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DOI: 10.1109/I2MTC.2019.8826907

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***Abstract*—Noise in work places is a critical problem and international regulations are becoming more restrictive on this aspect. The normal 'a-priori' way of stating the workers' exposure to the noise is becoming not enough to warrant that the worker is not exposed to a too high noise thus personal measuring systems are often required. In this paper one of these systems is described that is, not only capable of logging the noise the worker is subjected to, but also to raise an alarm if the noise seems to exceed the maximum allowed level. The system employs a 1$ microphone and off-the-shelf components and has a cost lower than 100$ so that any worker can be provided with a measuring system. The described solution connects to a central system via LoRa protocol without the necessity for the measuring system to be connected to the receiver or to be put close to it.**

***Index Terms*—Audio processing, Noise measurement, Worker safety**

I. Introduction

Workers' safety is a specific problem which is addressed in every country legislation. The generic concept of safety of course includes several different aspects of the working activity and workers' exposure to noise is one of the specific problems any employer has to address. The legislation changes from country to country, but in general several exposure values are defined which correspond to different required actions.

The problem is made more complex due to the long times a worker can be exposed and to the different tolerance capabilities of the hearing apparatus to the different noise length and frequencies.

Unfortunately, workers are subjected to varying noise during their activity so that an 'a-priori' computation is always a critical assessment since the real worker exposure is difficult to preview. A simple and cheap wearable solution which could be worn by all exposed worker would be a challenge.

II. Noise exposure measurement

A. Weighting curves

The noise measurement is usually defined making reference to specific sound weighting curves which takes the normal ear response into account. Such curves have been described in the ANSI S1.4.1983 [1] and S1.42-2001 [2] standards. Usually three types of weighting curves are defined which are referred to as A, B and C. All three curves take into account that the ear is especially sensitive to mid range frequencies while its sensitivity decreases for low and high frequencies.

All three curves have as their base the C curve, which has a double zero in the origin, a double pole at 20.6 Hz and a double pole at 12200 Hz. This curve represents the ear sensitivity for high sound levels of the order of 100 dB which is almost flat in the mid range:

$$H_C(s) = K_C \frac{s^2}{\left(1+\frac{s}{2\pi 20.6}\right)^2 \cdot \left(1+\frac{s}{2\pi 12200}\right)^2} \tag{1}$$

The B curve can be used for lower sound levels of the order of 70 dB at 1 kHz, when the ear starts decreasing its sensitivity for low and high frequencies and is derived by the C curve by adding a zero in the origin and a pole at 158.5 Hz:

$$H_b(s) = K_B \cdot H_C(s) \frac{s}{\left(1+\frac{s}{2\pi 158.5}\right)} \tag{2}$$

Eventually, the A curve is used for even lower sound levels of the order of 40 dB at 1 kHz where the ear has a much lower sensitivity to high and low frequencies and is derived from the C curve by adding two zeros in the origin and two poles at 107.7 Hz and 737.9 Hz:

$$H_A(s) = K_A \cdot H_C(s) \frac{s^2}{\left(1+\frac{s}{2\pi 107.7}\right) \cdot \left(1+\frac{s}{2\pi 737.9}\right)} \tag{3}$$

The three coefficients $K_A \approx 0.398 \cdot 10^{-6}$, $K_B \approx 1.016 \cdot 10^{-3}$, and $K_C \approx 60.1 \cdot 10^{-6}$ are set to have a unity gain at 1 kHz.

Fig. 1 shows the weighting of the three curves for the different frequencies.

Usually international regulations rely on the A curve for the normal working activities and employ the C curve only in the presence of quite high and impulsive noise.

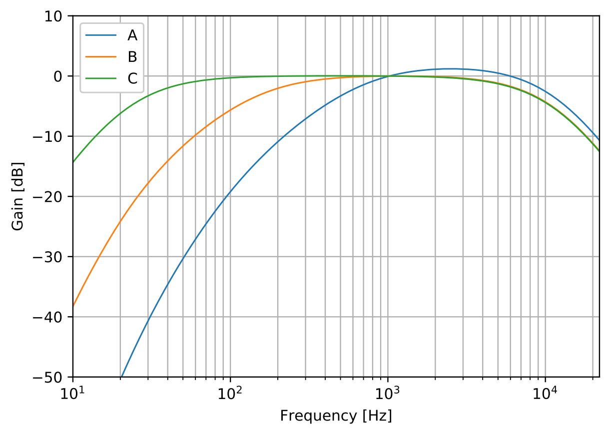

Fig. 1. A, B, and C weighting curves.

