Comparative study of the performance of smartphone-based sound level meter apps, with and without the application of a ½" IEC-61094-4 working standard microphone, to IEC-61672 standard metering equipment in the detection of various problematic workplace noise environments

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ABSTRACT

An increasing prevalence of sound level meter apps may appear to be a concern to manufacturers of metering equipment but such systems are readily disregarded by professionals due to unacceptable inaccuracy, incorrect measurement methods or parameters. On a technical basis, the [typically MEMS] microphone specifications are the primary limitation to the capabilities of such devices in meeting the requirements. This considered, the attachment of a high-quality condenser microphone and pre-amplifier, as used on professional equipment, may appear to be a solution for low-cost metering that meets IEC-61672, but it is shown that many other equipment factors affect the performance of the system, and conformance to the specifications. This study investigates the premise that, while it may be argued that approximate readings, provided by smartphone metering, can at least offer an indication that further investigation may be necessary, there exists the real chance that the shortfalls in equipment properly measuring the full range of required acoustical parameters will lead to non-detection of significant workplace or environmental noise problems.

Keywords: Sound, Meter, App, Smartphone, Mobile, Device
I-INCE Classification of Subjects Number(s): 72.1, 73.6,

1. INTRODUCTION

Modern sound level meters (SLMs) have moved on significantly in recent decades from the days of analogue metering. Beyond the pre-amplifier, few functions of the device involve analogue circuitry and, once sampled by an Analogue-to-Digital Converter (ADC) the processing of the data to return the desired acoustic parameters is carried out in the digital domain by the processor. Typical smartphone hardware architecture contains some form of the necessary components and similar design elements as a SLM and thus the smartphone platform lends itself very well to carrying out the same function.

Noise monitoring by an array of low-cost, mobile; or more appropriately, moving and track-able; devices is indicated to be of high interest in the industry and is presented as a useful utility in projects requiring extensive data sourcing by Maisonneuve *et. al.* (2009)[1], wherein the pragmatic benefits of the use of a vast number of low-cost sources is very well discussed.

A plethora of new and updated sound level meter (SLM) apps is available through various online channels on a variety of mobile operating systems; predominantly Android and iOS. These range quite significantly in capability, graphical manner of the presentation of data and the particular acoustical parameters reported. Without naming any specifics, it is not uncommon to find such apps reporting parameters which are not considered standard. Also, factors such as frequency weighting are sometimes not made explicit, not possible to deactivate/change or simply not present.

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1.1 Prior Research

Recent studies by Kardous and Shaw (2014)[2] have suggested that a handful of such SLM apps, when installed on certain devices and used to measure steady pink noise in a controlled test environment, are accurate enough to meet international standards for metering equipment. Similar results were reported by Nast, Speer and Le Prell (2014)[3], where devices were exposed to narrowband 250-8000Hz noise and also by Keene *et. al.* (2013)[4] whom again used a pink noise source. It is evident from these studies that there are many apps that can make rather accurate measurements within the constraints of the test; in the case of Kardous and Shaw, even without initial calibration, three apps were found to meet the specification marked out in the introductory passages of ANSI S1.4-1983[5], wherein in is stated that class 2 devices must have a total error of no more than ±2.3dB. However, such test environments are arguably not representative of the actual manner in which a smartphone is used when used as a SLM for real-world measurements. Consequentially, there are of course a vast number of other acoustical tests that form the complete ANSI S1.4 and IEC-61672 standards, addressing the directional response of the SLM, distortion, linearity, tone-burst response etc. Although not made explicitly within any found study, the suggestion that a device is meeting the ANSI standard by conforming to only one aspect of the specifications is misleading.

Investigations have been carried out by Ostendorf (2011[6], 2012[7], 2013[8]) that take the testing further and apply different noise sources. In complete contrast to the positive outcome of aforementioned steady-noise testing, the SLM apps were found to deviate drastically from that measured by a class 1 meter. With the same iPhone, different apps were used to measure various steady noise and single frequency tones and astounding differences of >38dB were seen between apps for a steady 80Hz sinusoid. Woolworth (2014)[9] reports differences of 10dB when performing field tests, both indoors and outdoors.

