HIDDEN IN PLAIN SIGHT: CHARACTERIZATION OF AIRBORNE ULTRASOUND SOURCES

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Abstract

The increasing spread of ultrasound technology is accompanied by a spread of the associated airborne ultrasound exposure. Current risk assessments and exposure limit recommendations are based on outdated measurements and are primarily aimed at occupational sound exposure. However, technological developments have led to many new high-frequency noise and ultrasound sources, especially for use in private and public areas. Unfortunately, only a few studies have been carried out to date on public exposure to airborne ultrasound. Thus, the existing body of knowledge on potential hazards posed by ultrasound noise in private and public spaces is limited.

Against this background, the Physikalisch-Technische Bundesanstalt (PTB) has been commissioned by the German Federal Office for Radiation Protection (BfS) to investigate the spread of airborne ultrasound in private and public environments. The aim of this study is to identify and assess possible risks to the general population arising from airborne ultrasound exposure. In addition to an extensive literature research, a series of measurements was conducted both in the field and in laboratory settings to identify and describe airborne ultrasound sources. For qualitative and quantitative characterisation, a range of measurement instruments was employed, such as acoustic cameras, an ultrasonic sound exposure meter and the scanning and calibration facilities of PTB. Selected examples from these investigations are presented.

Keywords: *high-frequency noise, airborne ultrasound, public sites, measurement*

1. Introduction

Ultrasound technology is becoming increasingly widespread across many areas of modern life. Although the underlying technology is relatively old, it remains highly versatile. In industrial applications in particular, it is considered robust and cost-effective. Ultrasound is used to cut food cleanly on assembly lines, seal foils securely, clean electronic parts down to the smallest joint and quickly check the tightness of soft drink bottles during filling.

Along with the growing prevalence of electronic devices, ultrasonic technology is also increasingly used in everyday applications, for example for distance measurement in vehicles, to deter martens and moles in gardens or to clean glasses and jewellery. Moreover, the ongoing miniaturisation of energy sources and power electronics has led to applications in which ultrasound is often generated as a by-product, such as in small power supply units or high-power inverters in solar energy systems. Recent developments make targeted use of airborne ultrasound at high sound pressure levels, for example to project audio signals into a confined area (e.g. in museum exhibits) [1] or to create virtual objects though haptic stimuli [2]. All these applications generate high-frequency noise and airborne ultrasound that may affect human hearing [3, 4]. This is particularly evident in airborne ultrasound applications designed for deterrence. However, high-frequency noise and airborne ultrasound is also emitted secondarily via vibrating surfaces in water or structure-borne sound applications such as ultrasonic cleaning or welding.

As early as 1982, the World Health Organisation (WHO) published a report proposing initial guidelines for limiting noise exposure from airborne ultrasound [5]. In 1984, the International Radiation Protection Association (IRPA) issued recommendations for exposure limits for both occupational settings and for the general public [6]. These were subsequently adopted, at least in part, into national regulations in various countries [7]. A recent review of the IRPA guide has shown that insufficient new evidence has been generated in recent decades to support a meaningful revision of the existing exposure limits [8].

In light of this, the Physikalisch-Technische Bundesanstalt (PTB) is currently investigating the

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sound fields of airborne ultrasound sources relevant to the general population in a project funded by the German Federal Office for Radiation Protection (BfS). The aim is to identify and quantitatively characterise sound sources in public spaces and to assess exposure both in private and public environments based on selected examples. In addition to extensive literature research, detailed measurements of airborne ultrasound sources are being conducted. Furthermore, selected sound sources are examined under a range of idealised usage conditions.
This contribution focuses on the detection and characterisation of potential ultrasound sources. It describes the measurement techniques employed and presents selected examples from field measurements in private and public environments, as well as from laboratory studies, to provide an initial insight into the investigations.

