dominate the worldwide market share, iOS continues to be the preferred development platform for audio-based and sound measurement applications. This is mainly due to the fact that all iOS mobile devices share a common audio architecture called Core Audio and because there are typically no more than 15 current variations of iOS mobile devices (including variants with different screen size) with 86% running the most recent version of iOS and 97% of these devices running an iOS that is no more than 2 years old [9]. In contrast, the Android market is much more fragmented with many different manufacturers producing a vast number of mobile devices ranging from the less capable, low-end to powerful, high-end devices and often relying on many different suppliers for microphones and audio processing tools and chipsets, furthermore, only 11.5% of Android devices run the most recent version of Android [10].

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Fig. 1. Sound level meter calibration system Brüel & Kjær Type 3630.

A laboratory-based study by Kardous and Shaw [11] have shown several iOS apps can have a mean difference of 2 dB compared with a type 1 sound level meter system across different iOS devices over a range of pink noise from 65 to 95 dBA in a reverberation room at the NIOSH Acoustics Laboratory. Their follow-up study [12] with external calibrated microphones showed even greater agreement with apps having ±1 dBA difference from the reference sound level meter. They also reported that none of the Android apps they tested met their testing criteria. They concluded that some iOS apps may be considered accurate enough for limited professional noise measurements. Another study by Murphy and King [13] examined 100 mobile phones (different models and operating systems) with several sound measuring apps. Their results show that there is a significant inter-device variability (standard deviation 6.81 dB) and on average, the measured level deviated 2.93 dBA from the true value on iOS devices and 2.79 dBA on Android devices. They concluded that mobile devices are not quite ready to replace sound level meters and that overall accuracy is often dependent on the age and condition of the smartphone and internal microphone.

Robinson and Tingay [14] evaluated several Android and iOS sound measurement apps on different "available" devices using workplace noise sources. Their results showed an average difference of 12 dB from the levels measured by a type 1 sound level meter. They pointed out several shortcomings of smartphones and noise measurement apps and concluded that one of the major limitations for using sound level meter apps on any smartphone for making an accurate measurement is the internal Micro-Electro-Mechanical-System (MEMS) microphone, the inability to calibrate such microphones using common calibration tools such as acoustical calibrators. Aumond et al. [15] examined the accuracy of mobile devices for measuring urban noise pollution. They conducted a total of 3409 noise measurements using 60 mobile phones at 28 selected locations in Paris, in parallel with fixed noise monitoring stations and a sound level meter. By processing the abundance of noise data gathered by 60 participants, they have mitigated the effect of inter-device variability and concluded that mobile phones could be a useful noise measurement tool. Although their research was performed on Android-based devices only (HTC-One X), they demonstrated that the noise levels measured with calibrated mobile phones correlate strongly with noise monitoring station and sound level meter measurements (root mean square error smaller than 3 dBA).

The most important issue with using smartphones and sound measurement apps to date is that none comply with international sound level meter standards such as IEC 61672-1:2013 [16] or ANSI S1.4-2014 [17] (a nationally adopted IEC 61672 standard), and as a result, they cannot be relied on to make regulatory-accepted environmental or occupational noise exposure assessments. This study aims to address this issue by subjecting a sound level measurement system consisting of our in-house developed iOS sound level meter app; an external, commercially-available, Class 2 compliant microphone; and an iOS-based smartphone to the Class 2 requirements of the IEC 61672 standard. In this paper, we present the results of the calibration and compliance testing of the first portion of our study - the requirements for periodic test specified in IEC 61672-3 [18]. This is the first study of its kind to address the compliance of smartphone-based systems with international standards for sound level meters.

2. Methods

2.1. Experimental setup

IEC 61672-1 states that "A sound level meter may be a self-contained hand-held instrument with an attached microphone and a built-in display device. A sound level meter may be comprised of separate components in one or more enclosures and may be capable of displaying a variety of acoustical signal levels."

The calibration of the sound level meter consisting of an iPhone 6 (running operating system iOS 10.3), NoiSee app (version 2.0.) [19] and an external microphone (MicW type i436 [20]) was performed on a professional sound level meter calibration system Brüel & Kjær type 3630 (Nærum, Denmark) (Fig. 1). The system consists of equipment listed in Table 1. This system is designed to comply with all relevant international standards and is used by major calibration laboratories and commercial calibration centers worldwide. The calibration system also allows for developing a custom software plugin enabling it to control (i.e. to start, stop and reset a measurement) and to read the required parameters from any sound level meter. We have used C#

Table 1
List of equipment used in the professional calibration system.