1.2 MEMS microphones

One major limitation of sound level meter apps on any smartphone currently known to the authors at the time of writing is the microphone. As high-definition video capture becomes highly regarded, recorded audio of high quality is also becoming a desired specification on mobile devices, but to date the main function of the audio recording system is to sample the human voice. Thus, as it is well known that speech information can be conveyed within a bandwidth much smaller than the human auditory range, mobile telecommunication devices are only strictly required to be responsive to this smaller bandwidth and by economic matters it is beneficial for them to do so. Mobile device microphones therefore have not historically had the requirement for a flat, wider frequency spectrum response that is required of measurement microphones. Until recently, it would not be uncommon to find the microphones within mobile devices to be polymer membrane electret condenser types, with a resonance of only a few kilohertz.

Matters have greatly improved with the developments of Micro-Electro-Mechanical-System (MEMS) microphones. More recent MEMS microphones have remarkably flat responses; on a par with the best ½” electret or externally-polarised condenser microphones. This is understandable, as the transduction technology employed is essentially the same as a ¼”-1” electret condenser, but with much smaller components, thus a higher resonant frequency and therefore an extended region of flat response before resonance. Where MEMS devices suffer is the noise floor, with the better devices struggling to achieve much over 60dB (referenced to 94dBA) signal-to-noise ratio. At the time of writing, the best-reported SNR from one particular manufacturer is 70dB[10], although other specifications make the particular model microphone inappropriate for noise measurement (55Hz low frequency roll-off). The absolute sound pressure upper limit of MEMS microphones is also a limitation, with 120dBA being the general maximum.

Modern implementations of MEMS microphones commonly install the devices within the casings of the smartphone, and usually directly soldered to the circuit board. This adds to the robustness of the device but also introduces an acoustical filtering network, which can attenuate or amplify particular frequencies. MEMS devices are becoming near-equal contenders with electret condenser microphones (ECMs) by specification and applicability in noise measurement; Shelton (2014)[11] reports upon a recent project at the National Physical Laboratory, UK, wherein MEMS microphones have been seen to perform with the frequency response tolerances for type-1 working standard microphones by IEC 61094-4[12].

Regardless, the problem will always exist for the smartphone noise meter system that the exact device chosen by a smartphone manufacturer is unknown.

1.3 Other effects within the mobile device

Beyond the microphone, the signal chain is essentially unknown. Fundamentally, smartphone designers will be targeting 'high-quality'-sounding audio rather than a perfectly flat response. Many manufacturers apply high-pass filtering to the signal from the microphone to reduce 'pop' or wind noise. As reported by Faber (2012)[13] Apple devices with iOS firmware prior to version 6 have such filters applied, and these differ between devices. Remarkably, from measurements by Faber, an iPhone 3G-S with pre-version-6 iOS has a very high-order high pass filter, with the -3dB point over 200Hz and a roll-off of approximately 30dB/octave. It would be a fair hypothesis that, considering the date of the study with respect to the release date of iOS-6 (both 2012), the aforementioned result of Ostendorf with an 80Hz tone was affected by this filter; the difference between the apps could be the result of the app designer applying correction filters with differing levels of success. From iOS v. 6 onward, it is possible within software to turn off this filter but again, whether a particular app does this or not is unknown.

Digital signal processing algorithms are widely implemented within the regular audio channel of a mobile device in order to reduce the signal bandwidth and bitrate. Jarinen *et al* (2010) describe the relationship between the bandwidth of audio and the intelligibility of the speech, with an optimum ≈14kHz bandwidth above which there is no improvement; furthermore, even a slight detriment with a broader, full-audible-spectrum bandwidth. The last two decades have seen significant development of the coding of voice channels in mobile communications devices in order to reduce bitrates whilst keeping the audio quality high and intelligible; methods within often use psychoacoustic effects to remove portions of the audio signal that would not be perceived and thus unnecessary to transmit. Whilst it is perfectly valid to eliminate redundant sound on perceptual grounds, it is not valid to do so regarding exposure; whether or not a listener perceives portions of the total energy reaching their hearing system is irrespective of the amount of noise exposure they receive.

