Development of a high-frequency and ultrasound personal noise exposure meter for identification of sufficient sound rating quantities

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ABSTRACT

Many workplaces are exposed to high-frequency audible noise and/or ultrasonic noise with dominant contributions from frequencies between 10 and 40 kHz.
Apart from hearing loss, that may occur at high daily noise exposure levels, non-auditory health effects can arise at far lower sound pressure levels. Especially effects caused by tonal noise, high-frequency noise and ultrasound are not understood in depth.
Therefore, measurement quantities reflecting the noise exposure and possible non-auditory health effects on workers are also lacking. Such quantities should be easily and reproducibly determined during workplace noise measurements.
To improve this situation, investigations involving comprehensive noise measurements at workplaces combined with questionnaires aiming at capturing mental stress and strain of workers are planned to be carried out. High-precision sound level meters are too heavy to be carried around all day and cannot capture ultrasonic noise. Moreover, common personal noise exposure meters only cover frequencies up to 10 kHz. So, a new measurement device is needed as basis to perform the above-mentioned investigations.
We show first results of the development process of a personal high-frequency and ultrasound noise exposure meter.

INTRODUCTION

The problem of potential negative health effects resulting from the exposure to airborne ultrasonic noise has troubled researchers ever since the first applications of the industrial equipment producing sounds in the high-frequency and ultrasonic range. The investigations conducted in the 1960s suggested no direct link between the industrial ultrasound exposure and auditory or subjective effects [1], [2]. In fact, as the ultrasonic noise emitted by industrial equipment is usually accompanied by a significant content of high-frequency audible sounds, the negative health effects described have been assigned to the latter. However, a follow-up study from 1974 by Acton indicates that ultrasound exposure can indeed have negative influence on human well-being [3]. The early study by Acton also concluded that a lack of temporary threshold shift, following exposure to high-frequency or ultrasonic industrial equipment, is unlikely to cause a permanent threshold shift. As a result, the possible hearing damage due to ultrasound exposure was dismissed at that time [1]. A further study by Grzesik and Pluta, where a new approach for assessment of the hearing threshold level (HTL) between 10 and 20 kHz was applied, showed elevated levels for the operators of industrial ultrasonic welding and cleaning equipment [4]. Until recently, this was one of very few studies, where negative impact of the ultrasound exposure on the HTL was presented. Despite numerous studies performed over the years, it remains unclear whether the negative health effects are caused by ultrasound or the accompanying high-frequency audible sound [5].

Occupational Sound Measurements

Measurement strategies of exposure to audible sound in a workplace are well-defined and regulated by the ISO 9612:2009 standard [6] which in many countries is mirrored to national standards or even included in national occupational safety and health (OSH) regulations. In ISO 9612:2009 it is specified that measurements can be performed with either a hand-held sound level meter or a personal sound exposimeter, whose specifications are defined in IEC 61672-1:2013 and IEC 61252:1993, respectively [7], [8]. However, with an increasing number of ultrasonic appliances - washers, welders, drills, soldering guns, cutting machines - being used in industry, a more standardized, and internationally recognized, approach is also needed for the determination of ultrasound exposure in a workplace [9], [10]. Currently, industrial ultrasound exposure can be determined using sound level meters – or frequency analyzers – meeting the requirements of Class-1 devices specified in IEC 61672-1:2013, and microphones adhering to the specifications listed in IEC 61094-4:1995 [7], [11]. Frequency range of both must cover the frequencies to be measured, but should at least include the 40 kHz third-octave band. Furthermore, due to the requirements of governmental occupational health monitoring regulations, such devices are subject to periodic conformance tests in accredited approval centers. Further national regulations or guidelines may exist that state guideline or threshold values for different types of measurement quantities. Some of them are listed in [12]. If national guideline or threshold values exist, they typically cover frequencies up to 40 kHz TOB. As IEC 61672-1:2013 and IEC 61252:1993 cover only frequencies up to 20 kHz complementary requirements accounting for the performance of measurement devices at higher frequencies need to be specified.