Equipment	Model	Manufacturer
Generator	Pulse generator	Brüel & Kjær
Amplifier divider	3111 Output Module	Brüel & Kjær
Adaptor	WA0302A, 12 pF	Brüel & Kjær
Calibrator	4226	Brüel & Kjær
Voltmeter	DMM34970A	Agilent
Weather station	2290-4	Ahlborn

programming language to develop such a custom plugin for the calibration system. The setup works as follows: an iPhone running the sound level meter app joins the same network as the PC running the 3630 calibration software using a Wi-Fi connection. TCP (Transmission Control Protocol) communication is established between the app and the Brüel & Kjær type 3630 system by means of our custom plugin. Through the TCP link, the plugin sends the start, stop and reset measurement commands from the calibration system to the app and retrieves the noise parameters from the app when they are requested by the calibration system. The app had to be modified to support remote measurement control. A special calibration mode has been built into the app, which is initiated manually by the operator before the sound level meter calibration is started. While in calibration mode, a measurement in the app can only be controlled via the TCP link. The start and stop buttons on the app's user interface are disabled, which prevents the user from interfering with the measurement. All noise parameters are displayed in the app, while it is in calibration mode. By comparing the noise parameter values on the app's user interface with the values read by the plugin into 3630, we were able to validate correct operation of the plugin.

2.2. IEC 61672 general requirements

Occupational and general-purpose noise measurements are conducted using sound measurement instruments that meet the specifications for Class 1 or Class 2 requirements of IEC 61672 standard. For compliance with occupational and environmental noise requirements, most regulatory bodies require that instruments meet Class 2 specifications. Tolerance specifications for Class 2 instruments are generally equal to or larger than those of Class 1 instruments. For the purpose of this study, the sound level meter system is tested for compliance with Class 2 specifications. The general requirements and tolerances for Class 2 are listed in Tables 2 and 3, respectively. Table 2 shows the general requirements for Class 2 instruments. Table 3 shows the frequency weighting tolerances for the standards.

2.3. Calibration considerations

The first design choice was to select a mobile platform. Important aspects of the app-based sound level meter were taken into consideration. An iOS platform was chosen because of uniform audio architecture - thus lower number of different hardware variants to be tested - and because of higher adoption of the most recently released iOS operating system by smartphone users.

In order to achieve the desired level of performance, an external microphone is required. Very few measurement-grade microphones with an audio jack connector are available on the market today. Most commercially available external microphones are targeted at speech recording and not general purpose audio applications which typically require a flat frequency response up to 20 kHz. The dimensions of most external microphone are non-standard, which prevents the use of commercial acoustical calibrators that have standard 1/2-in. or 1/4-in. microphone adapters. For this reason, we have selected a Mic-W i436 microphone [20], which is an omnidirectional prepolarized electret condenser microphone. It measures 1/4-in. in diameter and has a flat response (within ±2 dB) from 20 Hz to 20 kHz. It complies with IEC 61672 Class 2 requirements. The reasons the performance assessment is limited to an external microphone are threefold: First, the calibration process requires an electrical test where a measurement microphone is substituted with an electrical signal. The electrical substitution can only be achieved with an external microphone, which can be physically removed. Second, the Mic-W i436 external microphone can fit perfectly into the 1/4-in. adapter for an acoustical calibrator. And last, NIOSH conducted an evaluation of the performance of the internal and two external microphones (MicW i437L and iTestMic2) over octave and 1/3-octave frequency bands to determine the effect of the frequency response of the different types of microphones on the overall app measurements. The external microphones showed closer agreement with a reference sound level meter over each of the 1/3-octave bands than the internal microphones.

Table 3
Frequency response tolerances for Class 2 defined in IEC 61672 standard.

Frequency [Hz]	Tolerance [dB]	Frequency [Hz]	Tolerance [dB]
10	+5.5/−∞	500	±1.9
12.5	+5.5/−∞	630	±1.9
16	+5.5/−∞	800	±1.9
20	±3.5	1000	±1.4
25	±3.5	1250	±1.9
31.5	±3.5	1600	±2.6
40	±2.5	2000	±2.6
50	±2.5	2500	±3.1
63	±2.5	3150	±3.1
80	±2.5	4000	±3.6
100	±2.0	5000	±4.1
125	±2.0	6300	±5.1
160	±2.0	8000	±5.6
200	±2.0	10,000	+5.6/−∞
250	±1.9	12,500	+6.0/−∞
315	±1.9	16,000	+6.0/−∞
400	±1.9	20,000	+6.0/−∞

Table 2
Summary: IEC 61672 – Class 2 general requirements.