2. Measurement instrumentation used

When assessing conventional audible noise, the source of the noise can usually be quickly identified, and sound pressure levels are readily measured using a commercial sound level meter. The measurement process becomes more complex when dealing with high-frequency and ultrasound noise. First, the source must be identified. As ultrasound frequencies exceed the normal range of human hearing, a technical measurement device is required for initial localisation. In addition, sound fields produced by high-frequency sources are often characterised by interference effects due to reflections and are therefore highly complex. As a result, it is often difficult to localise a source using a single-channel sound level meter, for instance by 'direction finding' or by exploiting the level-distance relationship. In this context, acoustic cameras can provide significant advantages. By using an array of correlated microphones, the direction of sound incidence can be determined and visualised as a colour map overlaid on a video image. This enables the acoustic camera to intuitively show the location of the noise source. For the investigations presented here, A CAE SoundCam Ultra 3 was used [9]. The system is compact and portable and enables sound source localisation in the frequency range from 2 kHz to 100 kHz.
However, acoustic cameras do not allow for conventional signal analysis and do not provide calibrated sound pressure levels comparable with those obtained with standard sound level meters. Therefore, a portable, high-frequency-capable personal sound exposure meter HiFUSPEx (High-Frequency and Ultrasound Personal Expositmeter) developed at PTB, was used for the quantitative investigations [10]. The device can be calibrated and is capable of recording both raw data and pre-evaluated sound pressure levels up to 100 kHz. Due to its compact size and mobility, it can flexibly be used in different environments. The implemented algorithms have been validated and compute the required acoustic metrics - such as Z- and AU-weighted equivalent sound pressure level, exposure level, peak sound pressure level, one-third octave band sound pressure levels - in accordance with relevant guidelines, such as the German VDI 3766 [11].
In addition, a commercial ultrasound-capable sound level meter, the Norsonic Nor145, was also used. The device covers the frequency range up to 40 kHz and is primarily suitable for evaluating the near-ultrasonic range.
For the laboratory investigations various sound field scanning systems at PTB were used. Under free-field-like conditions, microphones were automatically positioned around fixed sound sources along circular paths or within Cartesian grids, enabling the mapping of directional characteristics and cross-sections of sound fields.
The measurement chains used in these systems, as well as the HiFUSPEx, were calibrated in PTB's own calibration facilities up to 100 kHz, ensuring traceable sound pressure level measurements [12].

Figure 1. Solar inverter installed on the wall of a private garage.

Figure 2. Localisation image produced by the acoustic camera.

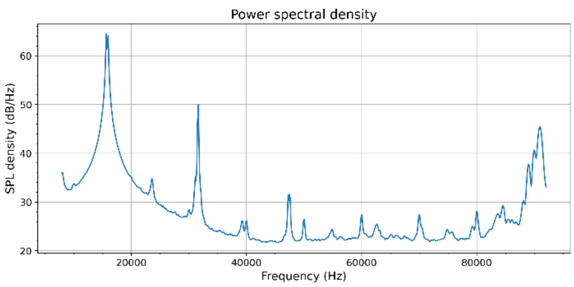

Figure 3. Power spectral density of the signal measured at the distance of approximately 2 m from the solar inverter.

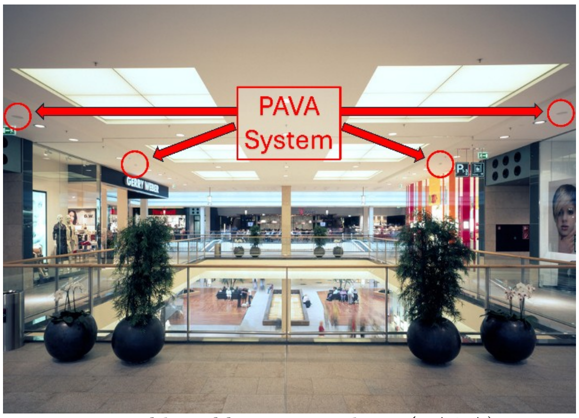

Figure 4. Public address voice alarm (PAVA) system installed in the ceiling of a shopping centre in Braunschweig, Germany.

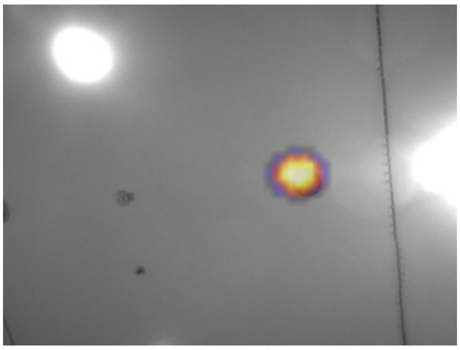
Figure 5. Illustration of one of the loudspeakers of the PAVA system in a shopping centre.

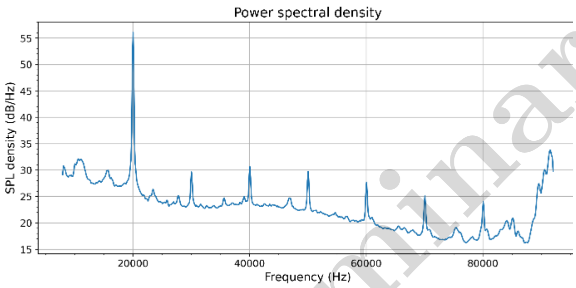

Figure 6. Power spectral density of the signal measured at the distance of approximately 2 m away from the source.