2. METHODOLOGY

2.1 Hardware choice

Devices were essentially chosen by availability and then by form, software environment and age. Different sizes of device were included, from a handheld 4"-screened smartphone to 10" tablet. Android and iOS devices were selected, with a range of levels of hardware technologies and financial costs. Whilst this opened the gate wide to a lack of control over the affecting variables, and thus one may readily question the validity of conclusions arising from the resulting measurements, it is suggested that this is entirely representative of 'real-world' situations. To expand; the typical end-user is entirely unlikely to have chosen their smartphone device on the merits of its ability to accurately measure noise; more likely it has been chosen due to other marketed factors such as the screen size, processor speed, storage capacity, design aesthetics or simply the brand or colour. Additionally, any attachments such as cases fitted to the devices *were left attached*.

While blazingly obvious to the technical community that this would have an effect upon the measurement, it is entirely representative of the manner in which the un-trained or poorly-informed user may download such an application to their *personal* mobile device.

For comparative measurements, a type-approved IEC 61672 Class 1 SLM (Cirrus Research CR:171C) was used. Calibration using a type-approved IEC 60942 Class 1 acoustic calibrator (Cirrus Research CR:515) was carried out before all measurements.

The vast majority of smartphone devices will switch from the internal microphone when an alternative microphone is connected to the headset input. The same model of microphone and preamplifier from the SLM used for comparison measurements was used. The preamplifier was fitted with independent battery power, the gain increased by 20dB to make it appropriate for a smartphone input and a 5kΩ potentiometer used to trim the output voltage such that calibrations could be carried out using the acoustic calibrator when attached to the smartphone.

2.2 Test procedures

The study implemented four different tests with a selection of devices:

2.2.1 Variance of measured sound level using different devices with the same SLM app

To demonstrate the variance in measurements made by devices which are not designed to be sound level meters, a study was devised to be typical of a workplace noise measurement, with the level measured by three different mobile devices and the Class 1 SLM. Test subjects were selected based upon their having no knowledge of the correct operation of a sound level meter. Each of the four devices were placed upon a bench and the users instructed to use each device in turn to measure the noise level experienced by an employee positioned 1m from a small air compressor unit. The room had no acoustical treatment and results would clearly vary by the manner in which measurements were made. Additionally, the actual position of the measurement relative to the intended measured point was different, chosen by the operator.

2.2.2 Wind noise

Tests were performed in a quiet, dry, outdoor environment in the middle of a grass field, well away from any residences or roads on a gusty day, where the wind varied between near-zero and over $6ms^{-1}$. All meters/smartphone apps were set to fast time weighting. Meters/devices were held outstretched at shoulder height and the ambient noise level recorded when the wind speed was below $0.2ms^{-1}$, the speed at which the anemometer (ATP DT-618B) just began to spin and give a reading. When the wind speed reached $5ms^{-1}$, the noise levels displayed by each device were recorded. Similar measurements were made with the Class 1 meter when fitted with and without a windshield. All measurements were repeated ten times per smartphone/app combination and the averages reported in Table 1.

2.2.3 Measurement of workplace noise

Three sound sources were used; the noise from a lathe, running alone with no cutting taking place (thus only motor and gear noise), the noise from an aluminium tube being hit with a hammer with a frequency of 2Hz (timed using a metronome) and the combination of both noises simultaneously. Devices were held in the hand at a distance of 1m from the noise sources, with the device held down and then repositioned back before taking subsequent measurements; ten in total per combination.

2.2.4 Comparative use of a type 1 microphone capsule to measure workplace noise

Various workplace noise sources were selected to give a good range of qualities; steady, impulsive, high and low crest factors, and a variety of frequency content; particularly sources with and without significant content at the extremes of the frequency range. For each noise source, the position of the microphone was kept constant. In the case of the external type 1 capsule, the sound calibrator was attached, with the trim between the pre-amplifier and smartphone device under test adjusted until the device displayed 93.7dBA before making the measurement.

2.3 Software choice

Good agreement was found with the app selection process of Shaw and Kardous (2014)[2] and five SLM applications were selected at random from the list of ten used in their study. This presented a list of paid-for and free apps. Of the five apps chosen, only one was available for iOS and Android; the iPhone result is only presented for this one app.