Requirement	Value
Mandatory frequency weightings	A
Measured parameters	LAF and LAeq for integrating sound level meter (SLM)
Hold feature	Required
Response of frequency weightings	0 dB ±1.0 dB at 1 kHz
Acoustical calibration	Required
Difference between freq. weightings at 1 kHz	±0.2 dB
Difference between time weightings at 1 kHz (A-weighted)	±0.1 dB
Linearity range at 1 kHz	> 60 dB
Level linearity error	±1.1 dB
Required time weightings	F
Overload indication	Required (at least 1 s or as long as overload condition exists)
Under-range indication	Required (at least 1 s or as long as under-range condition exists)
C peak level	Required
Level stability. Difference between initial and final A-weighted level after 30 min	±0.3 dB
High level stability. Difference between initial and final A-weighted level after 5 min at 1 dB below upper boundary of linear range.	±0.3 dB
Reset function	Required

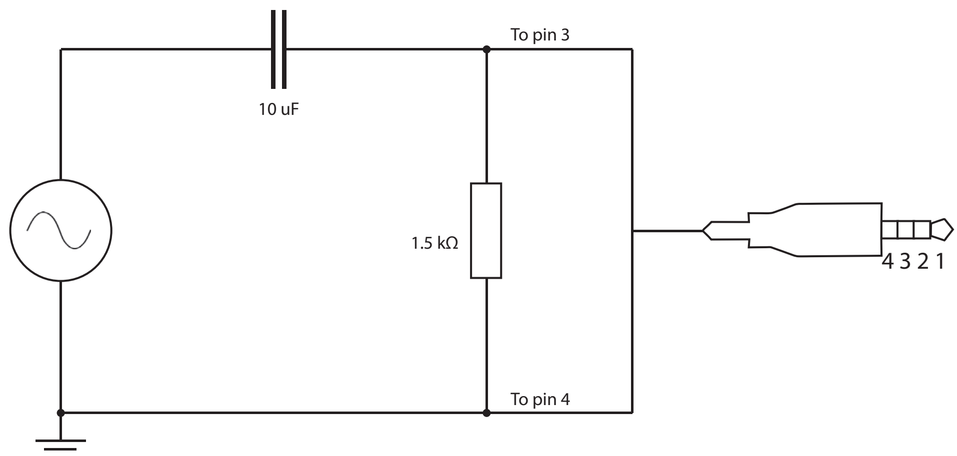

Fig. 2. Electrical diagram of a microphone substitution circuit.

2.3.1. iPhone's audio system

Mobile devices running iOS have multiple audio inputs, which include one or more built-in microphones, and jacks to plug in external microphones. Several internal microphones are used for ambient noise suppression. The two aspects of the audio system that must be accounted for when developing a sound measuring app:

- The iOS operating system applies various techniques to improve the quality of the audio input signal and to suppress ambient noise, mainly to improve speech communication. This is typically accomplished by processing the audio signal through digital filters and polar patterns. Although this improves user speech communication experience, it often alters the shape and content of the audio signal for use in applications that require access to the original audio signal, and thus influences the accuracy of a typical sound measurement. Apple recognized the need to provide developers with the ability to bypass such filters and have access to the original audio signal. Our sound level meter apps disable these features before sound acquisition.
- A mobile phone is a highly dynamic device, where unpredictable interruptions may happen during a sound level measurement (such as a phone call, which interrupts the audio acquisition). The availability of audio inputs may change, e.g. a Bluetooth headset is connected/disconnected, or an external microphone is plugged/unplugged. In the laboratory environment, this can be controlled by putting mobile phone into off-line mode, where it is unable to receive calls. In everyday use, the app detects interruption and pauses an ongoing measurement. The measurement continues when the interruption ends. If an external microphone is unplugged, a measurement is stopped and only a new measurement with internal microphone can be started.

2.3.2. Selecting analog gain

Some iOS devices allow for changing analog gain of audio input. This applies for the built-in microphone as well as any external microphone. The analog amplification means the input signal is amplified (or attenuated) before it is sampled, therefore it offers an opportunity to adjust the amplitude of the input signal to the desired range of sound levels. Since the sensitivity and the dynamic range of the microphone remain constant, reducing the gain allows an application to measure higher sound levels before overloading the input. However, this also affects the lower limit that can be measured, as it shifts up as well.

When dealing with occupational noise exposure, measuring lower noise levels (50 dBA or below) is generally less important, as the noise limits for the exposure are much higher. Also, the current thresholds on sound level meters (as required by occupational noise regulation and guidelines in the U.S.) are between 80 and 90 dBA. Therefore, for our applications (NoiSee or NIOSH SLM apps), our aim was to select the gain calculations to adjust the range of input values to better fit occupational noise measurements.