3. Field tests

The following section presents selected results from the investigations of various high-frequency noise and ultrasound sources. On-site measurements formed a key part of the study, which were conducted to identify sources for more detailed laboratory investigations to follow.

3.1 A solar inverter in a private garage

A solar inverter was installed in a private household equipped with a photovoltaic system. Following repeated complaints from some of the residents, the device was relocated from the house to the garage. In this configuration, the device was investigated with respect to ultrasonic noise emissions. Figure 1 shows the device in situ and Figure 2 presents the localisation image of the acoustic source produced by the acoustic camera. The corresponding power spectral density (PSD) plot as calculated from the recorded time signal is shown in Figure 3. The main switching frequency of the device is approximately 16 kHz, with pronounced harmonic ultrasound components, primarily at 32 kHz and 48 kHz.

3.2 Measurement in a shopping mall

Measurements were performed at various locations and times in a shopping centre. Initially, measurements were conducted prior to opening hours in order to obtain data under conditions that were as undisturbed as possible. Subsequently, the measurements were repeated during operating hours in the presence of customers, allowing for comparison under real-world conditions and for the identification of further potential sources.

The identified ultrasound sources included sensors of automatic door openers, fans and switching components of air conditioning units, electromagnetic anti-theft systems at shop entrances, as well as displays and power supply units of entertainment devices in the children's area. A particularly notable source was the public address and voice alarm (PAVA) system, which was installed throughout public corridors, across all levels, and individual shops of the shopping centre. (see Figure 4). An image from the acoustic camera – presented in Figure 5 – illustrates one of the loudspeakers of the PAVA system.

The ceiling-mounted loudspeakers spaced approximately 3 m to 5 m apart, emitted a continuous tonal signal at 20 kHz, resulting in equivalent sound pressure levels of up to 78 dB depending on the surrounding conditions. Figure 6 presents the qualitative PSD for selected measurements using the HiFUSPEx.

4. Laboratory studies

Selected sound sources identified during the on-site measurements and literature study were studied in greater detail under laboratory conditions. The aim is to characterise properties such as emitted sound pressure levels, signal characteristics and directivity. As surrounding structures can strongly influence the sound field of high- frequency sources, the investigations were carried out, as far as possible, under free-field or free-field-like conditions.


Figure 7. A photograph of the marten repellent tested (left), and the same device installed in the scanning unit at PTB (right).

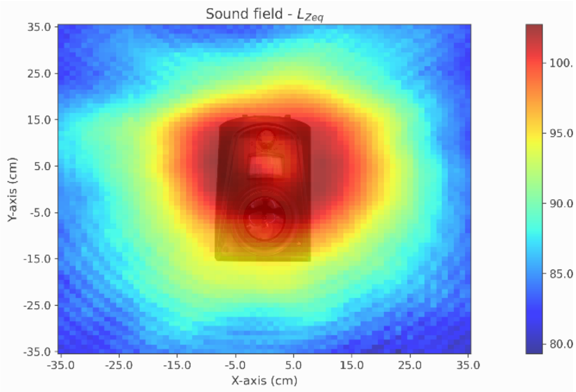

Figure 8. Illustration of the sound field produced by the marten repellent with the distance of 20 cm between the microphone and the device tested.

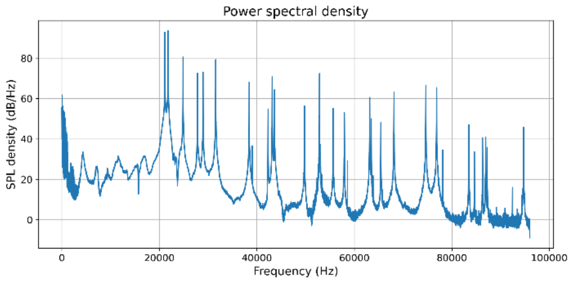

Figure 9. Power spectral density representation of a typical signal section from the sound field produced by the marten repellent.

4.1 Marten repellent

Several different animal repellent devices were investigated. These are typically characterised by non-stationary signal patterns to prevent habituation and to maximise discomfort for the targeted animals. The sound fields of these devices were mapped point by point in close vicinity of the sources using PTB's large 3-axes volume scanner. As spatial scanning over several hundred or thousand points can take several hours, the long-term stability of the sources had to be verified in advance. Where necessary, the operation of the devices was adapted to ensure sufficiently repeatable sound emission over the entire measurement period. One of the marten repellents examined in this study is presented in Figure 7. A cross-section of the resulting sound field is illustrated in Figure 8, whereas the corresponding spectral representation of a typical signal is shown in Figure 9.