3. RESULTS

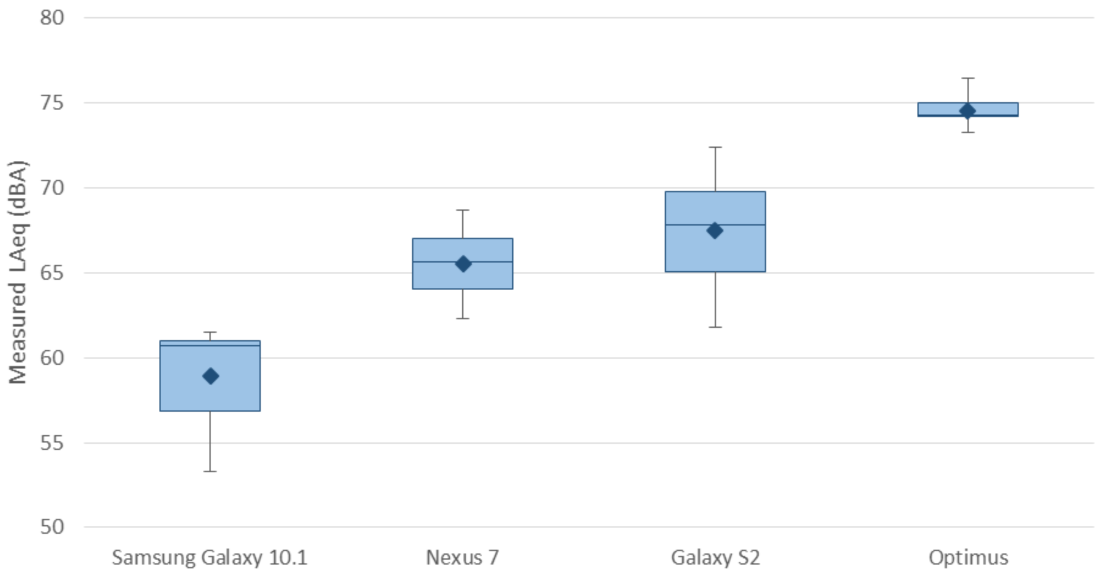

Figure 1: Box plot of the variance in measurement made by untrained users with an IEC61672 Class 1 meter and three different format mobile devices

Table 1: Wind noise measurements

Optimus Class 1 meter

Device	No. apps tested	Average increase reading between <0.25ms^{-1} and 5ms^{-1} (dBA)
Optimus Class 1 SLM with windshield	n/a	1
Optimus Class 1 SLM without windshield	n/a	8
Samsung Galaxy S2	5	12
Nexus 7	3	11
iPhone 5	3	7