The sound signal is available to the app from the audio API (application programming interface) of the iOS. Since it is a raw sound signal and not calibrated, an equation that relates the raw signal, the analog input gain, and the resulting sound levels had to be established empirically. The following procedure was used to determine the lower and the upper bounds of the noise level range and the signal scaling factor:

1. The analog gain value was set to a value, for which we wanted to determine the range of sound levels.
2. The microphone input was excited with an electrical signal with frequency $f = 1$ kHz and RMS value of $U_i = 7$ mV, which corresponds to 94 dB of sound pressure level, taking into account the nominal sensitivity of Mic-W i436, which is 7 mV/Pa.
3. The level reading of the app was adjusted, so it showed 94 dB SPL (sound pressure level) (1 Pa).
4. The lower bound is defined as the level when the excitation signal is absent ($U_i = 0$ mV).
5. The input signal level was steadily increased until the input was saturated and signal clipping occurred. This level was recorded as the upper bound.

2.3.3. Microphone substitution

The calibration process includes an acoustical test and an electrical test. A microphone substitution circuit had to be developed to enable the electrical test calibration. The external microphone is connected to pin 3 of the standard 3.5 audio jack connector. A small DC (direct current) voltage is present on this pin, which is used by the mobile phone to detect the presence of an external microphone and to power it. Fig. 2 shows the microphone substitution circuit and Table 4 shows the corresponding pin connections.

A 1.5 kΩ resistor is required to substitute the impedance of the microphone. The value is determined by measuring the resistance across the MicW i436 external microphone. When plugged into an iPhone, the resistance causes iPhone to enable a signal acquisition for

Table 4
Pin connections of the 3.5 audio jack connector.

Pin	Function
1	Left headphone
2	Right headphone
3	Microphone
4	Ground

Fig. 3. Electrical substitution of external microphone.

external input. A capacitor is used to decouple the DC voltage of the microphone input from the signal generator (the signal generator is used to provide the calibration signal). The cut-off frequency of the RC circuit is set at about 10 Hz, which is below the usable frequency range of the audio input. The substitution circuit is housed in a custom-made metal enclosure to reduce the possible electromagnetic interference from nearby electrical sources and attached to the end of a BNC connector (Fig. 3).

3. Calibration results

In this study, we subjected the app and the external microphone to the main periodic performance requirements from the IEC 61672-3. IEC 61672-3 states: "The purpose of periodic testing is to assure the user that the performance of the sound level meter conforms to the applicable specifications of IEC 61672-1 for a limited set of key tests and the environmental conditions under which the tests were performed. The extent of the tests in this part of IEC 61672 is deliberately restricted to the minimum considered necessary for periodic tests."

The results from calibration were used to assess the compliance with the IEC standard. The sound level meter was preconditioned for 12 h at a temperature of 23 °C (73 °F). Table 5 shows the environmental conditions at the time of calibration. The calibration was performed in a calibration laboratory, where a constant temperature and relative humidity is maintained. The environmental conditions were monitored by Ahlborn Weather station type 2290-4.

The measurement uncertainty stated in each of the tables is specified by the manufacturer of the calibration system.

3.1. Frequency weighting – acoustical test

Frequency weightings are tested with the acoustical signal using a multifunction calibrator Brüel & Kjær 4226 at a reference level of 94 dB SPL. The expected level accounts for the attenuation of the frequency weighting. The measured parameter is a FAST-weighted sound pressure level. The testing is done at octave band frequencies 125 Hz, 1 kHz, and 8 kHz as required by IEC 61672-3 for Class 2 instruments. The measured values and negative and positive acceptance limits are as specified in IEC 61672-1. The IEC standard does not specify a calibration level. Most acoustical calibrators provide two calibration levels, 94 dB SPL and 114 dB SPL. For our evaluation, a calibration level of 94 dB was chosen, because most of noise exposures in the occupational or environmental setting fall in the range between 80 and 95 dBA. The results are shown in Tables 6–8 respectively.

Table 5
Environmental conditions at the time of calibration.

	Air temperature [°C/°F]	Air pressure [kPa]	Rel. humidity [%]
Before calibration	23.0/73.4	101.3	45
After calibration	23.1/73.6	101.3	44

3.1.1. A-weighting
See Table 6.

3.1.2. C-weighting
See Table 7.

3.1.3. Z-weighting
See Table 8.

3.2. Frequency weighting – electrical test

Frequency weightings are tested with the signal amplitude, which is adjusted by the exact acoustical weighting design goal to provide a constant reading on the sound level meter. The measured parameter is a FAST-weighted sound pressure level. The testing is done at octave band frequencies from 63 Hz to 8 kHz as required by IEC 61672-3 for Class 2 instruments. The measured values and negative and positive acceptance limits are as specified in Table 3 of IEC 61672-1. The results are shown in Tables 9–11 respectively.