B. Limits of environmental noise exposure

Two kinds of noises can produce ear damage: strong short 'pulse' noise and lower, but prolonged noise.

The first type of noise is capable of producing an immediate ear damage level, which happens at noise levels at the order of $140\ \mathrm{dB}$, which corresponds to a Sound Pressure Level (SPL) of about $200\ \mathrm{Pa}$. The measurement of extremely high noise does not require any weighting curve and should be treated separately from any other type of noise.

Lower noise levels, but affecting the worker for a long time, may also produce a damage to the hearing system which appears as a permanent reduction of the hearing capability and should be avoided.

As an example, in 2003 using a working time of eight hours and the frequency content as defined by the weighting curve of type A, the European Union [3] defined a lower exposure action value of 80 dB, an upper exposure action value of 85 dB, and an exposure limit value of 87 dB.

All these values are to be satisfied at worker ears so after the use of any possible countermeasure, such as a protecting earphone. The employers should start acting when the lower action exposure limit is reached and the standard prescribes different types of actions according to the noise level.

Similar values are prescribed or recommended worldwide [4], [5] so the problem is how to insure and prove the respect of the limits for all workers.

C. Estimation of environmental noise exposure

According to the International Standard ISO 1999:2013 [6], the equivalent level of exposure $L_{ex,8h}$ during a regular working time of eight hours can be estimated if the worker is supposed to be exposed to specific noise levels connected to specific fixed duties. In this case the exposure can be estimated as:

$$L_{ex,8h} = 10 \cdot log_{10} \left(\frac{1}{T_0} \sum_{i=1}^{N} 10^{0.1 L_i} \cdot T_i \right) \tag{4}$$

where T_0 is the total work duration, T_i is the duration of i duty, L_i is the noise level during this duty in dB and weighted with the selected curve (A, B or C), and N is the number of duties.

Estimations based on eqn. 4, which are often used in the absence of other specific measurement devices, only require one either to estimate or to measure once for all the exposure noise level of the different operations and to define the time devoted to each operation. Unfortunately the real position and operating time of each worker, especially in case of small companies, hardly obey a fixed scheduling, so the application of this approach often leads to not significant results.

D. Personal noise measurement

A solution to the measurement of noise, which avoids the use of 'a-priori' equations like the eqn. 4, is to provide each worker with a personal noise measurement system capable of logging the exposure to noise for all the working period. Devices for noise measurement are quite common and discussed [7], but in this case some specific requirements are present. A device of this type could be used either for noise assessment or for immediate alarm when the noise exposure gets over a predefined threshold. In any case the system should:

- be small and light enough to be worn without discomfort by the worker;
- be without cables to avoid impairing the worker movements;
- be capable of measuring the noise regardless of the worker position and posture;
- be capable of logging the noise for a long period, at least for the entire working cycle;
- be capable of capturing the noise according to the different regulations (e.g. weighing curves A, B, C);
- if an immediate alarm is required the system should also be able to wireless connect to a server to instantiate the alarm, otherwise a way to download the logged data is required.

This solution is of course not new as several "noise badges" appeared on the market. Unfortunately, none of them seems to have an immediate alarm capability and their price is definitely expensive, usually more than 800$, so a capillary measurement approach, extended to all workers, is hard to be obtained.

III. The Proposed Measurement System

A. Hardware

The proposed measuring system which is capable of satisfying all the requirements expressed in previous section can be designed by using a TeensyDuino 3.6, which is a microcontroller based development board easily available off-the shelf, a digital microphone and a LoRa transceiver.

The complete block diagram of such a system is shown in fig. 2. The figure shows:

- The microphone, which is the front end of the system and which is responsible for acquiring the noise. This microphone can be of any type, provided that its band is large enough to capture all the noise and the maximum sound level which can be measured is high enough to comply with [3] and the other similar standards. Even though analog microphones can be of course employed, a digital solution can greatly reduce the problems connected to this component. The authors decided to use a MEMS component type SPH0644HM4H-1 produced by Knowles, which has a cost of the order of 1$ and can be easily interfaced with a microcontroller [8]. The microphone is omni-directional, has a one-bit Pulse Density Modulation (PDM) output and can easily measure sounds of more than $130\ \mathrm{dB}$. Its power request is lower than $1\ \mathrm{mA}$ and its footprint is limited to $3.5\ \mathrm{mm} \times 2.65\ \mathrm{mm}$.

