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Research Paper

Ultrasonic Haptic Devices: Ultrasonic Noise Assessment

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Ultrasonic haptic technology is one of the more interesting novel technologies being intensively developed in recent years. Such technology has a number of undoubted advantages and potential applications, but it can also be a source of ultrasonic noise. Pursuant to the provisions of the labor law, ultrasonic noise at a high sound pressure level can be a harmful factor for human health. The article presents the results of the assessment of ultrasonic noise emitted by an ultrasonic haptic device and the assessment of exposure to noise of a person using the device. The tests were carried out using one of the haptic devices readily available on the market. Ultrasonic noise emission tests were carried out around the device, at selected points placed on the surface of a hemisphere of a radius of 0.5 m, for various haptic objects. The analyzed parameter was the equivalent sound pressure level in the 1/3 octave band with a center frequency of 40 kHz. Variable sound pressure levels ranged from 96 dB to 137 dB. Noise exposure tests were carried out both using the KEMAR measurement dummy and with test participants of different heights. In most cases, the sound pressure level exceeded 110 dB, and in the worst case it exceeded 131 dB. Comparison of the results of ultrasonic noise assessments with the permissible values of this noise in the working environment shows that in the case of prolonged or improper use of the device, the permissible values may be exceeded.

Keywords: ultrasonic haptic devices; ultrasonic noise.

1. Introduction

The effective engagement of the sense of touch in the daily interactions with various interfaces has inspired many, leading to the incorporation of buzzers and various motors into popular devices, such as smartphones or wristwatches. The next step, that researchers have been trying to reach for years (Iwamoto *et al.*, 2008), is the development of touchless haptic interfaces. Various solutions have been presented and one of the most promising ones is the use of ultrasound for the induction of a feeling of touch on human skin. The research on that topic has been ongoing since 1977 and begun with the presentation of the detection thresholds for human skin (Gavrilov *et al.*, 1977). This knowledge was later used as a basis for excitation of the touch receptors in human skin using acoustic radiation pressure, first in water (Dalecki *et al.*, 1995), and later, after further discoveries (Carter *et al.*, 2013; Hoshi *et al.*, 2010), in air (Rakkolainen *et al.*, 2021). In order to create detectable shapes in mid-air, the sound signal used should be of a high frequency, usually in the range of 40 kHz to 70 kHz (Frier *et al.*, 2019). The signal should be modulated with the frequency of 0.4 Hz to 500 Hz, to allow for a detectable deflection of the skin by the touch receptors (Gesheider *et al.*, 2002). At the same time, it should be noted that the ultrasonic haptic technology is based on the use of ultrasound with high sound pressure levels (up to 150 dB at the focus point) and thus can be a source of ultrasonic noise (Radosz, Pleban, 2018; Śliwiński, 2016). Pursuant to the provisions of labor law in force, in Poland (Internet System of Legal Acts, 2018), ultrasonic noise is a harmful factor, because at sufficiently high sound pressure levels it has an adverse effect on the human body (Smagowska, Pawlaczyk-Łuszczyńska, 2013). Despite the safety concerns the research usually focuses not on the exploration of threats, but rather possibilities that ultrasonic haptic technology can create. Since the inventions of new ways to use the technology influences the way in which it operates, it can also influence the specific needs for risk assessment. Research on the characteristics of generated signals can indicate which signal parameters or which generation types can be most commonly used in an industrial or commercial setting. A review of the literature shows current trends in the development and research topics concerning the ultrasonic haptic technology.

The latest studies and publications on the ultrasonic haptic technology can be mostly assigned to one of two categories: applications of the ultrasonic haptic technology or exploring issues related to the generation and perception of haptic signals. An interesting example of the use of ultrasonic haptic technology is presented in (Romanus *et al.*, 2019). The authors describe their device, which integrates three technologies: virtual reality goggles, ultrasonic haptic devices, and wearable devices. The haptic device was used to create a holographic, animated image of a heart, which can be felt with the sense of touch and which movement (beating) is synchronized with the heartbeat of the person operating the device. Another interesting proposal was to use the ultrasonic haptic technology in the process of hand-guided programming of collaborative industrial robots, as presented in (Rivera Pinto *et al.*, 2020). This type of programming consists of manually guiding the robot arm by a human in the way, which later allows the robot to mimic the sequence of actions performed by the human. Such programming could minimize production line downtime and can be implemented with the use of virtual reality technologies. However, for a person performing such a task, the lack of feedback in the form of sensory stimuli is a major obstacle. In this work, virtual reality was enriched with sensory stimuli using the ultrasonic haptic technology and the use of virtual reality goggles can shield the user from potential adverse effects of ultrasonic noise or become a convenient mounting point for hearing protection.

Discussion of the most important of the anticipated applications of the ultrasonic haptic technology is also presented in the review by Rakkolainen *et al.* (2021). The proposed applications are divided into groups covering: sterile medical interfaces, applications in the automotive industry, advertising and sales, and augmented virtual reality and mixed reality. The paper also reviews issues related to the creation of tactile objects with the use of ultrasonic haptic technology, their precision and perception. Issues related to the safety of the technology, resulting from the presence of ultrasonic waves with a high level of sound pressure (ultrasonic noise) were also discussed. The authors point out that even at a great distance from the focus of the ultrasound, its level may exceed 110 dB, and further research into the impact of ultrasound on the hearing organ is necessary to fully assess this issue, although some recent studies (Carcagno *et al.*, 2019) have not demonstrated the impact of ultrasound with a frequency of 40 kHz to shift the threshold of hearing.

Di Battista *et al.* (2022) focused on the burdensome, non-auditory impact of ultrasonic noise, which may occur when ultrasonic haptic technology is used in consumer devices. The conducted research concerned the impact of ultrasound with a frequency of 40 kHz and high sound pressure levels on the cognitive functions of the exposed persons. The conducted research showed no adverse effects of exposure to ultrasonic noise on the test subjects, assessed both by the number of correct answers given in the conducted tests as well as the reaction time. The authors state that ultrasounds with a frequency of 40 kHz and a level of 120 dB have no effect on human cognitive functions.