3.2.1. A-weighting
See Table 9.

3.2.2. C-weighting
See Table 10.

3.2.3. Z-weighting
See Table 11.

3.3. Time weightings

3.3.1. Frequency and time weighting at 1 kHz
The readings from all frequency weightings and different time weightings are checked at the reference calibration frequency using an electrical signal. The difference should not exceed acceptance limits defined in clause 5.8 of IEC 61672-1. The results are shown in Table 12.

3.3.2. Tone burst response, time weighting FAST
The FAST-weighted sound level is measured at a continuous sinusoidal signal of 4 kHz. The same signal is applied to the sound level meter in bursts of specified duration and the maximum FAST-weighted level is measured. The expected burst level is determined with a continuous signal and Table 4 of IEC 61672-1. The results are shown in Table 13.

3.3.3. Tone burst response, time weighting SLOW
The SLOW-weighted sound level is measured at a continuous sinusoidal signal of 4 kHz. The same signal is applied to the sound level meter in bursts of specified duration, and the maximum SLOW-weighted level is measured. The expected burst level is determined with a continuous signal and Table 4 of IEC 61672-1. The results are shown in Table 14.

Table 6
Response of the A-weighting filter to the acoustical signal excitation.

Frequency [Hz]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
1000 Ref.	94.0	94.0	0.0	−0.5	0.5	0.36
125	77.81	78.4	0.59	−1.5	1.5	0.34
4000	94.96	95.5	0.54	−1.5	1.5	0.40
8000	92.86	94.3	1.44	−1.5	1.5	0.55

Table 7
Response of the C-weighting filter to the acoustical signal excitation.

Frequency [Hz]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
1000 Ref.	94.0	94.0	0.0	−0.5	0.5	0.36
125	93.83	94.2	0.37	−1.5	1.5	0.34
4000	93.17	93.7	0.53	−1.5	1.5	0.40
8000	90.96	92.4	1.44	−1.5	1.5	0.55

Table 8
Response of the Z-weighting filter to the acoustical signal excitation.

Frequency [Hz]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
1000 Ref.	94.0	94.0	0.0	−0.5	0.5	0.36
125	94.0	94.4	0.4	−1.5	1.5	0.34
4000	94.0	94.5	0.5	−1.5	1.5	0.40
8000	94.0	95.4	1.4	−1.5	1.5	0.55

Table 9
Response of the A-weighting filter to the electrical signal excitation.

Frequency [Hz]	Input level [dBV]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
1000 Ref.	−33.89	75.0	75.0	0.0	−0.5	0.5	0.12
63.096	−44.01	75.0	74.0	−1.0	−1.5	1.5	0.12
125.89	−44.01	75.0	74.5	−0.5	−1.5	1.5	0.12
251.19	−51.51	75.0	74.9	−0.1	−1.5	1.5	0.12
501.19	−56.91	75.0	75.0	0.0	−1.5	1.5	0.12
1995.3	−61.31	75.0	75.0	0.0	−2.0	2.0	0.12
3981.1	−61.11	75.0	74.9	−0.1	−3.0	3.0	0.12
7943.3	−59.01	75.0	74.5	−0.5	−5.0	5.0	0.12

3.3.4. Tone burst response, time weighting Leq

The equivalent sound level is measured at a continuous sinusoidal signal of 4 kHz. The same signal is applied to the sound level meter in bursts of specified duration and a time averaged (equivalent) level is measured. The expected burst level is determined with a continuous signal and Table 4 of IEC 61672-1. The results are shown in Table 15.

3.4. Level linearity

The linearity is tested in 5-dB steps at a frequency of 1 kHz from the reference level of 94 dB up until the overload indication is triggered. The linearity is tested with an electrical signal of 8 kHz. The test is repeated in 5-dB steps from the reference level down, until the under-range indication is triggered. Within the range the deviation should not exceed acceptance levels defined in clause 5.6 of IEC 61672. The results of the level linearity testing are shown in Tables 16 and 17.

3.4.1. Level linearity on reference level range – upper

See Table 16.

3.4.2. Level linearity on reference level range – lower

See Table 17.