- The TeensyDuino 3.6 is the core of the system and is a simple off-the-shelf component embedding a $180\ \mathrm{MHz}$ Cortex-M4 CPU with floating point unit and a $1\ \mathrm{MByte}$ flash memory for a cost of the order of 30$ (fig. 3). This component has also the I2S bus which is used to connect to the microphone, a microSD card and the pins which are required to interface the LoRa transmitter. By using this component it is possible to run without problems all the required processing tasks and it is possible to program it by using the free Arduino environment. The current required by this component is only of the order of $70\ \mathrm{mA}$ so that a common lithium battery can be used to power it for a quite long time. The TeensyDuino performs all processing required for the sound measurement, which are shown in fig. 2 and specifically, the initial filtering and decimation to obtain a data stream at $44.1\ \mathrm{kHz}$, the digital filtering to implement the A-weight filter, the sound estimation, the data storage into the flash memory and the LoRa data transmission.
- The LoRa (Long Range) transceiver which enables the communication of the data over a distance of more than one kilometer. Even though several different connection solutions can be employed, such as Bluethooth and WiFi, the LoRa protocol allows transmission of data to a large distance and with a reasonable speed so that it represents a good compromise between cost and transmission range [9], [**?**], [**?**]. The authors employed an RF-LoRa-868-SO (fig. 3), which has a maximum current requirement of $125\ \mathrm{mA}$. In order to reduce as much as possible the current requirement, the LoRa transmitter can be turned off when a transmission is not required so that the current is of the order of $7\ \mathrm{mA}$. The transmitter can be turned on only when a request is received or when an alarm has to be delivered.
- A rechargeable LiPo battery is used to power the entire system. The average current cunsumption of the system is less than $100\ \mathrm{mA}$, thus, by using a $2\ \mathrm{Ah}$ battery whose dimensions are $40\ \mathrm{mm} \times 60\ \mathrm{mm} \times 7\ \mathrm{mm}$, more that 20 hours of continuous operations can be obtained thus insuring even the longest working cycle is covered.
- The alarm LED is turned on when the system detects the noise is too high either because of a strong pulse noise or due to a long time noise which might overcome the threshold limits.

Fig. 3 shows the TeensyDuino 3.6 development board and the LoRa transceiver, along with a marker highlighting the minimal dimension of the used components.

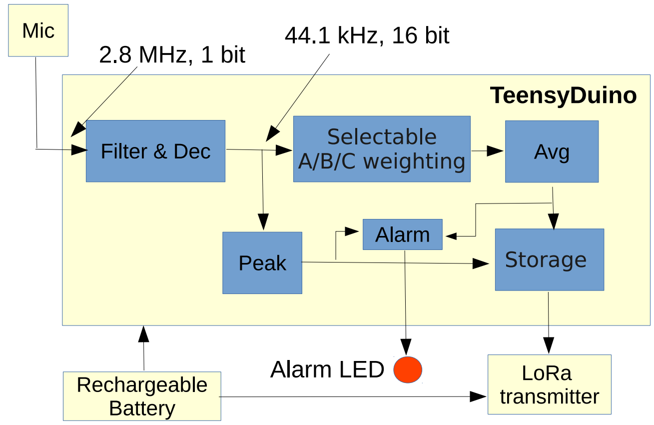

Fig. 2. Block diagram of the proposed system.