Taking into account the current progress in the development of ultrasonic haptic technology, ultrasonic haptic devices have a real chance to become tools used in everyday work. Because ultrasonic haptic technology can provide tactile sensations that provide feedback to actions taken, its potential future applications include workplaces related to control, design or diagnostics in virtual reality or augmented reality environments. Ultrasonic haptic technology can be especially valuable for people with visual impairments, helping to accommodate their needs in the workplace. In such cases, ultrasonic haptic devices would turn from technological gadgets into tools intended for long hours of work. This makes it all the more important to assess the technologies introduced to the market in terms of potential hazards to employees caused by the generated ultrasonic noise. The main focus of the studies presented in this article is the possible impact the ultrasonic noise can have on the persons using it on a daily basis. It presents the results of measurement and assessment of ultrasonic noise emitted by an ultrasonic haptic transducer, taking into account the criteria adopted for the assessment of ultrasonic noise in the work environment in Poland.

2. Method and experimental setup

Estimating exposure to ultrasonic noise generated by an ultrasonic haptic device is a difficult issue due to the multitude of factors that may affect the value of this exposure, most of which depend on how the device is used. Ultrasonic noise is significantly reduced by propagation in the air. Moreover, ultrasonic noise sources, in particular haptic transducers in which an ultrasonic beam with appropriate parameters is intentionally generated, are directional sources. This means that the exposure of a given person to ultrasonic noise will be influenced by the position of the person's head (especially their ears) in relation to the haptic device, in terms of both the distance from the device and the angular position in relation to it. The position of the head of a person using an ultrasonic haptic device in relation to this device will be influenced by factors such as: the method of using the device (sitting or standing), the person's height, arm length, the height of the device in relation to the human body, the way the upper limb is positioned (straight, bent). Depending on these factors, the distance of the person's head from the haptic device will most often range from 50 cm to 90 cm. The sound pressure level of the ultrasonic noise produced by the device, as well as the directional characteristics of the noise radiation, will be influenced by factors such as: the type of the generated haptic object, its position in relation to the device and its intensity, and the parameters of the modulation used. It should be noted here that haptic devices may enable adjustment of the intensity of the generated object by adjusting the amplitude of the generated signals, thus reducing the sound pressure level of noise, but reduced intensity of the generated object deteriorates the tactile sensations felt by the user. Another factor that will influence the sound pressure level of noise reaching the ears of a person using a haptic device is the presence of a person's hand touching the generated haptic object and acting as a kind of acoustic screen for the ultrasonic wave. Obviously, due to the directional nature of the spread of ultrasonic noise, this is most important when a person's hand is aligned with both the person's ear and the haptic device. This situation will occur when the person is standing and the haptic device is placed low relative to the user. For a seated person and a haptic device placed higher, the signal shielding effect of the hand may be much smaller or negligible. For safety reasons, the optimal solution would be for the device to generate a haptic object when it detects the user's hand in the space above the ultrasonic matrix of the haptic transducer, which requires the use of a hand position or presence sensor in the device. However, device manufacturers are not obliged to use this type of sensors, so it is possible that a person is close to a working haptic transducer but does not touch the object, thereby disabling the acoustic shielding effect. For example, as an office worker may use the keyboard as the main tool in their work, an ultrasonic haptic device could also be used in the same manner, yet neither of those tools would be operated constantly throughout the whole working day. Because of this it cannot be assumed that the hands of the user would shield them from potential harm at all times.

In our research, we attempted to assess how the type and parameters of the generated haptic object affect the sound pressure level of ultrasonic noise to which the user of the haptic device may be exposed, and the directionality of noise radiation (in particular in the direction in which the user of the device is located). These studies also allowed to assess the impact of the user's height and hand position on exposure to ultrasonic noise. For this purpose, three experiments described below were carried out, including measurements of sound pressure levels at selected points of a hemisphere with a radius of 50 cm, and measurements of ultrasonic noise near the ears of the user of the haptic device first by carrying out tests using a measuring dummy and then with participants.

Tests of ultrasonic noise emitted by an ultrasonic haptic device at selected points of the hemisphere were carried out in an acoustic test chamber characterized by a short reverberation time (semi-anechoic properties). The tests were carried out using the STRATOS Inspire haptic device, performing, for selected haptic objects, measurements of the equivalent sound pressure level in the $1/3$ octave band with a center frequency of 40 kHz (which, according to previous studies, poses the greatest hazard to the users) at the selected points of the hemisphere with a radius of 50 cm, which is the closest assumed distance of the head of the user from the haptic device. The diagram of the measuring system is shown in Fig. 1.

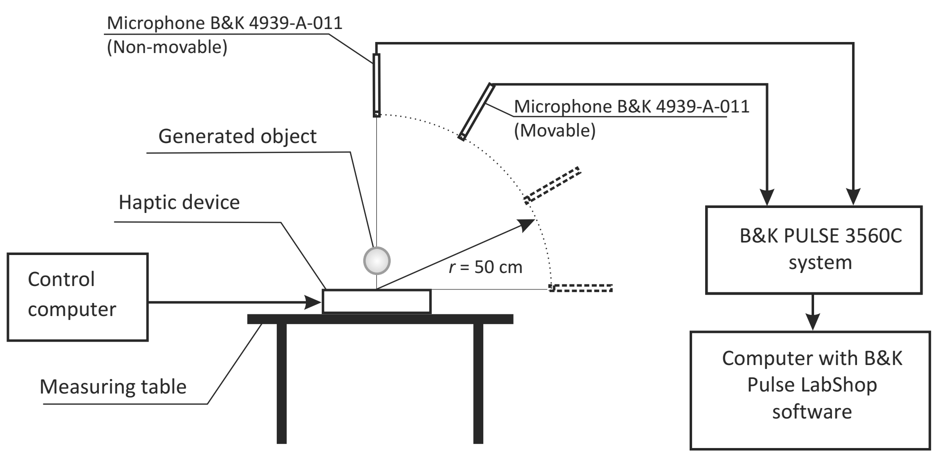

Fig. 1. Scheme of the measurement system for testing ultrasonic noise emitted by an ultrasonic haptic device.