3.5. C-weighted peak

Peak detection is tested by applying a continuous sinusoidal signal of 8 kHz to the input and reading the C-weighted peak level. The level of the signal is adjusted in such a way that FAST-time weighted and C-frequency weighted level is 8 dB below upper boundary of operating range. After that, a single cycle of the same sinusoidal signal in applied to the input and the C-weighted peak level is read again. The same test is repeated with only a positive and a negative half of period of the sine signal. The expected levels and acceptance limits are specified in Table 5 of IEC 61672-1. The results are shown in Tables 18 and 19.

3.5.1. Single-cycle sine at 8 kHz

See Table 18.

3.5.2. Half-sine at 500 Hz

See Table 19.

3.6. Overload indication

Overload indication is determined with a 4 kHz positive/negative half-cycle signal. The level at which the overload indication is signaled

Table 10
Response of the C-weighting filter to the electrical signal excitation.

Frequency [Hz]	Input level [dBV]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
1000 Ref.	−60.11	75.0	75.0	0.0	−0.5	0.5	0.12
63.096	−59.29	75.0	74.1	−0.9	−1.5	1.5	0.12
125.89	−59.91	75.0	74.4	−0.6	−1.5	1.5	0.12
251.19	−60.11	75.0	74.9	−0.1	−1.5	1.5	0.12
501.19	−60.11	75.0	75.0	0.0	−1.5	1.5	0.12
1995.3	−59.91	75.0	75.1	0.1	−2.0	2.0	0.12
3981.1	−59.31	75.0	74.9	−0.1	−3.0	3.0	0.12
7943.3	−57.11	75.0	74.4	−0.6	−5.0	5.0	0.12

Table 11
Response of the Z-weighting filter to the electrical signal excitation.

Frequency [Hz]	Input level [dBV]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
1000 Ref.	−60.11	75.0	75.0	0.0	−0.5	0.5	0.12
63.096	−60.11	75.0	74.1	−0.9	−1.5	1.5	0.12
125.89	−60.11	75.0	74.4	−0.6	−1.5	1.5	0.12
251.19	−60.11	75.0	74.9	−0.1	−1.5	1.5	0.12
501.19	−60.11	75.0	75.0	0.0	−1.5	1.5	0.12
1995.3	−60.11	75.0	75.0	0.0	−2.0	2.0	0.12
3981.1	−60.11	75.0	75.0	0.0	−3.0	3.0	0.12
7943.3	−60.11	75.0	75.0	0.0	−5.0	5.0	0.12

Table 12
Response of the different time weightings to a sinusoidal signal at calibration level and frequency.

Parameter	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
LAF, Ref.	94.0	94.0	0.0	−0.5	0.5	0.12
LCF	94.0	94.0	0.0	−0.2	0.2	0.12
LZF	94.0	94.0	0.0	−0.2	0.2	0.12
LAS	94.0	94.0	0.0	−0.1	0.1	0.12
LAeq	94.0	94.1	0.1	−0.1	0.1	0.12

Table 13
Response of the FAST time weighting to signal bursts.

Parameter	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
Continuous, Ref.	117.0	117.0	0.0	−0.5	0.5	0.12
200 ms Burst	116.0	116.1	0.1	−1.0	1.0	0.12
2 ms Burst	99.0	99.0	0.0	−2.5	1.0	0.12
0.25 ms Burst	90.0	89.9	−0.1	−5.0	1.5	0.12

Table 14
Response of the SLOW time weighting to signal bursts.

Parameter	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
Continuous, ref.	117.0	117.0	0.0	−0.5	0.5	0.12
200 ms Burst	109.6	109.6	0.0	−1.0	1.0	0.12
2 ms Burst	90.0	90.0	0.0	−5.0	1.0	0.12

Table 15
Response of the equivalent time weighting to signal bursts.

Parameter	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
Continuous, ref.	117.0	117.0	0.0	−0.5	0.5	0.12
200 ms Burst	100.0	99.5	−0.5	−1.0	1.0	0.12
2 ms Burst	80.0	79.5	−0.5	−2.5	1.0	0.12
0.25 ms Burst	71.0	70.4	−0.6	−5.0	1.5	0.12

Table 16
Level linearity from 94 dB up until overload.

Level [dB SPL]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
94 dB	94.0	94.0	0.0	−0.5	0.5	0.13
99 dB	99.0	99.0	0.0	−1.1	1.1	0.13
104 dB	104.0	104.0	0.0	−1.1	1.1	0.13
109 dB	109.0	109.0	0.0	−1.1	1.1	0.13
114 dB	114.0	113.9	−0.1	−1.1	1.1	0.13
115 dB	115.0	114.9	−0.1	−1.1	1.1	0.13
116 dB	116.0	115.9	−0.1	−1.1	1.1	0.13
117 dB	117.0	116.9	−0.1	−1.1	1.1	0.13

Table 17
Level linearity from 94 dB down until under-range.

