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Ears II - Development of an ultrasound measurement technique for use in occupational safety

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ABSTRACT

During the past several years ultrasound has gained importance in the field of occupational safety, since the dissemination of ultrasound technology in industrial applications has increased.

While several studies on airborne ultrasound and its effects on human health exist, no major research has been carried out in this area approximately since the seventies of the last century. Thus, airborne ultrasound still poses a potential risk to employees and the general population alike. To address this problem, among others, the EU-project “Ears II” was initiated.

For occupational safety, measuring airborne ultrasound in situ is vital. However, current measurement techniques apply to measuring audible sound only and do not cover ultrasound for several reasons. The ultrasound fields emitted by today’s industrial appliances are mostly unknown and likely to be complex. Additionally, no weighting for a comparable assessment of the exposure to ultrasonic noise is defined. We iteratively develop a measurement procedure by evaluating current laboratory and conventional in situ techniques as well as existing data and by performing in situ measurements.

We will present the current progress of the development and discuss possible caveats.

INTRODUCTION

Protecting workers from different risks that may occur at their workplaces is the task of occupational safety and health. One of the most important and challenging tasks within this field is the protection of a person’s ability to hear, since once it is damaged, it cannot be restored. On the other hand, if a person has already suffered a hearing loss, they might be entitled for compensation of some kind. Thus, to check the legitimacy of such claims is another important task.

However, the first step always is the assessment of the worker’s exposure to noise at their workplace. The assessment usually consists of an analysis of the workplace, measurements at the workplace and a detailed evaluation. The analysis covers different issues, e.g. if tasks have to be carried out regularly, how much time is spent on each task, if there are differences between workdays. Based on the result of the analysis, measurements are carried out and are then evaluated.

Depending on the result of the evaluation protective measures might have to be taken, such as ordering or recommending the use of hearing protection at the workplace. While overprotection possibly introduces new risks - the person might for example no longer hear alarm signals - and leads to isolation, which decreases the acceptance of hearing protection, a lack of protection in a noisy environment threatens the health of the employee.

For audible sound, i.e. sound in the frequency range between 16 Hz and 16 kHz (as defined in TRLV "Lärm" [1]), the dose-effect relation is well known [2]. As a result, audible sound is covered in national regulation and international and national standards. Valid and tested methods for measurement and evaluation of exposure to noise in the audible frequency range exist [3].

This is not true for ultrasound, i.e. sound with frequencies above 16 kHz. Although the use of ultrasonic technologies in general and especially in the industry has increased over the past decades, no valid dose-effect relation or measurement methods were developed [4]. Thus, ultrasound possibly poses a risk to workers and public alike.

To overcome this highly undesirable state, the EU-project "Ears II" [5] was initiated. The aim of this project is, amongst others, to contribute to the understanding of the effects and perception mechanisms of sound outside the audible frequency range. Additionally, a method for measuring and evaluating ultrasound in the context of occupational safety and health is to be developed, which will be covered in this paper.

BACKGROUND

Like conventional workplaces, workplaces at ultrasonic machines are diverse. There are, for example, welding machines, cleaning vessels and cutting machines, which vary in size and working frequency, i.e. the frequency which is used to achieve the desired effect. One of the major problems is that such machines usually use high power and thus emit ultrasound at high levels.

Special properties of airborne ultrasound fields

In an experiment by Walther and Kling [6], the ultrasound field of a ribbon tweeter was successfully recorded with a high spatial resolution (cf. Figure 1). This approach will also be used in the course of this project to determine the ultrasound field of industrial ultrasound appliances. As can be clearly observed from the results by Walther and Kling, ultrasound fields are complex. This complexity increases with increasing frequency. Additionally, ultrasound, in contrast to audible sound, might be reflected of the workers head and is also easily shielded or refracted. This fact makes measuring ultrasound and assessing the noise exposure correctly a challenging task.

Definition of frequency ranges

Frequency ranges are not uniformly defined. VDI 3766 [7] and IEC 61672-1 [8] for example define audible sound as sound in the frequency range between 16 Hz and 16 kHz. This is in accordance with the German regulation TRLV "Lärm" [1]. Other definitions, however, extend this range up to 20 kHz. As a result, there is no uniform definition of ultrasound.

Frequency weightings

Frequency weightings were developed to accommodate for the differences in perception of sound on humans. The C-weighting for example represents the perception of sound at high levels, whereas the A-weighting resembles the perception of audible sound in general. The Z-weighting essentially applies no weighting at all. All weightings include definitions of maximum and minimum deviation from the real value of the sound pressure level at a given one-third octave [8].