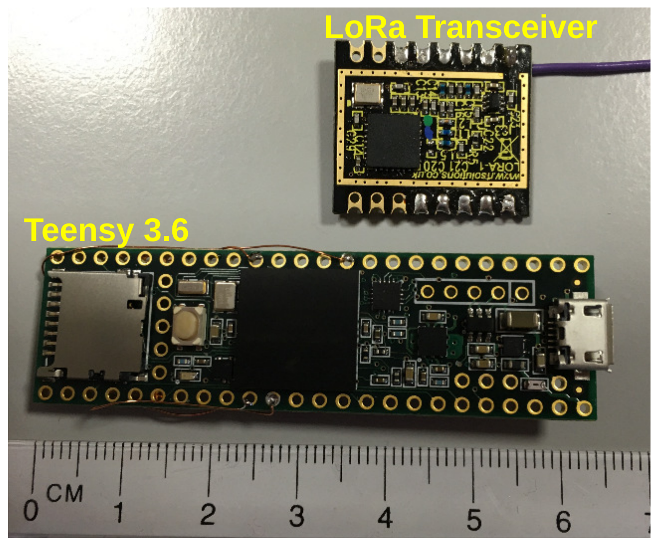

Fig. 3. Teensy 3.6 and LoRa transceiver used for arranging the noise measurement system.

B. Software

The software designed for the noise measurement system is mainly composed of the blocks shown in fig. 2:

1) Filter & Dec: the block acquires the bit stream from the microphone PDM output and converts it to a Pulse Code Modulation (PCM) representation suitable for the subsequent processing. The TeensyAudio library [10] has been rewritten in order to properly setup the microcontroller I2S interface and performing the following operations:

- generating the microphone clock signal at $2.8235\ \mathrm{MHz}$;
- acquiring the PDM bit stream from the microphone output;
- storing the bit stream in a dedicated double buffer using the microcontroller Direct Memory Access (DMA);
- reconstructing the audio from PDM by filtering and decimating the bit stream.

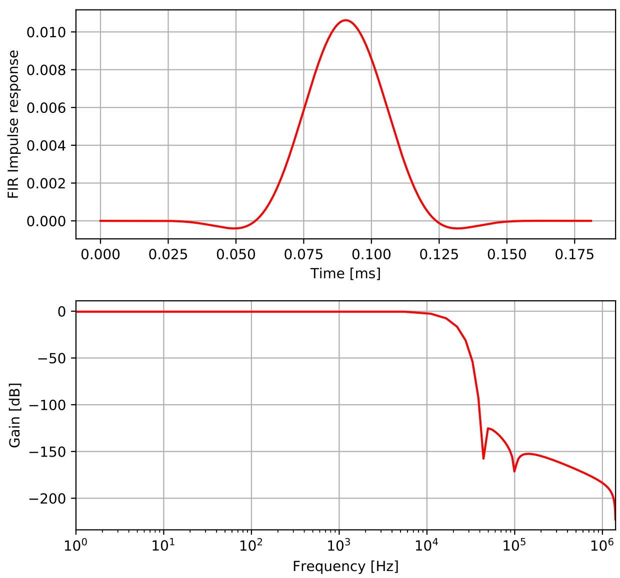

Fig. 4. Impulse and frequency response of the designed 512-taps FIR filter. The filter has a cutoff frequency of about 10 kHz and an attenuation in the stop band of more than 120 dB.

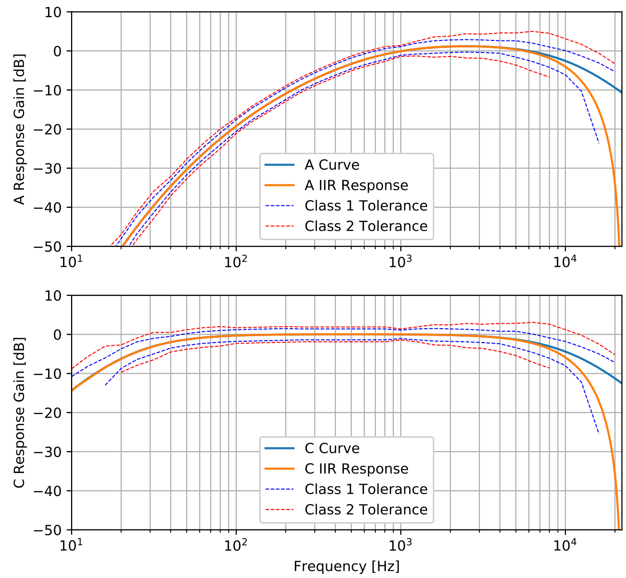

Fig. 5. Frequency responses of the designed IIR filter for A and C weighting compared with the IEC61672-3 specifications: the designed filter complies with the Class 1 tolerance for noise meters.