Level [dB SPL]	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
94 dB	94.0	94.0	0.0	−0.5	0.5	0.13
89 dB	89.0	89.0	0.0	−1.1	1.1	0.13
84 dB	84.0	84.0	0.0	−1.1	1.1	0.13
79 dB	79.0	79.0	0.0	−1.1	1.1	0.13
74 dB	74.0	74.0	0.0	−1.1	1.1	0.13
69 dB	69.0	69.0	0.0	−1.1	1.1	0.13
64 dB	64.0	64.0	0.0	−1.1	1.1	0.13
59 dB	59.0	59.0	0.0	−1.1	1.1	0.13
54 dB	54.0	54.0	0.0	−1.1	1.1	0.13
49 dB	49.0	49.1	0.1	−1.1	1.1	0.13
45 dB	45.0	45.2	0.2	−1.1	1.1	0.13
44 dB	44.0	44.3	0.3	−1.1	1.1	0.13
43 dB	43.0	43.3	0.3	−1.1	1.1	0.13
42 dB	42.0	42.4	0.4	−1.1	1.1	0.24
41 dB	41.0	41.5	0.5	−1.1	1.1	0.24
40 dB	40.0	40.6	0.6	−1.1	1.1	0.24
39 dB	39.0	39.9	0.9	−1.1	1.1	0.24
38 dB	38.0	39.1	1.1	−1.1	1.1	0.24

Table 18
Peak level response to the single-cycle burst

Signal	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept - Limit [dB]	Accept + Limit [dB]	Uncertainty [dB]
Continuous, Ref.	115.0	115.0	0.0	−0.5	0.5	0.09
Single Sine	118.4	118.8	0.4	−3.0	3.0	0.12

Table 19
Peak level response to a positive and negative half-sine burst.

Signal	Expected [dB SPL]	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
Continuous, ref.	115.0	115.0	0.0	−0.5	0.5	0.09
Half-sine, positive	117.4	116.3	−1.1	−2.0	2.0	0.12
Half-sine, negative	117.4	116.3	−1.1	−2.0	2.0	0.12

is determined with 0.1 dB resolution using positive and negative half-sine signals. The difference between the two levels should not exceed the acceptance levels defined in Clause 5.11 of IEC 61672-1. The results of the overload indication test are shown in Table 20.

3.7. Stability

3.7.1. Longterm stability

Long-term stability is evaluated from the difference between A-weighted sound level indicated in response to a steady 1 kHz sinusoidal signal applied at the beginning and end of the operation. The acceptance limits are specified in clause 5.14 of IEC 61672-1. The results of stability test are shown in Table 21.

3.7.2. High-level stability

High-level stability is tested by measuring the sound level over 5 min with 1 kHz sine signal. The level of the signal corresponds to a sound level that is 1 dB below the upper boundary of the operating range. The difference in measured A-weighted sound level should not exceed acceptance levels defined in Clause 5.15 of IEC 61672-1. The results of the high-level stability test are shown in Table 22.

Table 20
Overload indication

Signal	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
Continuous	120.0	0.0	−0.5	0.5	0.20
Half-sine, Positive	123.1	3.1	−10.0	10.0	0.20
Half-sine, Negative	123.1	3.1	−10.0	10.0	0.20
Difference	123.1	0.0	−1.5	1.5	0.24

Table 21
Longterm stability test results.

	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
Level, ref.	91.1	0.0	−0.1	0.1	0.10
Level, after 30 min.	91.1	0.0	−0.3	0.3	0.10

Table 22
High-level stability test results.

	Measured [dB SPL]	Deviation [dB]	Accept − limit [dB]	Accept + limit [dB]	Uncertainty [dB]
High-level, ref.	119.1	0.1	−0.5	0.5	0.10
High-level, after 5 min.	119.1	0.0	−0.3	0.3	0.10

4. Discussion

Environmental and occupational noise exposure monitoring have traditionally been conducted by national governments and major research or academic institutions since they require major funding and resources. Such monitoring is often accomplished using dedicated and expensive sound measurement instruments. The ubiquitous adoption of smartphones with their constant network connectivity, the built-in geographic positioning system functionality, and the user-interactivity features presents unique and distinct opportunities for researchers everywhere to conduct wide ranging studies using smartphone-based sound level measurements to examine the effect of noise on hearing health and overall well-being.