The tested device was connected to the control computer and placed in the center of the test table, located at a distance of not less than 1.5 m from each of the walls of the room. The measurement system consisted of a Brüel & Kjær Pulse type 3560C measuring cassette with a type 3110 input/output module and two measuring microphones type 4939-A-11. The microphone marked in Fig. 1 as "movable" was the actual measurement microphone and was set up at individual measurement points of the hemisphere during the tests. The microphone marked in Fig. 1 as "non-movable" was permanently placed in the upper part of the hemisphere, perpendicular to the surface of the haptic device and performed a control function, allowing to assess the variability of the acoustic signal generated by the haptic device after each repositioning of the movable microphone at the next measurement point and restarting the device. Measurements made with a non-movable microphone made it possible to check whether each switching on and off of the device (e.g., when setting up a moving microphone) does or does not cause significant differences in the sound pressure levels of the ultrasonic noise produced and whether the operation of the device is stable (i.e., whether there are any unpredictable changes in the generated signal resulting, for example, from the applied control of the matrix of ultrasonic transducers). Thus, the fixed microphone made it possible to verify whether the measurements made with the moving microphone are not measurements of random values depending on the successive activations of the haptic device.

A computer with the Pulse LabShop software and the analysis module in frequency bands was used to control the measurements and record the measurement results. During the tests, the values of the equivalent sound pressure level in the frequency band with a center frequency of 40 kHz (averaging time 20 s) were recorded at measurement points in the space around the device, located on a hemisphere. The research focused mainly on the front of the device (angular mark 0°), since this should be the position assumed by the person operating the device. In the frontal part of the hemisphere, the tests were carried out with a horizontal angular resolution of 15° in the range of ±45°. In the horizontal plane, tests were also carried out for angles of ±90° and ±180°. In the vertical plane, the tests were performed with an angular resolution of 15°. The diagram of the distribution of measurement points in the conducted research is shown in Figs. 2 and 3. For each angular position of the microphones in the horizontal plane (Fig. 2), measurements were made in all angular positions in the vertical plane (Fig. 3), while in the vertical 90° position, measurements were made only with a fixed microphone.

During tests haptic objects were generated in the form of two flat shapes: a point and a circle. The radius of the generated circle was 2 cm. The modulation frequency was 50 Hz or 200 Hz. The height of the generated objects above the haptic device (shape generation height, h_{sg}) was 10 cm, 20 cm, and 30 cm.

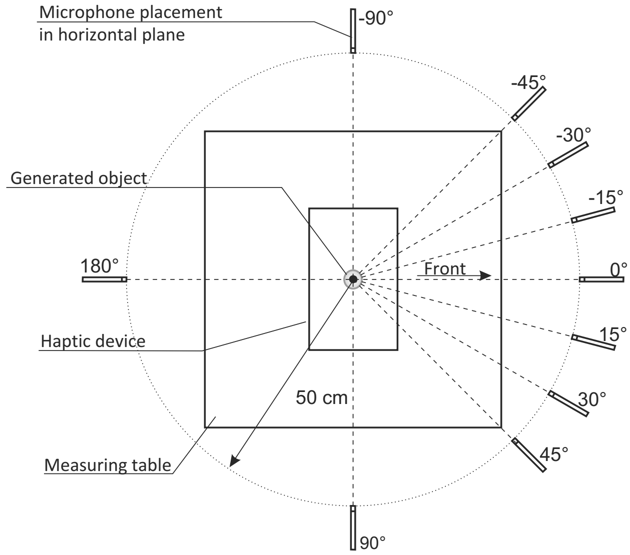

Fig. 2. Scheme of the arrangement of measurement points in the horizontal plane during testing of ultrasonic noise emitted by an ultrasonic haptic device.

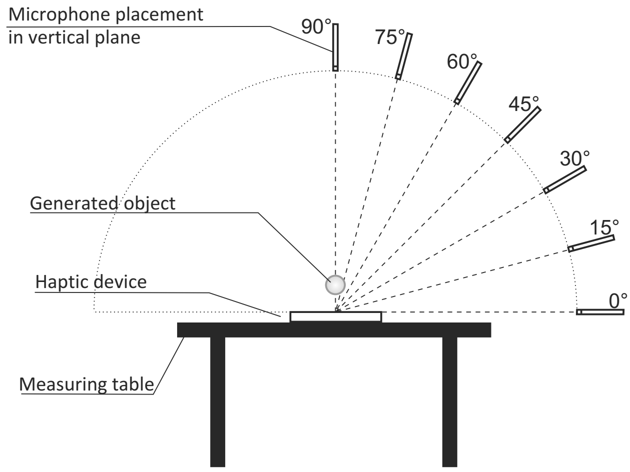

Fig. 3. Scheme of the distribution of measurement points in the vertical plane during measuring of ultrasonic noise emitted by an ultrasonic haptic device.

Ultrasonic noise tests using a test dummy were carried out for the STRATOS Inspire haptic device generating selected haptic objects. Measurements of the equivalent sound pressure level were made in the 1/3 octave band with a center frequency of 40 kHz. The tested haptic device was connected to the control computer and placed in the center of the test table, located at a distance of not less than 1.5 m from each of the walls of the room. A GRAS KEMAR measuring dummy was placed in front of the test table, where a person using a haptic device would be positioned (Fig. 4). The height of the dummy setting was

