PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Equal annoyance contours at frequencies 4 – 1000 Hz

Ville RAJALA[1]; Jarkko HAKALA[1]; Valtteri HONGISTO[1]

[1] Turku University of Applied Sciences, Turku, Finland

ABSTRACT

Knowledge about annoyance caused by infrasound is limited. The purpose of our study was to determine equal annoyance contours (EACs) at frequencies 4 – 1000 Hz. A psychoacoustic experiment was conducted in a laboratory environment for seven participants. The participants rated annoyance of 60 sine tones. The sounds were played in 20 frequencies in range 4 – 8000 Hz with sound pressure level (SPL) corresponding to loudness of 20, 40, and 60 phon. Three EACs were determined from mean annoyance ratings. The SPL yielding to equal annoyance increased with decreasing frequency. Up to 31.5 Hz, the EACs were more close to each other than on higher frequencies, suggesting that a small increase in SPL can significantly increase perceived annoyance. The results are preliminary and final contours will be published later involving a larger number of participants, hearing thresholds, and equal loudness contours.

Keywords: Infrasound, Psychoacoustics, Equal annoyance contour

1. INTRODUCTION

Knowledge of human perception of infrasound is very limited. Many textbooks unambiguously manifest that human cannot hear sound in frequency range below 20 Hz. However, there is vast research evidence that the hearing range can extend at least down to 3 Hz (1, 2).

If infrasound is perceivable, it can also be annoying. Thus, it is important to study human perception of audible infrasound. Typical psychoacoustic phenomena that are examined are hearing threshold, loudness, and annoyance. Investigating annoyance is of primary interest since noise annoyance is the most usual adverse health effect of sound and some countries have also published upper limits the sound pressure level (SPL) of infrasound for one-third octave bands 10, 12.5 and 16 Hz.

Pure sine tones are the simplest form of sound and thus a natural base for basic research of perception of sound. For example, hearing threshold and equal loudness contours are usually determined by using sine tones (3, 4).

Earlier research of hearing threshold of infrasound suggests that infrasound is audible but require high SPL to be perceivable (1). This sets special requirements for sound reproduction devices. The equipment must be able to produce high SPL in low frequencies with negligible distortion.

Only few studies deal with the annoyance of infrasound (5, 6). *Equal annoyance contour* (EAC) describes SPL for frequencies to be perceived equally annoying. Although the concept is analogue to equal loudness contours, there is very little knowledge of EACs (5, 7). The purpose of our study was to determine EACs at frequencies 4 – 1000 Hz.

2. METHODS

2.1 Overall design

We conducted a psychoacoustic experiment in a laboratory setting. The independent variable was the experimental sound and the dependent variable was the subjective measure *annoyance*.

2.2 Participants

The participants were recruited through Turku University of Applied Sciences mailing lists. The requirements for participants were: age in range 19 – 26 years, native Finnish language, and ability to conduct the experiment without using eyeglasses. The eyeglasses were set as an exclusion criterion

[1] ville.rajala@turkuamk.fi; jarkko.hakala@turkuamk.fi; valtteri.hongisto@turkuamk.fi

due to the use of headphones in the experiment. It was instructed that one should not participate the experiment during a flu or any other illness. The participant were not informed that the frequency range extends to infrasound region. Seven voluntary persons (6 female, 1 male) participated in the experiment. The participants were native Finnish speakers and their age ranged from 19 to 26 years (mean 23, standard deviation 2). The participants received a 30 euro gift token as a compensation for their participation. None of the participants was professionally related to our research group.

2.3 Sounds

The sounds were 60 sine tones in 20 frequencies listed in Table 1. The sounds were generated by using MATLAB R2017b (MathWorks Inc., Natick, MA, USA). Every frequency was played in three SPLs. The SPLs were selected to correspond the loudness levels 20, 40, and 60 phon. The SPL was calculated for frequencies 20 – 8000 Hz by using methods described in standard ISO 226 (4). For infrasound, SPL was acquired from reference (8). The sounds were saved in standard audio file format (.wav, 24 bit, f_s = 48 kHz).

Table 1 – The 20 frequencies in the annoyance testing and their SPLs.

Frequency, Hz	20 phon SPL, dB	40 phon SPL, dB	60 phon SPL, dB
4	120.7	124.8	127.4
5	118.0	122.0	126.0
6.3	115.0	120.0	125.0
8	109.4	114.3	118.1
10	107.0	112.0	116.0
12.5	103.0	108.0	115.0
16	95.1	101.3	106.9
20	89.6	99.9	109.5
25	82.7	93.9	104.2
31.5	76.0	88.2	99.1
63	58.6	73.1	85.9
125	43.9	60.6	75.6
250	32.0	50.4	67.5
500	23.4	43.1	62.1
1000	20.0	40.0	60.0
1500	21.4	42.5	63.2
2000	18.2	39.2	60.0
3000	14.3	35.6	56.4
4000	15.1	36.6	57.6
8000	31.5	51.8	71.7

2.4 Equipment and validation of the sounds

During the experiment the participant was located inside a pressure chamber (Figure 1). The chamber was located in an anechoic room in in Salo, Finland. The chamber was equipped with a ventilation system to maintain good air quality and constant temperature throughout the experiment.

Frequencies in range 4 – 63 Hz were played by using a loudspeaker and frequencies in range 125 – 8000 Hz by using headphones. The devices received signal from a sound card (D-audio USB Pre-Amp, Duran Audio Ltd., The Netherlands) connected to a computer.