One of the main obstacles towards achieving greater acceptance, and faced by many researchers conducting noise monitoring studies, is the quality of results collected by smartphone-based apps since neither the apps nor the smartphones are considered to be compliant with the international standards for sound measurement instruments. Laboratory-based studies of the accuracy of smartphone-based sound measurement apps have showed promising results, though the studies have been conducted over set noise level ranges, and controlled environments. [11,13]. However, field-based studies of real-world workplace noise environments using sound measurement apps showed greater discrepancies, some with much lower agreements with professional sound level meters [14], while other studies showed better agreement [21]. Other studies attempted to discover the adequacy of mobile phones for measuring environmental noise in cities [15,22] and in the home [23]. Those studies showed strong correlation between noise levels measured with smartphones and those measured with professional noise monitoring stations and standards-compliant sound level meters.

The common theme amongst all of the studies is the variations of mobile devices used, limited number of devices, and often relying on the uncalibrated results of the mobile phones' internal microphones. In this study, we have instead focused on determining the adequacy of the sound level meter system, consisting of a smartphone and a professional-grade external microphone by subjecting it to a standardized calibration routine according to the performance requirements for periodic testing in IEC 61672-1 and IEC 61672-3.

Our results showed excellent compliance of the app-based sound level meter with standard requirements when subjected to the same tests that are used to perform compliance of professional sound level meters. For the most part, the deviations were well within acceptance limits set in the tables of IEC 61672 standard. The frequency response of the microphone input seems to be the hardest to fulfill, but still falling within acceptance limits. This is due to the fact that the input is primarily designed to capture speech signals. In the speech frequency range (100–4000 Hz), the system's response is in very close agreement with the design goal of the standard.

The results of the frequency weighting acoustical tests (Tables 6–8) show that the deviations tend to increase towards higher frequencies. This is likely due to the frequency response of the MicW i436 microphone since the results of the electrical tests (without using the microphone, just an electrical signal) did not show such increases.

The results of testing at the reference calibration frequency using an electrical signal are in perfect agreement with the design goal as shown in Table 12. This is expected as all the parameters are calculated from the same digital signal, which is a sinusoidal signal of a constant frequency and amplitude, using digital filers and other signal processing techniques. Any difference could therefore arise only from an incorrect calculation.

The results of the tone bursts (Tables 13–15) show that when dealing with a burst signal, the analog part and its dynamic response could contribute to accuracy of the measurement. Indeed, the deviation at the burst test turned out to be slightly higher, but still within acceptance limits.

The level linearity testing for the upper and lower limits (Tables 16 and 17) shows perfect linearity and compliance with the design goal. The measured level tends to start to deviate slightly from the expected level on both ends of the operating range though. At lower levels, the measured level is expected to have a positive deviation because of the noise floor, which causes the meter to read higher. On the other hand, at high levels, the deviation tends to be negative because of the saturation of the audio input.

Additional periodic tests specified in IEC 61672-3 such as C-weighted peak detection, overload indication, and stability testing were all in perfect agreement with the standard's design goals.

The frequency response below 63 Hz and above 8000 kHz falls out of the tolerance limits, which can be attributed to the response of the smartphone's microphone input. In the frequency range from 63 Hz to 8000 kHz, the app-based sound level meter performed in compliance with the main performance requirements for periodic testing in an IEC standard. Since A-weighting is used for occupational and environmental noise measurements, the response of the sound level meter outside this frequency range is of lesser importance, since the noise in these frequency ranges (especially the low frequency part) is attenuated heavily by the A-weighting, thus contributing very little to the overall A-weighted noise level.

The major strength of this study is that it shows that a sound level measurement system consisting of an iOS smartphone, a professional grade, readily-available, external microphone, and a sound level meter app can meet the periodic testing requirements of the IEC 61672 sound level meter standard. What sets this system apart is that the apps (NoiSee and NIOSH SLM) were designed to bypass all speech filters that exist in most non-iOS smartphones. We have conducted tests in a calibration laboratory on a professional calibration system and showed that compliance with the rigorous requirements of IEC 61672–3 is achievable with the proper system and test protocols. This is the first step towards smartphone-based apps establishing compliance with international standards as we continue to explore additional requirements. For any smartphone-based system to achieve full compliance and regulatory acceptance, all testing requirements set in IEC 61672 parts 1 and 2 must also be met.

The major limitation of this study is that it was completed on a single iOS device (iPhone 6) and a single external microphone (MicW i436), but additional preliminary tests on newer model devices and external microphones have shown very similar levels of performance indicating that the iOS device selection and hardware do not play a major role for achieving similar results.

5. Conclusion

By performing a professional-grade calibration, we have demonstrated that a smartphone's audio input performs well, and the results of most of the tests are well within the limits for Class 2 of IEC standard. We conclude that the app-based sound level meter performs well, given an external measurement microphone is used, and shows potential to be used as an adequate measuring device.

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