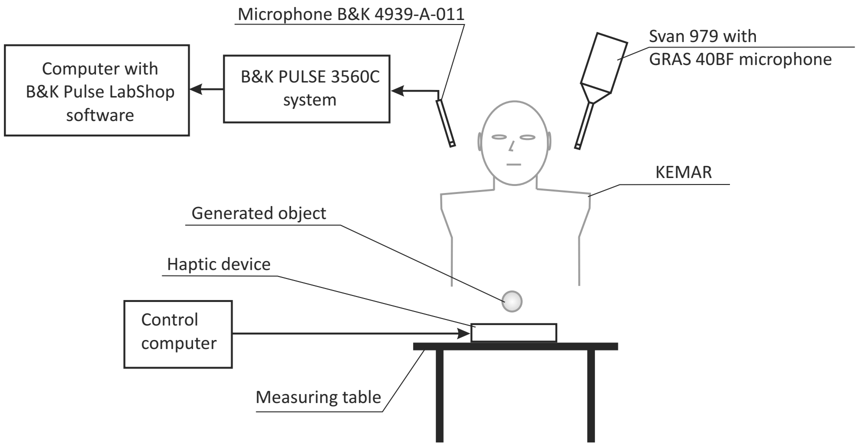

Fig. 4. Scheme of the measurement stand for testing ultrasonic noise with the use of the measuring dummy.

set to 168.5 cm (the average height of a person). Ultrasonic noise tests were carried out using two measurement systems, independently for each ear of the measuring dummy, which made it possible to assess the differences in exposure to ultrasonic noise between the right and left ear.

The first measurement system (measurement at the dummy's right ear) consisted of a Brüel & Kjær Pulse type 3560C measuring cassette with a type 3110 input/output module and a type 4939-A-11 measuring microphone. A computer with the Pulse LabShop software and the analysis module in frequency bands was used to control the measurements and record the measurement results. During the tests, the values of the equivalent sound pressure level in 1/3 octave bands (averaging time 20 s) were recorded. The second measurement system (measurement at the dummy's left ear) consisted of an integrating sound level meter SVAN 979 with a GRAS 40BF microphone and an SV17 preamplifier. During tests, the meter recorded the values of the equivalent sound pressure level in 1/3 octave bands (averaging time 20 s). In accordance with the ultrasonic noise measurement methodology (Radosz, 2012; 2020; Radosz, Pleban, 2018) and the provisions of the PN-Z-01339:2020-12 standard, the microphones of the measurement systems were placed 10 cm from the entrance to the outer ear canal of the dummy's appropriate ear and were directed towards the ultrasound source. The view of the test stand during the tests is shown in Fig. 5.

During tests, haptic objects were generated in the form of three flat shapes: a point, a circle and a square. The radius of the generated circle was 2 cm, and the side length of the generated square was 4 cm. The modulation frequency for all objects was 200 Hz and the generation height h_{sg} was 20 cm. The objects differed

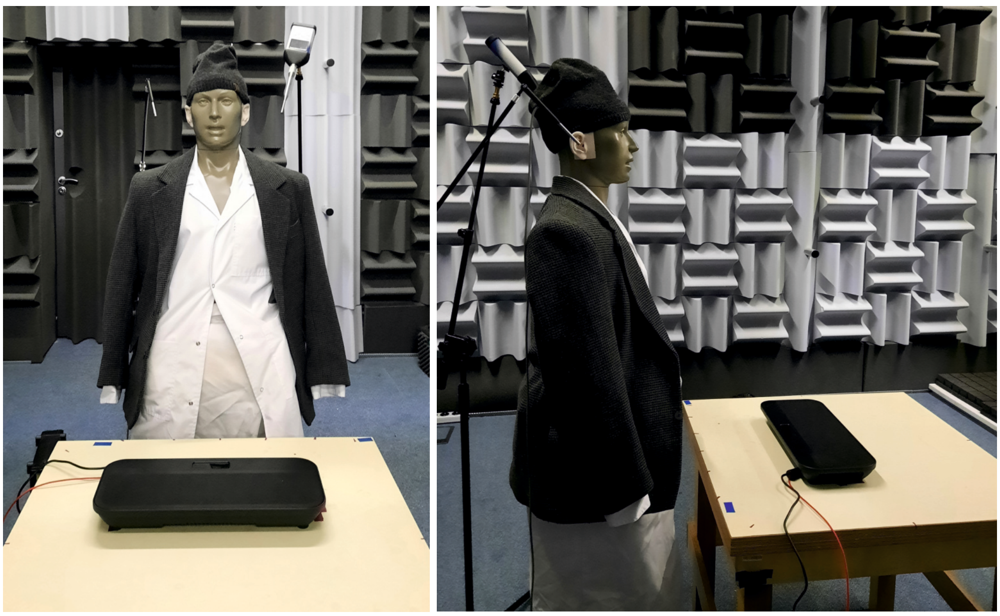

Fig. 5. View (front and side) of the ultrasonic noise testing stand.

in the type of modulation (amplitude – AM, spatio-temporal – SP).

Ultrasonic noise tests with participants for the STRATOS Inspire haptic device generating selected haptic objects were conducted with six participants of different heights, from 159 cm to 177 cm, which corresponds to the height of the measuring microphone in the range from 144 cm to 162 cm (Podleśna *et al.*, 2022). These tests allow to assess the impact of the haptic device user's height and the presence of his hand on the noise exposure.

The layout of the measuring stand (Fig. 6) was similar to that used for measurements using a measuring dummy, except that only one of the measuring systems produced by Brüel & Kjær was used. The microphone of the measurement system was placed 10 cm from the entrance to the outer ear canal of the participant's right ear and was directed towards the ultrasound source. Measurements of the equivalent sound pressure level (averaging time 20 s) were made in the 1/3 octave band with a center frequency of 40 kHz. The users were allowed to position themselves comfortably in front of the device. Measurements were made for two positions of the test participant's right hand: along the body and while touching a haptic object.

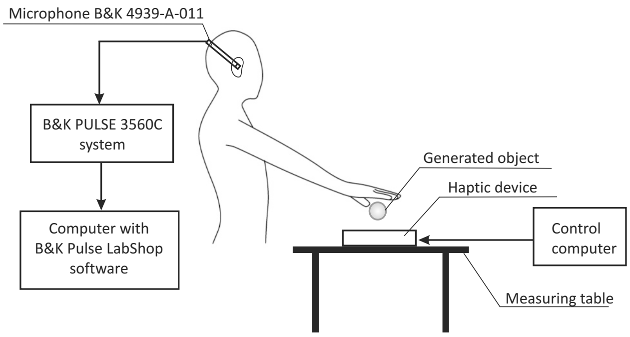

Fig. 6. Scheme of the measurement stand for testing ultrasonic noise with participants.