Further frequency weightings exist. However, no weighting for assessing noise produced by ultrasonic devices has been introduced into standardisation, since the AU-weighting defined in IEC 61012 [9] only accounts for audible sound in the presence of ultrasound. The only candidate of such a weighting is the ULTRA weighting by Brüel & Kjær (B&K), which was present in the filter set 1627. This weighting is a high-pass filter with a cut-off frequency of 12.5 kHz.

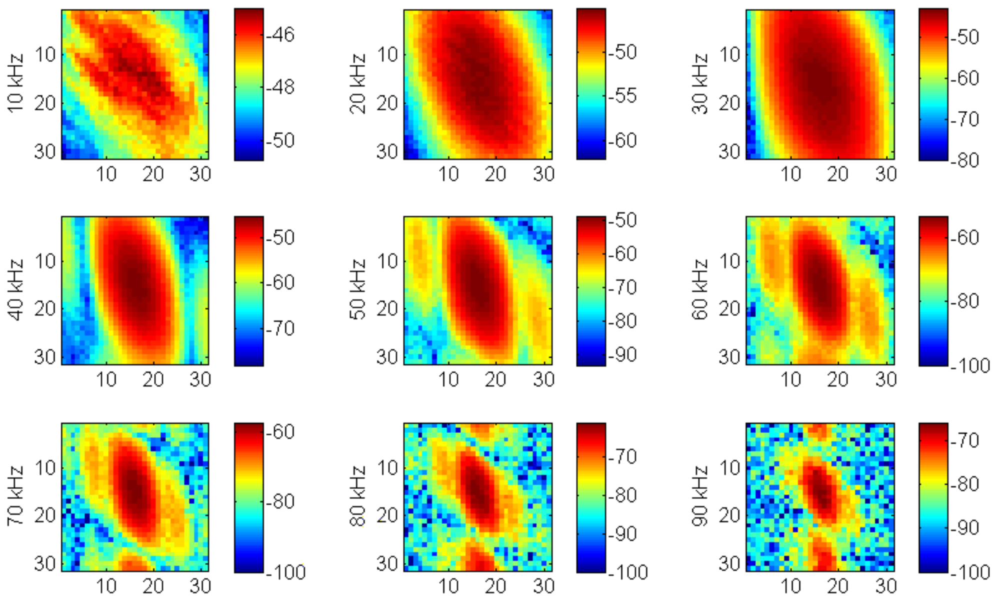

Figure 1: Ultrasound field of a ribbon tweeter as measured by Walther and Kling (cf. [6], fig. 7). An increase in complexity with increasing frequency can clearly be observed. Axes in cm.

Measurement devices

Currently measurement devices capable of measuring ultrasound are rare and only a few manufacturers offer them mainly for laboratory use. This has just recently begun to change slowly. Although, some of those devices are suitable for field use already, the usability is far from final. Those devices mostly consist of a laptop and further parts which are connected by wires. This introduces problems with, for example, electro-magnetic coupling in the presence of industrial appliances, because those devices are not covered by IEC 61672-1 [8] and the connection wires can easily and unintentionally function as antennae for electro-magnetic fields.

STANDARDS AND REGULATION

To reach the project's goal of developing a measurement strategy for airborne ultrasound, current measurement strategies and workplaces were to be evaluated. In order to define a reference workplace for laboratory measurement purposes, that is representative for a variety of workplaces, the current situation at ultrasound related workplaces has to be examined. To avoid redundant efforts and in order to know which standard may be extended to fit the project goal, a review of current measurement standards was carried out.

Standards

Several international and national standards deal with the measurement of audible sound. DIN EN ISO 9612 [3], VDI 3766 [7] and DIN 45645-2 [10] (for sound pressure levels below the risk of hearing damage) define measurement methods, while IEC 61672-1 [8], IEC 61012 [9] and DIN 45657 [11] describe requirements for the design of sound level meters. Finally limits and guidance levels for ultrasound exposure are defined e.g. in VDI 2058-2 [12], [13] and VDI 3766 [7] respectively.