The bit stream is easily converted to a 32-bit PCM format by processing it with a Finite Impulse Response (FIR) filter and by decimating the output to reduce the equivalent sampling frequency to slightly more than double the maximum expected frequency. By using a decimation factor of 64, i.e. by using one sample every 64, an equivalent sampling frequency of about $44.1\ \mathrm{kHz}$ can be obtained. The selection of a bit rate of $2.8235\ \mathrm{MHz}$ and a decimation factor of 64 allows to achieve a good trade-off between resolution and bandwidth of the PCM stream. The FIR filter can be implemented by using fixed-point mathematics to reduce the required computing power and it is inherently stable. By using a FIR filter with 512 taps, the bandwidth of the microphone output can be trimmed to slightly less than $20\ \mathrm{kHz}$ so that it is possible to avoid any aliasing and, at the same time, the high-frequency noise due to the PDM modulation can be effectively removed. The frequency and impulse response of the designed 512-taps FIR filter is shown in fig. 4. The FIR is efficiently implemented by using a pre-computed look-up-table (LUT) which can be applied to one out of 64 samples (decimation by 64) directly over groups of 8 samples. This way, the number of operation required for processing the audio is dramatically reduced:

- the number of additions is approximately reduced by a factor of 512, passing from $22.5 \cdot 10^6$ additions per second to about $44.1 \cdot 10^3$
- the number of multiplications, instead, passes from $22.5 \cdot 10^6$ multiplications per second to zero - no multiplication is performed.

Thus, less than the 15% of the CPU power is required to obtain the $44.1\ \mathrm{kHz}$ output stream from the $2.8\ \mathrm{MHz}$ PDM stream, being the TeensyDuino clock fixed to $180\ \mathrm{MHz}$.

2) A and C Weighting: the block is implemented by an Infinite Impulse Response (IIR) filter and takes advantage of the Floating Point Unit available inside the Cortex-M4 microcontroller on the TeensyDuino Board. The filter response is selected according to the regulations to fit either the specifications of the A-weighting curve or the C-weighting one. Fig. 5 shows the frequency responses of the designed filter and the allowed tolerance for Class 1 and Class 2 noise meters, as defined in the IEC61672-3. The designed filter complies the most stringent class all over the band for both the weighting curves. The IIR filter for A and C weighting curves is implemented by using respectively a total of 14 and 10 coefficients that are applied to all the stream samples.

3) Peak & Avg: the blocks are very simple and operate on the Root Mean Square (RMS) values calculated on the $44.1\ \mathrm{kHz}$ audio stream. In the case of the peak, the RMS is computed on a time window of $50\ \mathrm{ms}$ and then the maximum over $60\ \mathrm{s}$ is taken as an indicator of the exposure over that minute, while for the average value the RMS value is computed on a time window of about $60\ \mathrm{s}$. The values are then made available to the storage block and to the alarm block.

4) Storage: the block saves Peak and Avg values every minute on the TeensyDuino flash memory so that they are available for subsequent download. Each sample is stored as a floating point value, so 16 bytes are required each minute and a total of about $8\ \mathrm{kbytes}$ is enough for a measuring a one day session.

5) Alarm: the block continuously compares the Peak and Avg values provided by the relative blocks against the limits prescribed by the regulations. If the prescribed exposure limits are reached, the block can generate an alarm on the device

(Alarm LED blinking) and to send a notification to a central surveillance system using the LoRa wireless link.

IV. Calibration

The initial calibration is required to get rid of the uncertainty in the microphone sensitivity and is obtained by using an ND9 calibration device, which is capable of producing a 1 kHz tone with an intensity of 94 dB and 114 dB. The calibrator is a Class 1 IEC914 compliant device and has been calibrated with respect to a standard having an uncertainty of ± 0.5 dB.

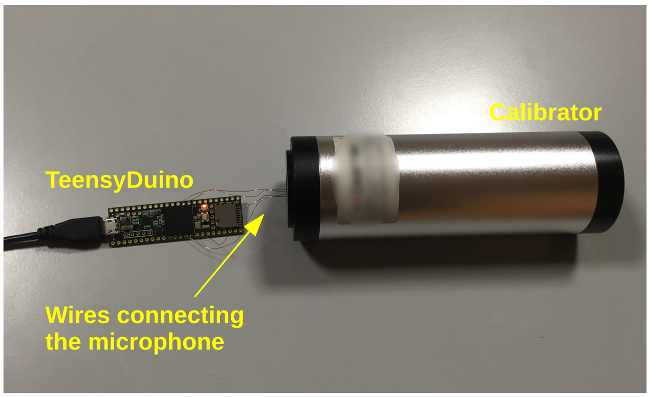

Fig. 6. Calibrator and the modified noise meter.