During tests, haptic objects were generated in the form of three flat shapes: a point, a circle, and a square. The radius of the generated circle was 2 cm, and the side length of the generated square was 4 cm. The modulation frequency for all objects was 200 Hz. The objects were generated at different generation heights, h_{sg}: 10 cm, 20 cm, and 30 cm. All objects were generated in a spatio-temporal manner.

3. Results

The test results for a haptic object in the form of a point are presented in Tables 1 and 2, and in Figs. 7 and 8. The tests were carried out for a point located at a height of 20 cm and for two different modulation frequencies: 200 Hz (Table 1 and Fig. 7) and 50 Hz (Table 2 and Fig. 8).

Table 1. Results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a point at a height of 20 cm (modulation frequency 200 Hz).

Vertical angular position [°]	Equivalent 1/3 octave band sound pressure level $L_{\text{eq},40\text{ kHz}}$ [dB]									
	Horizontal angular position [°]									
	–90	–45	–30	–15	0	15	30	45	90	180
0	96	100	105	108	97	100	102	93	101	105
15	111	108	111	112	115	111	111	104	109	111
30	110	115	111	115	119	112	113	111	120	117
45	113	118	120	124	116	113	124	125	122	114
60	118	121	118	110	119	113	111	118	109	121
75	131	116	119	116	105	120	115	123	131	119
90	131									

Table 2. Results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a point at a height of 20 cm (modulation frequency 50 Hz).

Vertical angular position [°]	Equivalent 1/3 octave band sound pressure level $L_{\text{eq},40\text{ kHz}}$ [dB]									
	Horizontal angular position [°]									
	–90	–45	–30	–15	0	15	30	45	90	180
0	97	102	105	107	97	100	102	87	101	105
15	114	106	111	111	115	110	111	104	108	111
30	110	115	110	114	120	113	114	111	120	117
45	113	119	121	124	116	112	124	126	122	114
60	118	120	119	111	119	113	113	118	108	121
75	131	115	119	116	108	120	114	123	131	119
90	131									

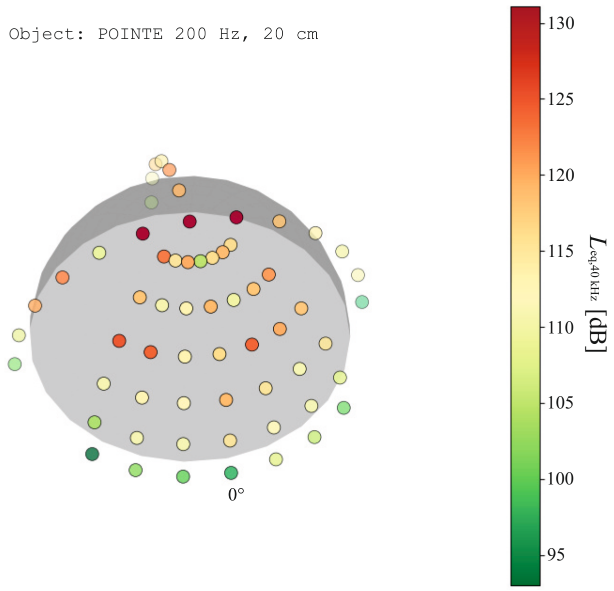

Fig. 7. Visualization of the results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a point at a height of 20 cm (modulation frequency 200 Hz).

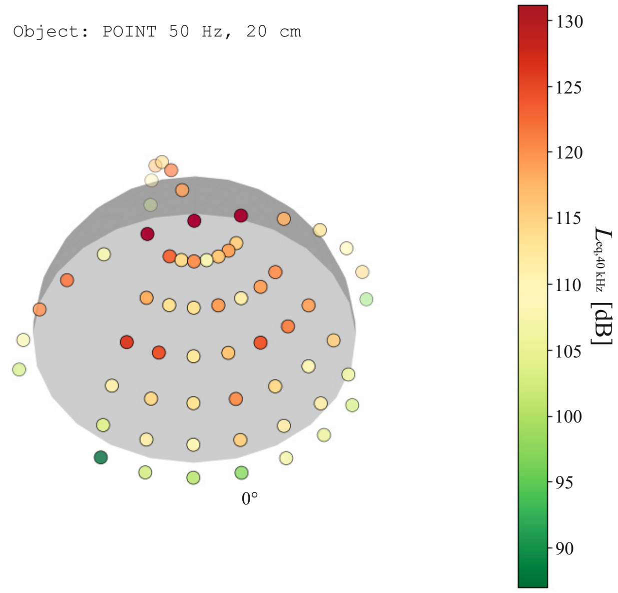

Fig. 8. Visualization of the results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a point at a height of 20 cm (modulation frequency 50 Hz).

The test results for a haptic object in the form of a circle are presented in Tables 3, 4, and 5 as well as in Figs. 9, 10, and 11. The tests were carried out for a circle with a radius of 2 cm and a modulation frequency of 200 Hz and for three different heights of the circle above the surface of the haptic device: 10 cm (Table 3 and Fig. 9), 20 cm (Table 4 and Fig. 10), and 30 cm (Table 5 and Fig. 11).

Table 3. Results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a circle at a height of 10 cm (r = 2 cm, modulation frequency 200 Hz).

Vertical angular position [°]	Equivalent 1/3 octave band sound pressure level $L_{eq,40\,kHz}$ [dB]									
	Horizontal angular position [°]									
	−90	−45	−30	−15	0	15	30	45	90	180
0	101	111	107	107	111	105	109	110	106	108
15	114	115	117	118	115	116	118	115	120	118
30	121	118	122	122	122	124	124	120	122	121
45	125	122	125	122	124	129	125	126	124	131
60	128	130	131	125	123	127	124	130	126	126
75	126	129	129	128	127	131	130	130	127	126
90	124									

Table 4. Results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a circle at a height of 20 cm (r = 2 cm, modulation frequency 200 Hz).