Requirements concerning sound level meters

The main standard concerning the design of sound level meters is IEC 61672-1. Essentially, it includes three frequency weightings A, C and Z and time weightings F and S. Sound level meters designed in accordance with this standard may be used for measuring sound in the frequency range perceptible by humans. However, IEC 61012 is referenced, which may be used for signals that contain frequencies above 20 kHz. IEC 61012 describes the U-weighting and the combined AU-weighting for assessment of noise in the presence of ultrasound. DIN 45657 is a German national standard which requires the AU-weighting to be present in sound level meters for measuring audible sound in the presence of ultrasound. The tolerances for deviation between the displayed and the real value range between +3 dB and -∞ dB for the 20 kHz one-third octave. For information on any of the weightings mentioned above, the reader is referred to the corresponding standard that contains its definition.

Measurement methods

DIN EN ISO 9612 is explicitly not to be used for measurements in the presence of ultrasound. The same is true for DIN 45645-2. Therefore, they do not account for special properties of ultrasound fields in terms of e.g. spatial variability.

VDI 3766 refers to DIN EN ISO 9612 for the basic measurement procedure, but makes modifications to account for special properties of ultrasound. Due to the wide thresholds specified in IEC 61672-1 and IEC 61012, VDI 3766 requires to use class 1 sound level meters only. These should additionally include all one-third octave bands at least up to the 40 kHz one-third octave. Also, in addition to the working frequency, harmonics and sub-harmonics of the working frequency should be included in the range of the device.

Furthermore, VDI 3766 makes requirements concerning measurement sites. While generally following DIN EN ISO 9612 regarding stationary and personal measurements, stationary measurements are required to be carried out for a representative amount of possible head positions. Additionally, a control measurement in presence of the employee is required for the position with maximum exposure and for the position which is occupied by the employee for more than 50 % of the measurement duration, to avoid significant changes in the results. Also following DIN EN ISO 9612, a personal measurement strategy is defined, which allows for measurements directly at the employees ear. However, VDI 3766 explicitly allows coming below the minimal measurement distance of 0.1 m defined in DIN EN ISO 9612, to account for the problems introduced by the presence of ultrasound.

The mandatory measurement quantities as described in VDI 3766 are AU-weighted noise exposure level, Z-weighted peak sound pressure level, Z-weighted noise exposure one-third octave band sound pressure level and Z-weighted maximum 5 minute one-third octave band sound pressure level. Optionally a narrow-band spectrum may be recorded. The frequency range of audible sound is defined by VDI 3766 and TRLV “Lärm” and ranges from 16 Hz to 16 kHz.

Guidance levels and limits

Guideline values and limits are described in VDI 3766 and VDI 2058-2. In VDI 3766 it is recommended that the AU-weighted noise exposure level should not exceed 85 dB and the

Z-weighted peak sound pressure level should not exceed 140 dB. Following the now obsolete VDI 2058-2:1988-06 a value of 110 dB Z-weighted one-third octave band energy-equivalent sound pressure level should not be exceeded for the 20 kHz one-third octave. In the recently published version of VDI 2058-2 the guidance values of VDI 3766 are referenced. The 110 dB threshold for the 20 kHz one-third octave is still included and was extended for preventive measures, so that it is now also valid for all one-third octave bands up to 40 kHz. Additionally, a threshold of 90 dB is defined for the 16 kHz one-third octave.

Workplaces

Ultrasound is used in a wide variety of applications ranging from medical devices over industrial applications to pest repellents. In the following only industrial workplaces are considered. In a non-representative survey of workplaces the BG ETEM (German Social Accident Insurance Institution for the energy, textile, electrical and media products sectors) and the IFA ("Institute for Occupational Safety and Health of the German Social Accident Insurance") encountered devices with working frequencies between 20 kHz and 40 kHz. Data from routine measurements were used for this purpose. Industrial devices cover a variety of applications. The three most frequent machine categories were welding machines, cleaning vessels and cutting machines (food and non-food). With machine category the enclosure type varied greatly, ranging from fully enclosed to partly enclosed machines and those with hardly any enclosure. At some machines the housing was removed e.g. to increase productivity.

Discussion

The main standards for the design of sound level meters (IEC 61672-1) and for measurement of noise at workplaces (DIN EN ISO 9612) contain restrictions on the frequency range to which they apply, explicitly excluding ultrasound. To account for the presence of ultrasound when measuring audible sound additional standards exist, which include measurement procedures and requirements for measurement devices.