Issues Related to Airborne Ultrasound Measurements

Over the years, there have been numerous studies extensively analyzing issues related to industrial ultrasound measurements. The list includes, but is not limited to, matters such as varying definition of ultrasound between countries, lack of clearly defined measurement methods and equipment, and no clear information in literature on the ultrasonic noise uncertainty budget [13], [14]. Despite the issues surrounding ultrasound measurement methodology, there is a number of health issues associated with industrial ultrasound exposure. These effects can be divided into four groups: subjective symptoms of exposure to ultrasonic noise, impact on hearing, thermal effects, and functional changes [15]. Subjective symptoms, such as headaches, migraines, nausea and fatigue, have been consistently reported by operators of ultrasonic machines [16], [17]. The aforementioned problem of ultrasonic noise being often accompanied by a high level of audible high-frequency noise makes it difficult to unquestionably judge the origins of the symptoms. However, an increasing number of studies dealing exclusively with ultrasonic noise suggest a direct link between those symptoms and ultrasound exposure [15], [18]. In a similar way, new studies begin to appear supporting the study by Grzesik and Pluta, where prolonged exposure to ultrasound noise is also linked to the hearing threshold shift [17], [19]. Other studies indicate that ultrasonic noise exposure may lead to increased body temperature, as well as functional changes (irritation, memory problems, concentration and learning difficulties) [15]. Furthermore, recent findings suggest that ultrasound fields can be highly inhomogeneous. Thus, ultrasonic noise exposure may vary due to different individual physiology [20], [21].

Personal Ultrasound Exposimeter

As the ultrasound fields can be highly inhomogeneous, it is of vital importance to reliably estimate one's ultrasound exposure at their individual workplace. In order to fully characterize ultrasonic field at one's workplace a hand-held sound level meter covering the required frequency range could be deployed. However, an accurate estimation of worker's exposure to ultrasonic noise, accounting for their mobility, would not be practicable due to portability issues of the device. A recent study by Schöneweiß et al. not only describes the measurement method and the technical requirements for the ultrasound measuring equipment, but also presents a practical study of welding machine characterization [21]. This study is accompanied by practical investigations of Ullisch-Nelken et al. showing reproducible measurement results for this measurement method [20]. Based on this work an ultrasound level meter (USPM - from German Ultraschall-Pegelmesssystem), which conforms with the Class-1 requirements of IEC 61672-1:2013, was developed at the Physikalisch-Technische Bundesanstalt (PTB) [7], [22]. It is therefore evident that an accurate estimation of worker's exposure to industrial airborne ultrasound can only be performed with a hand-held device (in contrast to a stationary device), in the case when worker's workplace is stationary. In other cases, a personal sound exposimeter is required. These devices can normally be worn throughout the day taking into account worker's mobility. However, the normative demands for such devices are currently limited to 8 kHz, with recommendations up to 12.5 kHz [8].

In this work the first prototype of a High-Frequency and Ultrasound Personal Exposimeter (HiFUSPEx) and some currently available results of initial testing are described. More detailed information on the technical specifications of the device and the testing procedure is provided in [23]. This is followed by a section covering discussion and conclusions of these results, as well as a comprehensive outlook.