Vertical angular position [°]	Equivalent 1/3 octave band sound pressure level $L_{eq,40\,kHz}$ [dB]									
	Horizontal angular position [°]									
	−90	−45	−30	−15	0	15	30	45	90	180
0	103	107	110	109	111	104	110	104	100	108
15	116	116	117	118	122	114	119	111	118	118
30	115	119	119	123	123	118	120	118	123	123
45	121	124	126	126	123	121	128	128	128	120
60	121	121	120	121	118	116	117	120	121	122
75	134	122	121	121	119	123	123	127	135	123
90	134									

Table 5. Results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a circle at a height of 30 cm (r = 2 cm, modulation frequency 200 Hz).

Vertical angular position [°]	Equivalent 1/3 octave band sound pressure level $L_{\text{eq},40\text{ kHz}}$ [dB]									
	Horizontal angular position [°]									
	−90	−45	−30	−15	0	15	30	45	90	180
0	104	104	104	114	109	108	102	104	103	107
15	120	116	111	125	117	118	117	110	121	114
30	115	120	123	128	124	115	117	118	121	123
45	121	125	124	119	119	116	127	119	122	114
60	116	118	115	118	113	116	119	112	122	116
75	125	116	120	124	115	122	122	123	126	125
90	137									

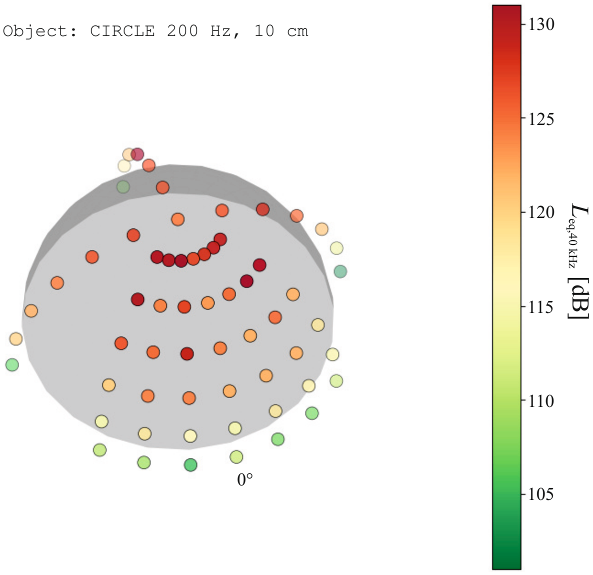

Fig. 9. Visualization of the results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a circle at a height of 10 cm (modulation frequency 200 Hz).

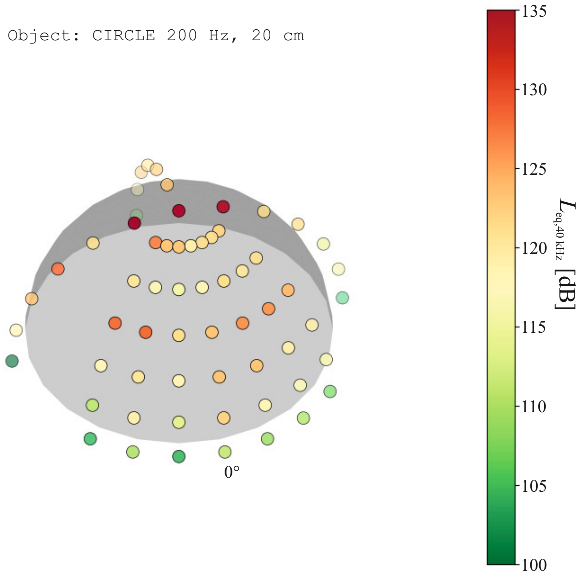

Fig. 10. Visualization of the results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a circle at a height of 20 cm (modulation frequency 200 Hz).

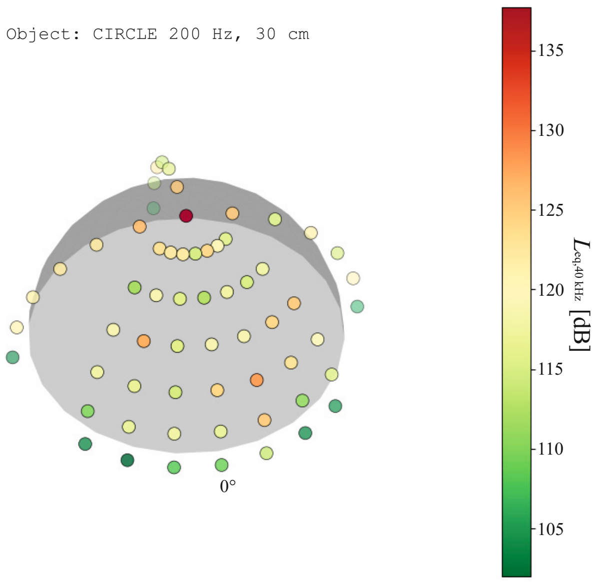

Fig. 11. Visualization of the results of ultrasonic noise tests at selected points of the hemisphere for an object in the form of a circle at a height of 30 cm (r = 2 cm, modulation frequency 200 Hz).

The test results for a haptic object in the form of a point show that the highest equivalent sound pressure level of 131 dB was measured in the upper part of the hemisphere, where the fixed microphone was placed and at measurement points located in the upper part of the hemisphere for the horizontal angular positions −90° and 90° and the vertical angular position 75°. High sound pressure levels (up to 126 dB) were also recorded in the front part of the hemisphere for a vertical angular position of 45°. The measurements results for a haptic object in the form of a circle show that the change in the generation height of the haptic object changes the angular position of the measurement points in which the highest sound pressure levels were recorded. In the case of a haptic object (circle) located at a height of 10 cm above the matrix of the haptic device, the highest sound pressure levels, reaching 131 dB, are observed for vertical angular positions of 60° and 75°. For a vertical angular position of 90°, the sound pressure level is lower and amounts to 124 dB. For a haptic object generated at a height of 30 cm, the highest sound pressure level, 137 dB, was recorded for a point at a vertical angle of 90°.