The calibrator requires positioning the microphone inside a small calibration chamber. Therefore, the microphone has been detached by the measuring system and connected to the TeensyDuino by using four thin copper wires. This allows performing the calibration without problems. The calibration setup is shown in fig. 6, while the acquired signals are shown at bottom of fig. 7.

Fig. 7 shows also the spectrum of the acquired signals during the calibration procedure without the calibration signal, and in the presence of the 94 dB and 114 dB 1 kHz tones. It is easy to observe how the environmental noise is negligible and in average below 20 dB with few spikes reaching 35 dB. The tones, after calibration, are measured as 94.1 dB and 113.9 dB with a deviation of less than 0.2 dB. An Spurious-Free Dynamic Range (SFDR) of 44 dB is obtained for both the calibration measurements.

V. Initial Results

After calibration, the proposed measuring system has been used to monitor the noise level in different environments, both with pulse noise and with continuous noise.

A. Pulse noise

The pulse noise measurement, performed by using the C-type filtering curve, has been carried out in the presence of a noise produced by an hammer hitting an iron element fixed into a wise. The recorded signal in this case appears as a series of pulses repeating approximately every 700 ms, as the work proceeds.

Each stroke is an impulse noise which vanishes in about 200 ms, as shown in fig. 8. This type of signal has a broad spectrum which extends to 10 kHz so that the C-type weighting curve has only a marginal effect.

The noise level is evaluated as explained in section III-B3 by computing the root mean square value over a time window

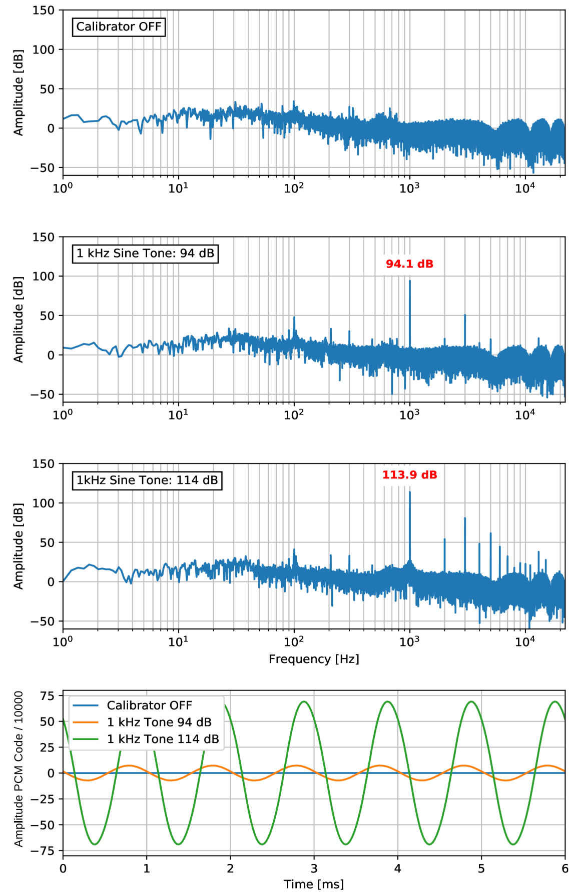

Fig. 7. Signals and their spectra acquired during the calibration after compensation of microphone sensitivity.

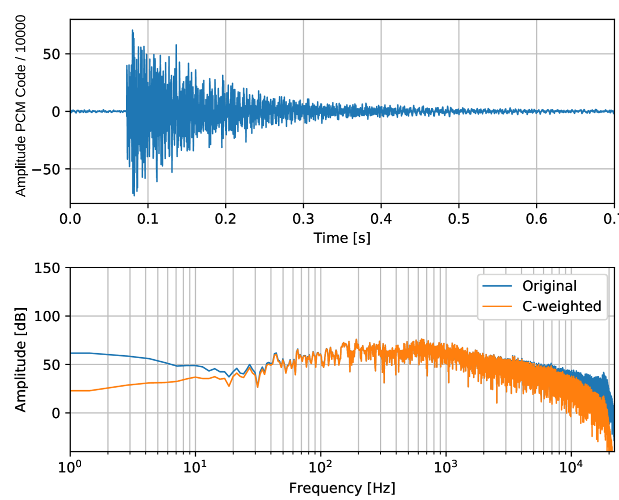

Fig. 8. Expansion of an hammer hit and its spectrum.