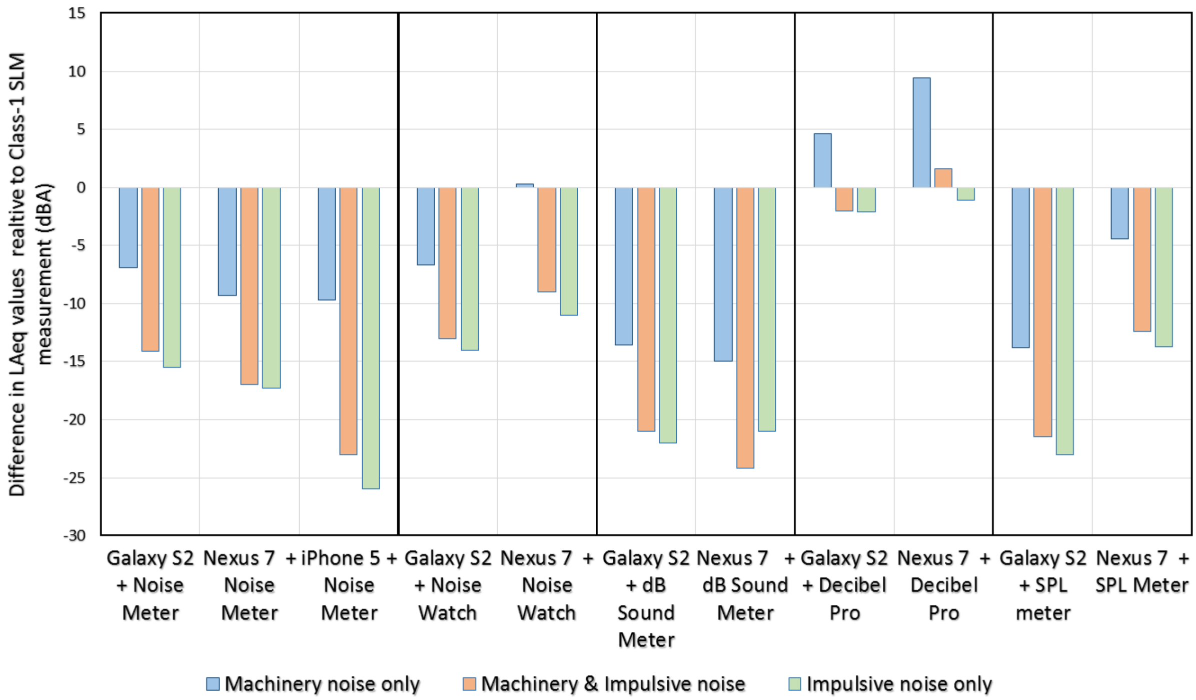

Figure 2: Comparison of same app running on different similar form devices, relative to IEC61672 Class 1 SLM reading

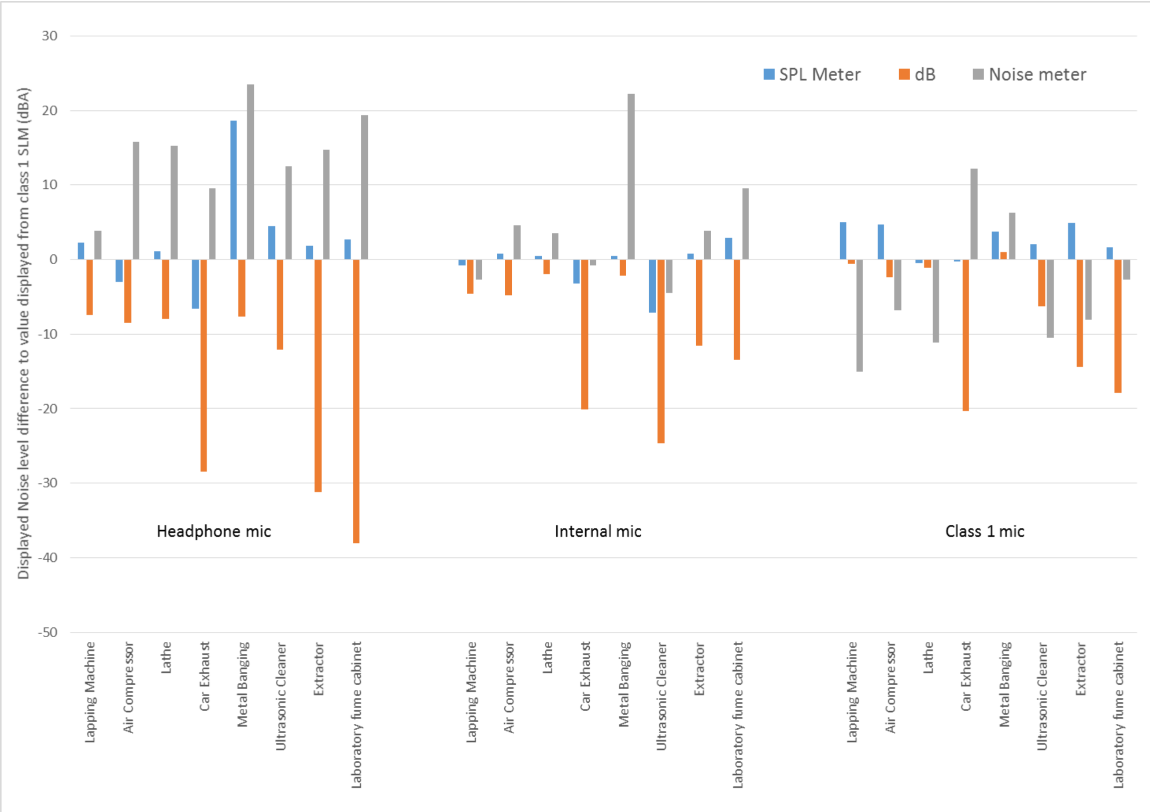

Figure 3: Difference in readings for a single iPad device, measuring different workplace noise with three different apps