The results of the ultrasonic noise measurement with using KEMAR measuring dummy are included in Table 6.

Table 6. Results of ultrasonic noise tests for microphones placed at KEMAR's ear.

Haptic object			Svan	B&K
Shape	Modulation type	Location height [cm]	$L_{\text{eq,40 kHz}}$ [dB]	$L_{\text{eq,40 kHz}}$ [dB]
Point	AM	20	114.1	114
	ST	20	112.3	112
	AM	10	123.6	117
	AM	30	113.4	101
Square	AM	10	117.5	117
	AM	20	113.8	112
	AM	30	114.5	112
Circle	ST	10	126.4	122
	ST	20	117.7	116
	ST	30	117.5	111

The measurements results presented in Table 6 show that the equivalent sound pressure level in the frequency band with a center frequency of 40 kHz near the dummy's ears exceeded 110 dB in each case, with the highest value recorded being 126.4 dB. Differences between sound pressure levels for the right and left ear can be several dB.

The results of the ultrasonic noise measurements with participants of different heights were presented in detail in a previously published work (Podleśna *et al.*, 2022). This article presents only additional synthesis and analysis of the measurement results obtained for the STRATOS Inspire device and the conclusions drawn from them. The results of measurements of the equivalent sound pressure level of ultrasonic noise in relation to the height of the measurement microphone, resulting from the height of the research participant are presented in Fig. 12. In the graphs presenting the test results in relation to the height of the measuring microphone, trend lines have been added for the measurement results obtained for the object generation height of 20 cm.

Test results show an impact of the presence of the user's hand above the device. The equivalent sound pressure level has never exceeded 130 dB while the user's hand was extended. That was the case however for 3 measurements while the user's hand was withdrawn. The highest equivalent sound pressure levels were measured in cases where the object generation height was 10 cm. This phenomenon can be explained based on the results of tests carried out on the hemisphere. When the haptic object is generated at a higher height, much of the acoustic energy is emitted upwards, above the haptic device (Fig. 8). When generating an acoustic object at a lower height (Fig. 9), a large part of the acoustic energy is emitted at smaller vertical angles, towards the user of the device. Out of 54 measurement cases the equivalent sound pressure level exceeded 110 dB in 48 cases (89 %) while the user's hand was touching haptic object and in all cases (100 %) while the user's hand was positioned along the body. In most cases, a hand placed on a haptic object reduced the noise by several dB (approx. 4 dB on average), but in extreme cases it was more than 20 dB. Such a large reduction concerned haptic objects generated at low heights. The height of the user has a significant impact on the test results, but this effect varied depending on the position of the research participant's hand. Considering the trend lines in Fig. 12, when a participant's hand touches a haptic object, the equivalent sound pressure level at the participant's ear was lower for taller participants. The reverse relationship can be observed when the research participant holds their hand along the body. These results indicate that when the ultrasound emitted from the haptic device is not shielded by the user's hand, the angular position of the user's head in relation to the transducer is more important than the distance of the user's head from the device.

4. Assessment of ultrasonic noise exposure and conclusions

The assessment of the exposure of the user of an ultrasonic haptic device to ultrasonic noise and the resulting risks should be carried out using appropriate criteria. In order to assess the risk posed by ultrasonic noise generated by an ultrasonic haptic device, the results of the conducted study were compared with