VDI 3766, for example, describes methods for measuring audible sound in the presence of ultrasound at workplaces. It accounts for properties of sound fields in the frequency range above 16 kHz, i.e. the potentially complex structure and great spatial variability. However, it contains no strategy for explicitly measuring the ultrasound part of a signal but focuses on audible sound in the presence of ultrasound. This is also true for IEC 61012, which contains the definition of filters excluding ultrasound above 16 kHz.

Guidance levels and limits for ultrasound exposure are formulated in VDI 3766 and VDI 2058-2 respectively. These values were set to avoid damage to the ear in the audible frequency range. However, the limits expressed in VDI 3766 mainly focus on damage from sub-harmonics (AU-weighted noise exposure level). The Z-weighted peak sound pressure level contains no information on the energy contained in a signal. The limit of 110 dB Z-weighted one-third octave band sound pressure level, mentioned in VDI 2058-2:1988-06, results from old data. Additionally, current studies on the impact of ultrasound on human health are lacking [4]. The problems concerning guidance levels and exposure limits will not be discussed any further, since they are subject of investigation in other parts of the project.

Nevertheless, a valid mechanism of determining the exposure to ultrasonic noise at the work place is vital. Therefore, Kusserow [14] proposes the use of $L_{ULTRAeq}$ to assess just the ultrasonic component of noise. Once the dose-effect relation has been investigated, this could be used to define guidance values or exposure limits. Kusserow suggests a single-value threshold of 110 dB $L_{ULTRAeq}$ for this purpose.

Following the German "LärmVibrationsArbSchV" [15] no risk assessment for ultrasound workplaces has to be carried out if no significant audible sound is produced. Therefore, IFA and BG ETEM are charged with measurements by the respective employer only if there are any complaints or concerns regarding a specific machine. Thus, measurements of IFA and BG ETEM are potentially biased towards machines at which problems occurred. No reliable information on the abundance of ultrasound machines can be taken from these data.

MEASUREMENTS AT WORKPLACES

For the development of a novel measurement method, a reference workplace is essential. At this reference workplace, the method can be developed and tested under controlled parameters, thus measurements are reproducible. Therefore, reference conditions, such as machine category, working frequency etc., for such a workplace have to be determined. To achieve this, data of existing measurements and current measurement techniques have to be evaluated in terms of abundance of different machine categories and working frequencies, levels and other criteria. The results of this analysis will be used to identify possible candidates for machines at the reference workplace.

Data acquisition and composition

Data on ultrasound noise exposure were collected by members of IFA and BG ETEM [14] over the past several years. The anonymised data of each institution were compiled into one global dataset for this study. The individual datasets were acquired on a per workplace basis, i.e. some individual machines occur more often than others in this study, because they are surrounded by a greater number of workplaces. All datasets at least contain information on machine category, machine type (e.g. manufacturer), working frequency and measurement device. The IFA used different measurement devices for data acquisition, thus different measurement quantities were acquired in each measurement. BG ETEM used only one device capable of capturing ultrasound up to 96 kHz. Therefore, each measurement contains the same set of measurement quantities.

The global dataset contains the information mentioned above plus a subset of $\mathbf{L_{A,eq}}$, $\mathbf{L_{AU,eq}}$, $\mathbf{L_{ULTRAeq}}$ ($\mathbf{L_{US1}}$), $\mathbf{L_{Z,peak}}$, $\mathbf{L_{A,eq}}$, $\mathbf{L_{EX,AU,8h}}$, $\mathbf{L_{pZ,1/3octave,20kHz}}$, $\mathbf{L_{pZ,1/3octave,20kHz,5min}}$. Additional information on presence of a machine enclosure and (sub-)harmonics is included.

Processing of data

The data were compiled into one excel document and evaluated using Python and the Pandas package. Using Pandas, the global data were grouped by machine category and working frequency, resulting in data subsets. It was checked whether they contain 10 or more data sets (n > 10). Subsets with n < 10 were not used for statistical analysis. Thereafter, another criterion was applied to the respective data subset, which checked for the availability of 10 or more data per measurement quantity.

Table 1: Statistical analysis of weighted sound pressure levels for ultrasound welding machines with a working frequency of 20 kHz; levels in dB.