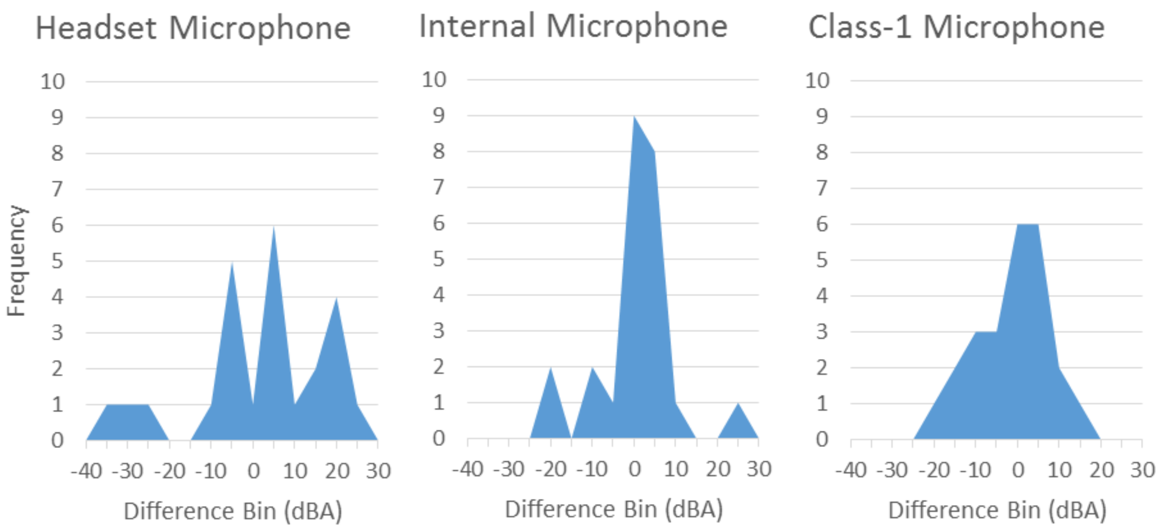

Figure 4: Histograms of differences in reported LAeq, grouped by microphone type

4. DISCUSSION

4.1 Comparison of devices running the same SLM app

An important design factor of a sound level meter is that the form of the device is ergonomically conducive to the proper manner of making a noise measurement. By the simple action of picking up the device, the microphone is directed appropriately, placed away from the user to avert reflections and diffraction from objects (i.e. the user) near or within the direct path to the sound source. One may readily argue that the reasons for such variance are clear; the microphones are placed in non-ideal locations, disguised within the body of the device sometimes with very small apertures and often easily obscured by cases or the placement of the users' hands. Within the test, some subjects chose, without guidance, to position the devices such that the microphone pointed toward the noise source; other subjects simply held the device as they would when performing a typical smartphone operation. There were two distinct occasions when the user appeared to have covered over the microphone when using the Samsung tablet, which may account for the majority of other measurements being considerably higher.

Although an increased variability is seen for two of the devices compared to the class 1 meter, there were insufficient samples in the set and additionally multiple variables simultaneously affecting the results of each test and it would be entirely inappropriate to draw any conclusions as to why a particular device had not achieved an accurate measurement. This methodology was entirely intentional however; it is this exact style environment within which a SLM app on a mobile device would be used and thus, disregarding the absolute accuracy of measurement, the methodology and results so far display an indication of the possible variability of measured LAeq due to the design of the device and the variety of manners in which the measurement could be taken.

There are numerous reasons as to why this would be; an inexhaustive list of which are:

- Devices were not calibrated,
- Hardware varies significantly, with no knowledge of the application designer in the absolute sensitivity of the microphone nor its response.
- Microphones were placed in a location on the device which was not suited for accurate acoustical measurement,
- Hardware capabilities are lacking in the ability to properly capture noise levels without refraction or reflection,
- Other software may be running on the device; apparent or not; with the possibility of interrupting background tasks,
- Performance may be compromised by the current state of the operating system; availability of free memory or storage,
- Filtering may or may not be applied to the microphone; it is often found that a high pass anti-pop filter is applied, which would detriment low-frequency measurements.