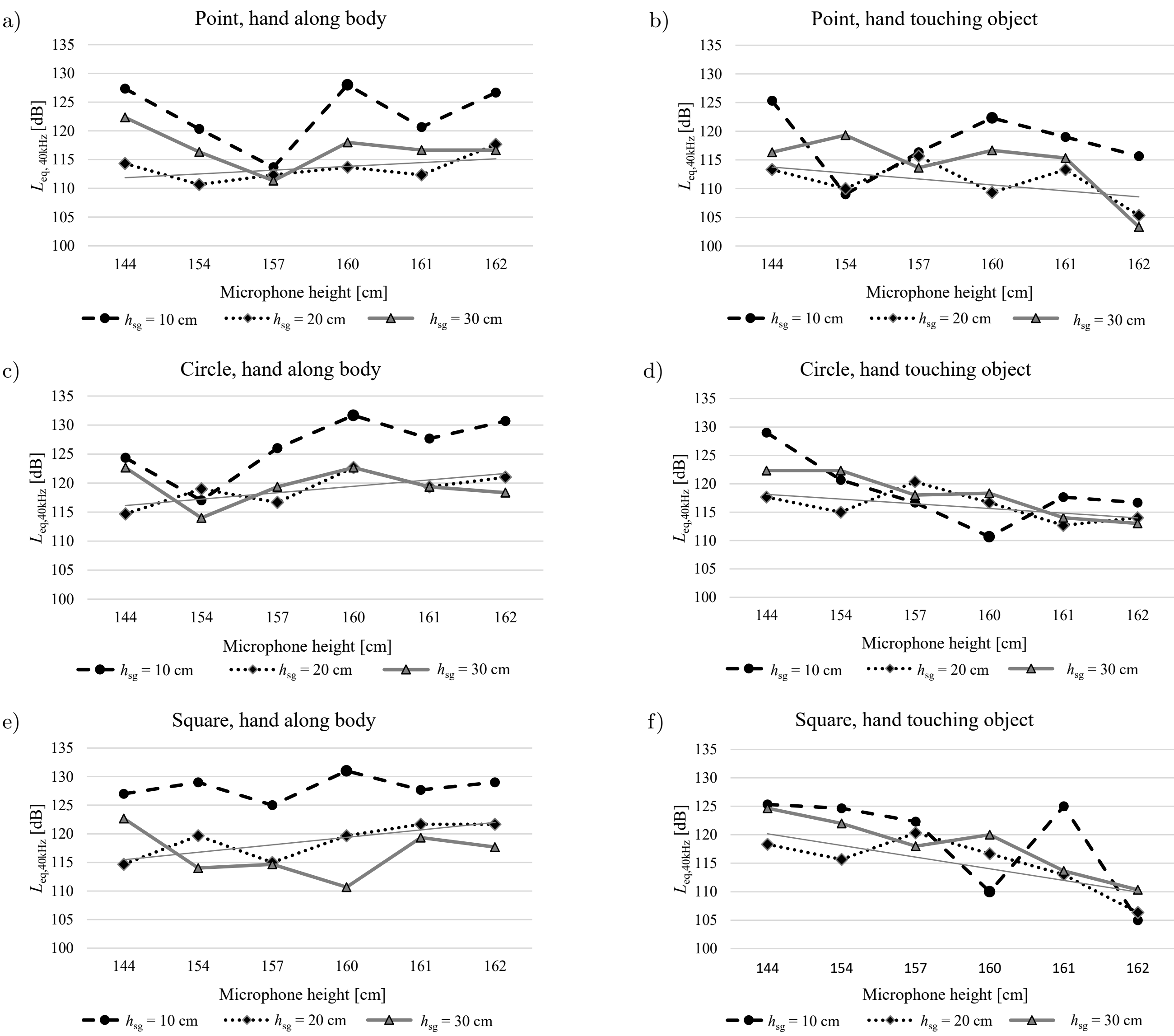

Fig. 12. Results of ultrasonic noise measurements for different haptic objects, object generation heights, participants heights, and their hands placed along body (on the left) and touching the haptic object (on the right). The solid gray line is the trend line for the test results for an object generation height of 20 cm.

the ultrasonic noise limit values applicable in Poland (Internet System of Legal Acts, 2018). The quantities characterizing ultrasonic noise in the working environment are:

– equivalent sound pressure levels in 1/3 octave bands with central frequencies ranging from 10 kHz to 40 kHz related to the 8-hour daily or weekly average working time specified in the Labour Code;
– maximum sound pressure levels in 1/3 octave bands with center frequencies from 10 kHz to 40 kHz.

The permissible values of ultrasonic noise are presented in Table 7.

Table 7. Permissible values of ultrasonic noise in Poland.

The center frequency of the 1/3 octave band [kHz]	Permissible equivalent sound pressure level related to the 8-hour daily or average weekly working time specified in the Labour Code [dB]	Permissible maximum sound pressure level [dB]
10, 12.5, 16	80	100
20	90	110
25	105	125
31.5, 40	110	130

The equivalent sound pressure level in the i-th 1/3 octave band, related to an 8-hour daily working time, $L_{\text{fi,eq,8 h}}$ is determined based on the equation:

$$L_{\text{fi,eq,8 h}} = L_{\text{fi,eq,T}_\text{e}} + 10 \log \frac{T_e}{T_o}, \tag{1}$$

where $L_{\text{fi,eq},T_e}$ is the equivalent sound pressure level in the i-th 1/3 octave band determined for the total exposure time T_e, and T_0 is the reference time of 8 h.

The results of the research of ultrasonic noise affecting the user of the haptic transducer showed that the values of the equivalent sound pressure level in the 1/3 octave band with a frequency of 40 kHz, recorded at the ear of the person using the haptic device, exceeded 110 dB in most of the conducted tests, approaching 131 dB in the worst cases. Taking into account Eq. (1), the test results indicate that with long-term, daily use of the haptic device, the permissible value of ultrasonic noise may be exceeded. If the equivalent sound pressure level exceeds 110 dB, the duration of daily use of the haptic device should be less than 8 hours. Each 3 dB increase in the equivalent sound pressure level above 110 dB means that the operating time of the haptic device must be halved in order to ensure that the permissible value of ultrasonic noise is not exceeded. Obviously, as shown in the presented research, factors influencing the amount of exposure include, among others, the type of generated object and its location, as well as the method of using the device, including the position of the user's hand. For this reason, without precisely defining the application of the transducer and how it is used, estimating the exposure to ultrasonic noise and the duration of use that will not result in exceeding the permissible value of ultrasonic noise is very difficult.

Ultrasonic noise emission tests carried out in selected points of the hemisphere with a radius of 50 cm around the transducer show that, depending on the type of the generated touch object, in some points of this hemisphere the values of the sound pressure level exceed 130 dB, sometimes reaching 137 dB. Equivalent sound pressure levels above 130 dB were also recorded in three cases of measurements with participants. This means that if the user's head is too close to the haptic transducer, e.g., as a result of the user leaning over the transducer they are using, the ultrasonic noise limit values specified for the maximum sound pressure level in the 1/3 octave band with a center frequency of 40 kHz will be exceeded.

Test results indicate that for low-lying tactile objects the acoustic energy is radiated at wider angles around the transducer. The noise exposure of the test subjects was significantly higher for objects generated at a height of 10 cm than for objects generated above that height. According to the obtained results, for low-lying tactile objects, the acoustic energy will be emitted towards the head of the person standing next to the transducer. From the point of view of protecting the employee against ultrasonic noise, it may be advantageous to use the transducer in a sitting position, so that the user's head is at a low vertical angular height relative to the haptic device, as well as avoiding generating low-lying objects.

To conclude, ultrasonic haptic technology piques the interest of many hoping to enhance the quality of human-machine interfaces and bring the dreams of the future to present day. However, many are also wary of the technology, as it employs ultrasound of high pressure levels. Appropriate studies are being conducted in order to properly assess the risk that such technology may pose to its users, including the presented paper. Presented results suggest that in order to safely use ultrasonic haptic technology, especially in work environment, specific guidelines should be created and implemented. Furthermore, additional studies should be conducted, including a wider range of devices, and a wider range of types of usage and environments, where such devices could be implemented. Considering the high sound pressure levels of ultrasonic noise emitted by haptic devices, research into the development of noise reduction measures to enable safer use of this new technology also appears necessary.

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