4.2 Electric hand dryer

Various models of hand dryers were analysed in a similar manner. These devices are commonly found in public toilets, where they provide a hygienic alternative to paper towels. They typically produce a constant, broadband noise that spans the entire audible frequency range and extends into the ultrasonic region. Depending on the design, the directivity of sound emission differs, potentially leading to significant variations in sound exposure depending on the user's height. During the measurements, care was taken to avoid directing the measurement microphones into the airflow, in order to prevent wind-induced flow noise from affecting the results. Consequently, some areas were omitted from the scan plots. Figure 10 shows the example of a Dyson Airblade 9kJ hand dryer while Figure 11 a cross-section of the associated sound field.

5. Discussion and Conclusions

The examples presented above demonstrate the measurements of a variety of high-frequency noise and ultrasound sources that have become very common in recent years. The first two sources considered here, where the measurements were performed on-site, exemplify signal frequencies exceeding the high end of the audible spectrum (≥ 16 kHz). The one-third-octave band spectra, presented in Figure 12, show a maximum sound pressure level of $L_{Zeq,16kHz} = 78$ dB for the solar inverter and $L_{Zeq,20kHz} = 70$ dB for the PAVA system in the shopping centre, respectively. In both cases measurements were performed at a distance of approximately 2 m from the sound source. As such, these signals may well be heard and perceived as disturbing by certain groups of the society.

In a similar way the one-third-octave band spectra plotted for the two sources investigated under laboratory conditions are shown in Figure 13. In this case, the sound pressure across the presented spectrum is evenly distributed around 80 dB level for the hand dryer. Therefore, the high levels of sound pressure in the audible range overlay those within the airborne

Figure 10. Dyson Airblade 9kJ hand dryer as installed within the scanning unit of the PTB.

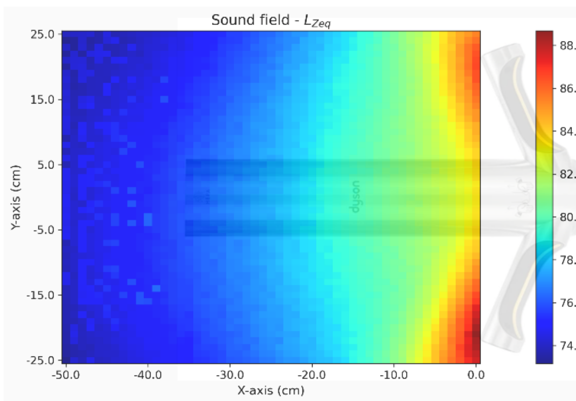

Figure 11. Sound field image as produced through the mapping performed around the hand dryer.

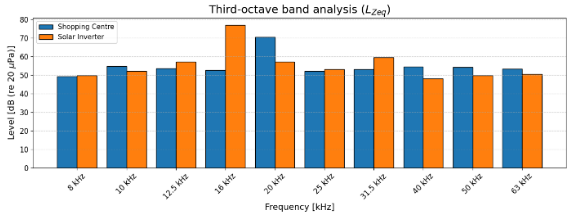

Figure 12. Third-octave band spectra, between 8 kHz and 63 kHz, of the solar inverter and PAVA system installed in the shopping centre.

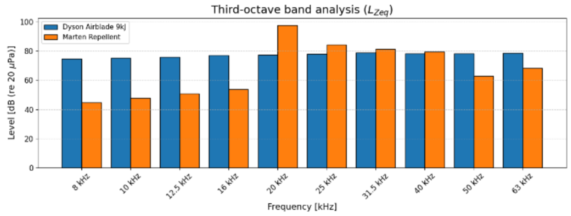

Figure 13. Third-octave band spectra, between 8 kHz and 63 kHz, of the hand dryer and marten repellent tested in the laboratory.

ultrasound spectrum (≥ 16 kHz). The third-octave band spectrum of the marten repellent shows the highest sound pressure level across the device's operational range between 20 kHz and 60 kHz. Nevertheless, the sound pressure level of 98 dB within the 20 kHz third-octave band may still be heard and perceived as disturbing.
Additional sound sources are continuously identified in both private and public areas and subsequently characterised under laboratory conditions. These include, for example, power supply units for various appliances, induction cookers, directional loudspeakers, ultrasonic knives, dimmable lights, arc lighters, electric vehicles. A complete overview of investigated devices and sites will be published at the end of the project.
The aim is to identify and characterise as many ultrasonic sources as possible within the limited time and vicinity. Based on these investigations, the noise exposure from selected sources will be analysed under varying spatial and environmental conditions. This approach is intended to provide a realistic assessment of everyday exposure and to support identification and evaluation of potential risks to the general population arising from airborne ultrasound. In conclusion, this work represents an initial step towards improving the assessment and management of ultrasound-related noise exposure.

6. Acknowledgments

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