	L_AUeq	L_ULTRAeq	L_Zpeak	L_Zeq,20kHz,5min	L_EXAU,8h	L_Z,20kHz	L_Aeq
count	53,0	63,0	53,0	36,0	23,0	36,0	36,0
mean	83,6	103,3	128,3	104,0	80,8	103,1	96,6
std	8,4	11,5	9,9	10,6	8,9	10,8	10,0
min	70,6	69,3	105,0	76,2	65,0	75,4	74,6
25%	77,1	96,3	122,0	99,9	72,5	98,7	91,7
50%	81,3	106,1	131,0	105,1	85,0	104,5	97,4
75%	90,3	111,3	134,9	113,1	86,0	112,7	105,3
max	111,4	118,0	144,8	117,1	99,0	116,0	111,0

Results

Only one subset, ultrasound welding machines with a working frequency of 20 kHz, fulfilled both criteria and was analysed. The global dataset also contained cutting machines, cleaning vessels and welding machines at different working frequencies, most of which did not fulfil the first criterion of n > 10 for a subset (machine category, working frequency). The amount of measured data varies per measurement quantity which can clearly be observed from Table 1, with 63 values for $L_{ULTRAeq}$ and 23 values for $L_{EXAU,8h}$.

The most relevant quantities are highlighted in Table 1. For the AU-weighted noise exposure level and Z-weighted peak sound pressure level, guidance levels are given in VDI 3677. The corresponding values are 85 dB and 140 dB respectively. For $L_{pZ\ one\text{-}third\ octave,20\ kHz}$ a guidance level of 110 dB is given in VDI 2058-2:1988-06. The guidance value of L_{pZpeak} is not exceeded by the 75 % quantile. The $L_{pZ,1/3\ octave,20\ kHz}$ limit on the other hand is exceeded by the 75 % quantile. The guidance level of $L_{EXAU,8h}$ is reached exactly by the median value (cf. Figure 2).

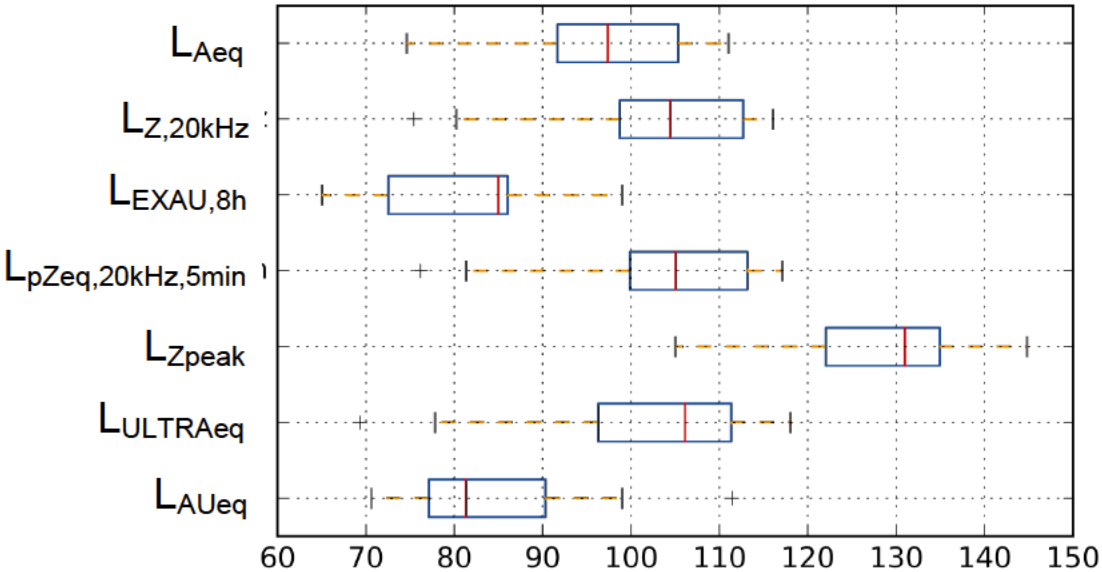

Figure 2: Graphical representation of the statistical analysis shown in Table 1.

Discussion

The results may seem satisfying at first glance, because only 25 % of the machines exceed the guidance levels of the Z-weighted peak sound pressure level and the Z-weighted 20 kHz one-third octave sound pressure level. Nevertheless, the transgression of the guidance level for the $L_{EXAU,8h}$ is troubling, since it resembles the $L_{EX,8h}$ (A-weighted noise exposure level) in the presence of ultrasound. Overstepping this guidance value over a long period of time will most likely lead to a noise-induced hearing loss. However, only 23 values were measured for this parameter.