A PROTOTYPE OF A HIGH-FREQUENCY AND ULTRASOUND PERSONAL EXPOSIMETER – HIFUSPEX

General technical built

The block diagram of HiFUSPEx is presented in Fig. 1, which comprises a free-field microphone set (consisting of a free-field microphone and a matching preamplifier), a signal conditioning stage (consisting of a conditioning module and an analog signal conditioning circuit), an analog to digital converter (ADC), and a digital signal processing unit. At the final stage the signal is digitally filtered for the required frequency range and the time and frequency weightings are applied for the specific value to be measured. These are subsequently shown on a digital display in real time. The acousto-electric conversion is performed through GRAS 46BE 1/4" Constant Current Power (CCP) Free-field Standard Microphone Set, consisting of GRAS 40BE 1/4" Prepolarized Free-Field Microphone and GRAS 26CB 1/4" CCP Standard Preamplifier [24]. GRAS 46BE 1/4" microphone cartridge is regarded as suitable for measuring ultrasonic noise, since it fulfills the technical requirements specified for the ultrasound measurements [20]. At the same time, it is a small (length: 53 mm) and low-weight (8 g) device, which makes it well-suited for portable applications. The microphone set is powered by M29 Conditioning Module from METRA, whose small dimensions enable it to be easily packaged in the prototype's housing [25]. Moreover, METRA M29 can be easily powered from a regulated 5V supply. The microphone set and the conditioning module are connected via customized microdot-LEMO cable.
The ADC is the core element of the electrical processing part whose characteristics, such as sampling rate and resolution, define the frequency range and the dynamic range of the complete device, respectively. Therefore, an ADC from Texas Instruments (TI) - ADS127L01

with a sampling rate set to 256 kSPS and 24-bit resolution was chosen [18], [26]. For the purposes of digital signal processing Teensy 4.0 development platform was chosen. It can operate at speeds up to 600 MHz and is specifically tailored for real-time application. It also boasts 1 MB of onchip RAM, providing a sufficient space for audio buffering requirements. The incoming digitized data in collected into blocks. All further processing, including compensation functions, calibration, time and frequency weighting, is performed on these blocks. Octave and Third-Octave band filtering is available. The processed data can be stored on a microSD card. Also raw data can be recorded. The system is also equipped with an XBee-S2C wireless communication module for remote live-monitoring of the HiFUSPEx, as well as with temperature, pressure and humidity sensors for internal conditions monitoring. The prototype is powered from a rechargeable 2-cell Lithium-Ion battery (7.4 V, 3450 mA). With the average power consumption of 1 W, the capacity of the battery is sufficient for the all-day measurements (8 hours).

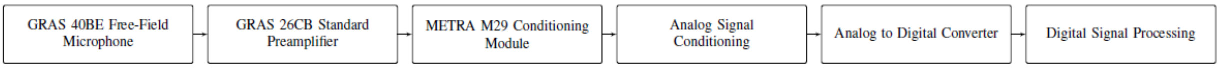

Figure 1: Block diagram of the prototype of HiFUSPEx.

Accompanying computer application

To ensure a comfortable way of communication between the device and its users, a self-contained graphical user interface will be developed. Fundamental requirements cover an ergonomic graphical surface, corded and wireless connectivity as well as a download possibility for measurement data. Further vital features comprise the possibility of composing measurement setups and sending it to the device, graphic representation and post-processing of measured data and remote live-monitoring of measurement data during workplace measurements.

Initial testing

In order to test the ultrasound detection capabilities of the HiFUSPEx prototype, a simple experimental set-up was built within a scanning unit, with an integrated free-field environment, at the PTB in Braunschweig, Germany. Therein, a scanning rod is available, where a microphone can be mounted and navigated in a three-dimensional coordinate system. In this simple case, two different 1/4” microphones were attached in turn to the rod in order to measure the high-frequency and ultrasonic field produced by ScanSpeak D2104/712000 loudspeaker. The USPM was connected to Brüel & Kjaer type 4939 1/4” freefield microphone, together with GRAS 26AC 1/4” Standard Preamplifier [25], [26]. Both microphones were acoustically calibrated in accordance with the national standard at the PTB. The ScanSpeak D2104/712000 ultrasound loudspeaker was placed inside the free-field environment of the scanning unit. The height of the rod over the loudspeaker was navigated in such way, that the distance between the center of the loudspeaker and the tip of the microphone was equal to 1 m. The open panel of the scanning unit was then closed, and the test signals were fed through the loudspeaker.