4.2 Wind noise

By design, mobile devices rarely have physical protection against wind noise; such matters are instead 'band-aided' by methods of filtering and signal processing of the microphone signal. Taking this investigation further would require an acoustic laminar wind flow chamber; clearly beyond the scope of the study, but nevertheless, the devices were definitely susceptible to wind noise, with approximately 10dBA increase in measured level. Without any protection, measurements in anything other than still air environments would be unacceptably inaccurate.

4.3 Similar form devices running different software for workplace noise

In the results displayed in Figure 2, it would appear that there are regular trends in the measurements. Taking the results between each device using "Noise Meter", the measured levels relative to other measurements would suggest that, if some offset were applied by calibration, the smartphone apps would be reporting similar values. However, at best, this approach would produce a result similar to "Decibel Pro", which is still at best 2dB away from the Class 1 reading.

Further control of the test conditions would be required to determine more intricate matters, although this was not the intent of the test. It would be suggested that a calibration of the sound source could be made first, presenting a steady 1kHz sine tone at the beginning of the recording, the volume of which could be then adjusted until the smartphone app. Overall, there are two matters indicated by these results:

• Non-calibration of smartphone meter apps leads to very high inaccuracies in the majority of cases,
• It would appear that there are better and worse combinations of software and hardware.

Overall, taking the difference of all results from each smartphone/app combination into account, an average difference of 11.8dB from the level measured by a Class 1 SLM.

4.4 iPad tests using the internal, a headset-mounted and a class 1 microphone

Consideration of the results from the headset microphone suggest the combination to be drastically poor; a difference of 57dBA between different apps using the same hardware is difficult to believe. There are three distinct noise sources for which exceptional disagreement is seen between the app measurements; considering the qualities of the sound source in each of these three cases, all of which had high-amplitude at low-frequency content, it is clearly seen that some effect within the smartphone is rejecting low frequency content. It would be a reasonable assumption and scope for investigation that the mobile device was performing some form of high-pass filtering, by single-tone measurements in controlled acoustic conditions. This is a known issue for older iPhone devices with firmware prior to iOS-6, as described by Faber (2009)[14], whereby very high-order filters are used by some devices, seen in Figure 5.

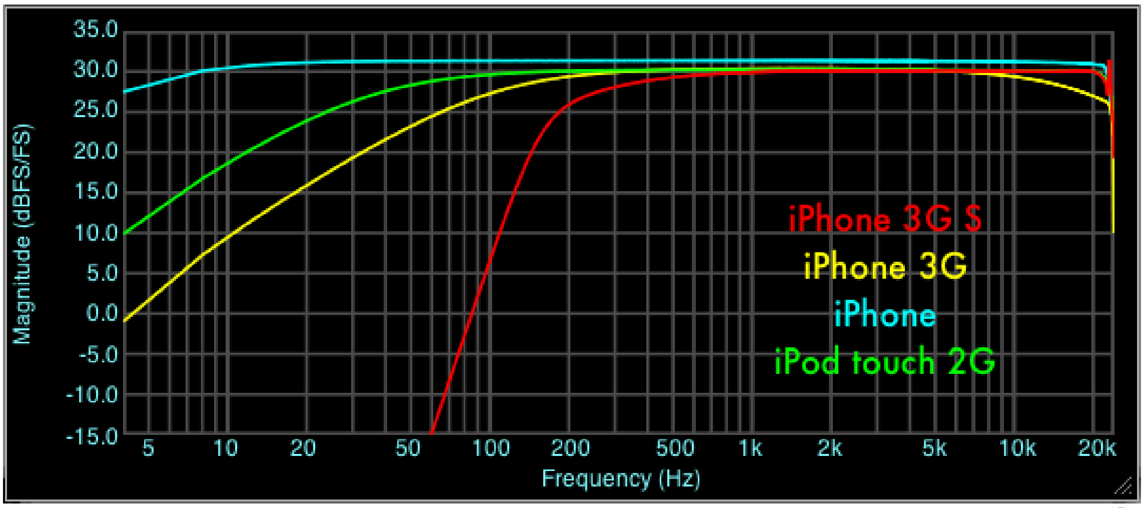

Figure 5: Input frequency response of various iPhone models, indicating high-pass filtering[15].

Considering the distributions of the differences in measurements from that given by the class 1 meter, seen in Figure 4, attachment of a type 1 microphone to a smartphone can result in marginal improvement over the use of the internal microphone.