The ultrasound part of the sound is represented best in the data subset of $L_{ULTRAeq}$ with 63 measurements. The limit of 110 dB $L_{ULTRAeq}$, recommended by Kusserow [14], is exceeded at some workplaces. Due to missing specifications in terms of precision of measurement devices above 20 kHz in IEC 61672-1 and the unsatisfying allowed uncertainty of +3 dB and -∞ dB at 20 kHz, the measurements are possibly biased. On the other hand, the required frequency range and corresponding tolerances are extended by VDI 3766.

The data seem to imply that ultrasound welding machines with a working frequency of 20 kHz are more frequent than any other machine category. Since no risk assessment for ultrasound workplaces has to be carried out if no significant audible sound is produced, IFA and

BG ETEM are charged with measurements by the respective employer only if there are any complaints or concerns regarding a specific machine. Thus, measurements of IFA and BG ETEM are potentially biased towards machines at which problems occurred. Nevertheless, it is possible that a machine produces no significant (sub-)harmonics but produces high levels of ultrasound [14].

To account for a possible bias towards a certain machine category, data on machine distribution and frequency should be collected. For use in a reference workplace as part of the "Ears II" project a specimen of the most common machine category should be used. This data would also be valuable for identification of possibly hazardous machine categories. The bias from the workplace based approach should not be eliminated in future measurements, as it represents the existing conditions at workplaces best. Additionally, a more consistent form of data acquisition in terms of recorded parameters must be demanded for future measurements. For example, the data provided by BG ETEM contain nearly all parameters considered valuable at the moment, except $L_{EXAU,8h}$, as well as a variety of additional information.

REFERENCE WORKPLACE

After the preparatory tasks were completed, the reference workplace could be specified and built. At the PTB ("Physikalisch-Technische Bundesanstalt"; National Metrology Institute of Germany) measurements will be carried out in a scanner, which can be used to characterize sound fields with high spatial resolution. At the IFA, a semi-anechoic room will be used for measurements with a measurement setup to allow for data exchange with the PTB and to enable comparative measurements. Therefore, the measurement of the microphone and machine position in the two laboratories had to be synchronized.

Scanner

Since it is undesirable for practical use of a measurement technique to have a high number of measurement points, the reduction of measurement positions is a key goal. However, the (random) reduction of measurement positions most certainly leads to an erroneous determination of the noise exposure, since ultrasound fields tend to be complex. Thus, the ultrasound field has to be well known to select the points or areas which significantly contribute to the noise.

Platform

At the PTB a 3-axis scanner is already in use, to measure the respective position. At the IFA, however, no such device was present and a reference environment had to be developed. The challenge within this task was not to introduce reflective surfaces or any other obstacles into the sound field, because this would most likely lead to changes in the sound field and thus yield unrepresentative und unreliable results. Since the IFA pursues a practically oriented approach a simple method had to be found.

Finally, after a short development process, a system consisting of two line lasers and a platform with a grid (cf. Figure 3) was chosen. The platform has a total size of 3 m x 3 m and is made of 4 equally sized square elements with an edge length of 1.5 m. The plates are laser engraved with a 2 cm square grid and mounted onto torsion-resistant profiles. Those profiles are equipped with height-adjustable feet and thus allow for levelling the entire platform. Additionally, one of the feet of each element is fixed in a rail which is embedded in the floor.

The platform provides a 2-d plane in which the coordinates of e.g. a tripod can be determined easily. However, the microphone is usually positioned above ground level at the assumed position of a worker. Therefore, a system of two self-levelling line lasers was chosen to extrapolate this plane into any desired height. Additionally, this setup allows for easy levelling of the measurement microphone.