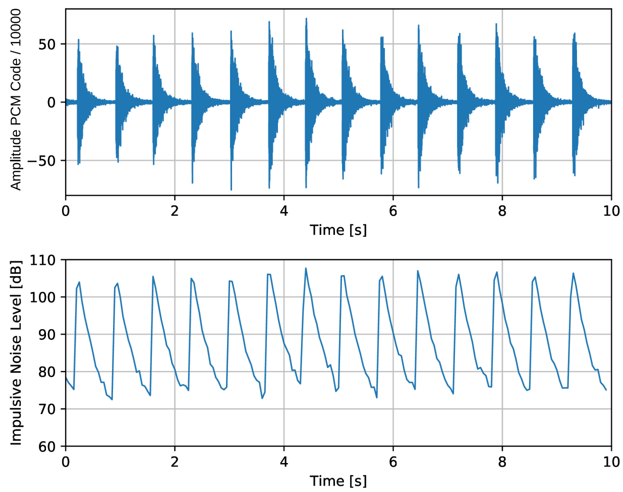

Fig. 9. Example of acquired signal of an hammer hitting an iron element. The hammer hits the iron at intervals of about 700 ms.

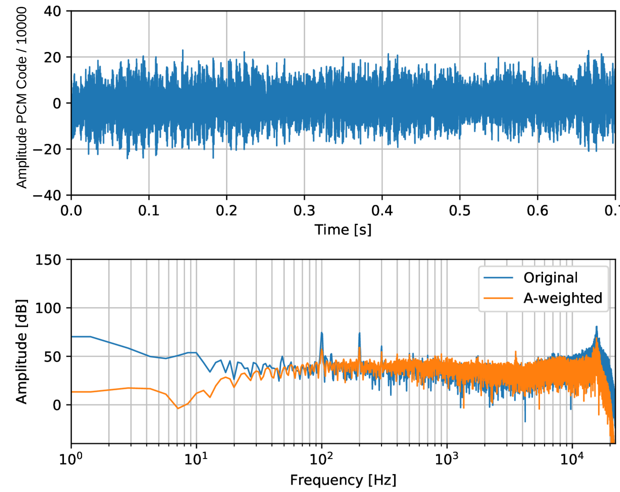

Fig. 10. Example of measurement performed close to a a cleaning machine.

of 50 ms and taking the maximum over one minute. Fig. 9 shows as an example the noise computed over few seconds. The maximum, in this case, is slightly above 105 dB and therefore much lower than the allowed noise threshold.

B. Continued noise exposure

The estimation of the long-term noise the worker is subjected to relies on the A-type weighting curve and on an estimation based on measurements every minute as described in section III-B3. In order to test the proposed measuring system in the presence of continuous noise, a measurement has been performed close to a ultra-sonic cleaning machine working continuously at a distance of about 2 m. Fig. 10 shows an example of data acquired near such a machine. It is easy to observe how the signal amplitude is much lower than in the case of the impulsive noise, with maximum levels below an amplitude PCM Code of 20000 instead of the amplitude of 50000 reached in the case of the hammer. As it is shown in the bottom of fig. 10, the acquired signal has an almost flat spectrum that increases significantly starting from 10 kHz. However, this part of the spectrum is greatly rejected because of the A-weighting curve. The computed average noise level is of about 83 dB, level which exceeds the lower action exposure threshold and requires proper countermeasures to be undertaken.

VI. Conclusions

The described system appears to be a simple and reliable device which can be used by all workers in any environment. The meter insures the worker exposure to noise is continuously monitored avoiding any a-priori estimation which would require a fixed working timing. The system has been calibrated and tested for monitoring the noise in working places both for impulsive noise and long term noise. The proposed solution which has a cost below 100$ appears therefore an interesting addition for the correct way of employing workers. Additional tests are being performed to assess the different exposures of workers according to their position during the work.

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