Even with the additional benefit of calibration however, there are still clearly large discrepancies for noise sources of extremes of frequency content (car exhaust, extractor unit and laboratory fume cabinet in Figure 3), and issues with impulsive noise.

Upgrading the smartphone hardware system with a more appropriate/accurate measurement device clearly provides more scope for improvement, but this still does not eliminate the additional complications that are implicit in the use of a personalised, multi-function device, with various unknown additional software installed. Fundamentally, it is totally undeniable that the high-SPL-level insufficiency of the MEMS microphones fitted to the vast majority of mobile devices makes such a device unsuitable for the measurement of workplace noise.

It is proposed that, if the aforementioned considerations are incorporated and the device is stripped of all other functions and software, fitted with a few hundred pounds worth of improved front-end transducing equipment, with the software sampling and performing calculations in the proper manner, a smartphone device could very readily be transformed into an accurate acoustic measurement device, but at the end-point of such a process, the result would be drastically uneconomical, of unproven reliability and due to uncertainties of the exact hardware installed certainly not anything that could be presented for pattern approval. It is duly noted that applications are available, such as those by Faber Acoustics[13], where most of these matters are taken into account & go a long way toward producing a class-meeting SLM from a production smartphone. The breadth of testing and the documentation provided by Faber, places Faber Acoustic's flagship SLM software in a performance class far above the free/low-cost SLM apps; consequentially, retailing at £70 (and hence the omission of it from this study). Additionally, the smartphone itself is very high-value; with the availability of metering equipment thus well within the financial outlay of the smartphone-based approach, one would clearly ask whether there would be any benefit at all; especially when the loss of one's treasured smartphone as actually being one's smartphone is taken into account!

5. CONCLUSIONS

Additional testing would be required to draw statistically confident results; perhaps by this, more exacting reasons as to why a smartphone is particularly inaccurate could be investigated and improvements then made.

It is readily accepted, as found in previous studies, that current smartphone/app combinations can measure mid-level, steady, broadband noise sources with acceptable accuracy to meet *that single aspect* of international standards. However, it is argued that laboratory-based testing performed so far do not represent the methods in which a smartphone will actually be used when taken into real-world environments, especially industrial, higher-noise-level environments where workplace noise is likely to be problematic. The real-world approach taken in this study demonstrates that the use of smartphone apps in genuine noise-problematic situations is fraught with inaccuracy; it is postulated that well-trained ears would be better indicators than some of the software/hardware combinations.

If the limitation is made that a given SLM app is designed for one particular model and variant smartphone, it is considered achievable that an IEC-61672-standard noise monitoring device could be producible, but with the unrestricted variation in hardware between manufactures, their models and even period/factory of manufacture it is highly dubious that an app can be applicable to a wide range of devices. Even then, acquiring type approval for a SLM is a lengthy process involving numerous diverse test procedures, the cost of which runs into many tens of thousands of pounds, let alone the development costs leading up to the point of testing.

Calibration is clearly a huge aspect of achieving an accurate measurement and the inability of the majority of users to be able to perform a calibration is a major factor in the [in-] accuracy of a particular device. The application of IEC-standard microphones, or at least capsules with a body that can be attached to a calibrator makes steps toward resolving this issue, but without this, the user would typically require access to a reverberation chamber or other controlled acoustic facility to perform a calibration, which is clearly not accessible to the vast majority of users.

Used appropriately, and in each individual case of measurement taking into account the limitations of the hardware/software, it is suggested that a calibrated, quality smartphone device with an app tailored to that specific hardware can be a useful tool to a qualified professional, but the development of the consensus within the general public that generic smartphone SLM apps installed on any device are an appropriate approach in which workplace noise can be monitored is a highly questionable avenue to continue upon.

ACKNOWLEDGEMENTS

The authors thank Ben Faber of Faber Acoustics for information and permission to use material within this study.

DISCLAIMER

It is not the intention of this study to prove or disprove any functionality of the devices, software nor combination thereof and whilst specific mention has been made to particular device brands or software, this is only made with the intention of enabling third parties making future comparisons to the results presented. Any indications of accuracy or inaccuracy are not to be considered an endorsement by the authors nor Cirrus Research PLC.

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