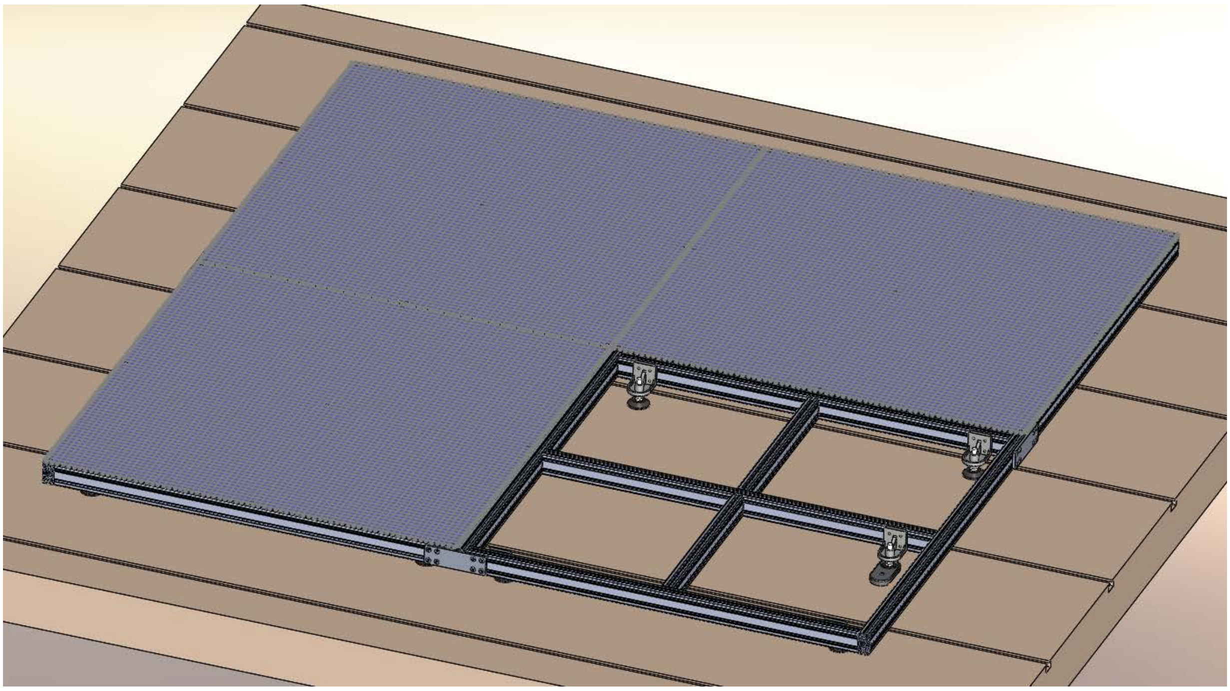

Figure 3: 3-d model of the platform for the reference workplace at the IFA. One of the elements is removed to expose the underlying construction.

Machine

During a measurement campaign at the facility of a cooperating manufacturer of ultrasound machines (Herrmann Ultraschall), a representative machine was to be chosen. Therefore, an anechoic chamber was built around a potentially suitable machine from plates of Basotect G+. In this semi-anechoic chamber, qualitative measurements were performed in different positions and for a set of tools and modes of operation.

Resulting from these measurements, a 20 kHz ultrasound welding machine with different tools was chosen. To explicitly account for variances in emitted noise during production use of ultrasound technology, a set of tools was requested from the manufacturer to represent maximum and minimum noise emission as well as a typical tool in terms of sales numbers.

Discussion

Although a finer or coarser grid could have been chosen, the resulting grid size seemed to be the best compromise between visibility and flexibility. While a grid size of 2 cm allows for easy discrimination between two neighbouring lines, it also makes the use of a finer grid possible by e.g. connecting nodes and use the resulting diagonal 1 cm grid as new reference.

The chosen machine certainly does not represent all imaginable ultrasound related workplaces. However, it represents the majority of work places where complaints have been filed, thus it delivers a solid starting point for the development of a measurement technique.

CONCLUSION

The main focus with the existing sound measurement methods lies on measuring audible sound in the presence of ultrasound. However, VDI 3766 describes the pitfalls when measuring ultrasound and describes solutions for achieving correct results. Therefore, VDI 3766 should be investigated in the course of the project on whether it also yields correct results when applied to measuring ultrasound. Additionally, to assess the ultrasound part of a signal, a filter has to be designed to exclude the frequency spectrum of audible sound. The B&K Ultra Filter, included in the filter set 1627, poses a good starting point.

The definition of the audible frequency range leaves room for interpretation. It is for example not clear, whether the frequency boundaries have to be interpreted as one-third octave centre frequencies or as exact frequency boundaries. Nevertheless, a consistent and unambiguous definition of ultrasound is vital for future efforts in standardisation.

In the course of this project a variety of tasks have to be carried out in order to eventually receive a valid measurement technique for ultrasound. First, existing standards and measurement techniques were evaluated along with an analysis of existing workplaces. Second, data on ultrasonic noise exposure were analysed to find a suitable machine representing the majority of workplaces. Then, a reference work place was built for development and testing of the new measurement technique. The method will then be field tested and revised if necessary. Finally, the results of this project will be brought into standardisation.

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EMPIR EURAMET

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