In order to analyze the acoustical response of the prototype to the ultrasonic noise, which can be commonly encountered in an industrial environment, the signal spectrum was limited to 5-45 kHz. So far, two different signal types, a sinusoidal sweep and a multisine signal were fed through the loudspeaker. In both cases data were in turn recorded with the USPM and HiFUSPEx.

Results

Based on the existing literature, most of the industrial ultrasonic equipment produce airborne noise with frequencies up to 40 kHz. Therefore, in each experimental scenario the output of third-octave band filters covering the range between 5 - 40 kHz was observed. For each of the two signals fed through the signal generation chain, the data were recorded for the period of 5 minutes on both devices. The signal was generated in this way to correspond to the noise often observed around industrial ultrasonic welding equipment. The data collected using both devices were compiled together into a bar plot. Fig. 2 shows the results for the multisine signal.

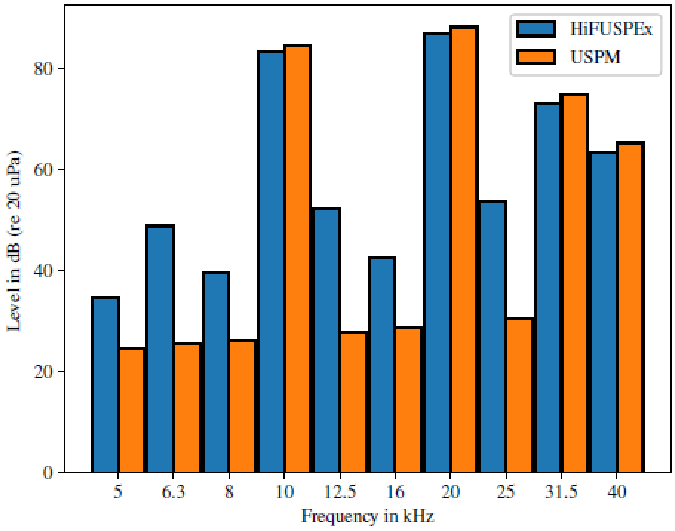

Figure 2: Comparison of the Z-weighted equivalent (averaged over 5 minutes) third-octave fraction levels with both devices exposed to the sound field produced by the multisine signal fed through the generation chain.

CONCLUSIONS AND OUTLOOK

In this article, HiFUSPEx prototype is presented. Introduction presents the reader with a review of the current limitations related to measurement of airborne ultrasound exposure in a workplace. It is followed by a brief description of the first prototype of a portable ultrasound level meter - HiFUSPEx. Following that, first results of the performed experiments are presented, showing a good potential of the device, whose sound measurement performance can be deemed comparable with Class-1 device according to IEC 61672-1:2013, as long as the measured sound level is above the noise floor level of the prototype [7]. Nonetheless, further experiments are required in order to fully characterize the high-frequency and ultrasonic noise detection capabilities of HiFUSPEx. Therefore, a set of further long-time experiments has been designed and is currently performed within the scanning unit at the PTB, where additional industrial scenarios are simulated and tested.
Moreover, a number of devices has also been handed out to experienced technical staff who performs field measurements with similar devices on a regular basis. In this way, not only an insight into the prototype's measurement performance, but also into its wearability and user-friendliness will be gained. These pre-tests will be rounded off by a comprehensive field measurement campaign where the HiFUSPEx is deployed under realistic conditions at industrial workplaces for regular OSH measurements.

With a well-tested measurement device and method available, combined systematic investigations of the individual noise exposure together with mental stress and strain as well as non-auditory health effects become possible.
A comparable national project investigating the relationship of noise, room acoustics and mental stress at workplaces of the textile and food retail trade has already been carried out successfully [27]. In this study, the survey of employees employing validated tests turned out to be a very effective objective measure for assessing the mental stress. It could be shown that the mental strain does not only depend on the individual's noise sensitivity but also upon the form of noise nuisance. We expect a comparable investigation with focus on ultrasonic sounds to be similarly successful.

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