The SPL was measured and verified individually for all sounds used in the experiment. Frequency-wise SPL correction was applied to compensate the anomalies in the frequency response of the system. The SPL was verified in range 4 – 63 Hz by using a precision sound level meter (Norsonic NOR150), a microphone preamplifier (G.R.A.S. 26CI, Denmark), and a microphone (G.R.A.S. 46AZ, Denmark). In range 125 – 8000 Hz, the SPL was verified with a head-and-torso simulator (Brüel&Kjær 4100, Denmark), a microphone power supply (Bruel&Kjaer 2804, Denmark), and a portable multitrack recorder (TASCAM DR-680MKII, Montebello, USA). MATLAB was used to measure and adjust the SPL to match the target values. The frequency dependent diffuse-field correction was applied (Brüel&Kjær Pulse Sound Quality 15.1.0, Denmark), which compensates the amplification of SPL at high frequencies caused by the artificial ear of the head-and-torso simulator.

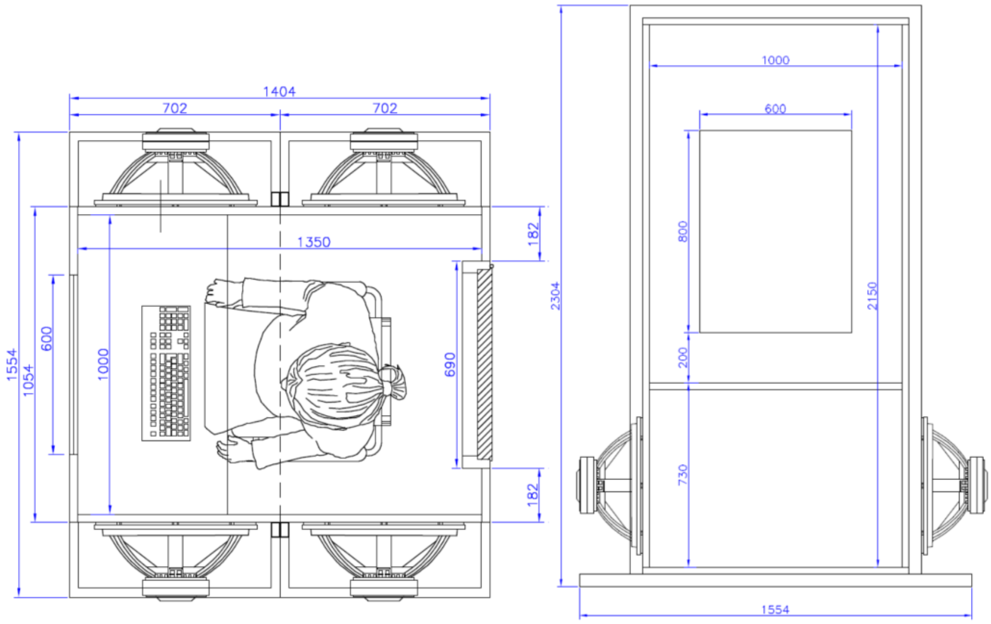

Figure 1 – Overview and the dimensions of the pressure chamber used in the experiment.

2.5 The experimental procedure

Each participant rated the annoyance of all sounds in Table 1. One participant at a time conducted the experiment by using a computer and a MATLAB based software with a graphical user interface. The experiment constituted of 12 phases. In phase 1, the participant read and signed information consent form. The phases 2, 3, and 5 included loudness rating which methods and results are not presented in this paper. Phase 7 was a hearing threshold test which results are not discussed in this paper. Phases 4, 6, and 8 were short voluntary breaks.

Phase 9 was a rehearsal for annoyance rating to make the participant familiar with the procedure and to allow them ask any questions regarding the rating procedure. The participant rated six sounds. The ratings given in the rehearsal phase were not analyzed.

The annoyance rating (phase 10) was conducted in close relationship to standard ISO 15666 (9). The participants were inquired a question "*How much does the sound bother, disturb, or annoy you?*" The eleven step response scale was from 0 to 10, where 10 was labeled as "Extremely annoying" and 0 as "Not at all". The participants were instructed to use the full scale and try to make their answers as consistent as possible. As some of the sounds were close to the hearing threshold, the participants could also respond: "*The sound is inaudible*". If the participant felt that the sound was associated with other sensations than a hearing sensation, they could express it by selecting a button labeled "*Auditive sensation is associated with other sensation*". The participants had to listen the sound for 5 seconds before they were able to give the rating. The sounds were played in one of four predetermined pseudorandom orders. The four orders were decided so that the same sound was never presented at same point in different orders.

In phase 11 the participant described the possible other sensations associated to the played sounds. The results are not presented in this paper. After the experiment, the participants received a gift token and a short introduction of the goals and impacts of the conducted experiment. The participants had a change to ask any questions related to the experiment. The participants were not informed that the experiment included infrasound. The participants stayed in the laboratory on average 2.5 hours.

2.6 Determination of equal annoyance contours

The EACs were determined by using the following method:

1. Mean annoyance of every sound was calculated by using all annoyance ratings.
2. A linear fit was determined using three mean annoyance values and their corresponding SPL by using equation

$$A = kL_i + b, \quad (1)$$

where k and b are the coefficients of the linear fit and L_i is the SPL. The fit was calculated for all 20 frequencies. Figure 2 shows an example of the fit for frequencies 4 and 1000 Hz.

3. Annoyance of 1000 Hz at SPLs 20, 40, and 50 dB was selected to be the basic points of the EACs. The annoyance values corresponding to these levels (A_{20}, A_{40}, A_{50}) were calculated by using equation (1).
4. SPL corresponding to annoyance A_{20}, A_{40}, and A_{50} was calculated in all frequencies by using equation

$$L = (A_i - b)/k, \quad (2)$$

where b and k are the linear fit coefficient of the frequency and A_i=(A_{20}, A_{40}, A_{50}). Figure 2 shows an example of SPL calculation for frequencies 4 and 1000 Hz.

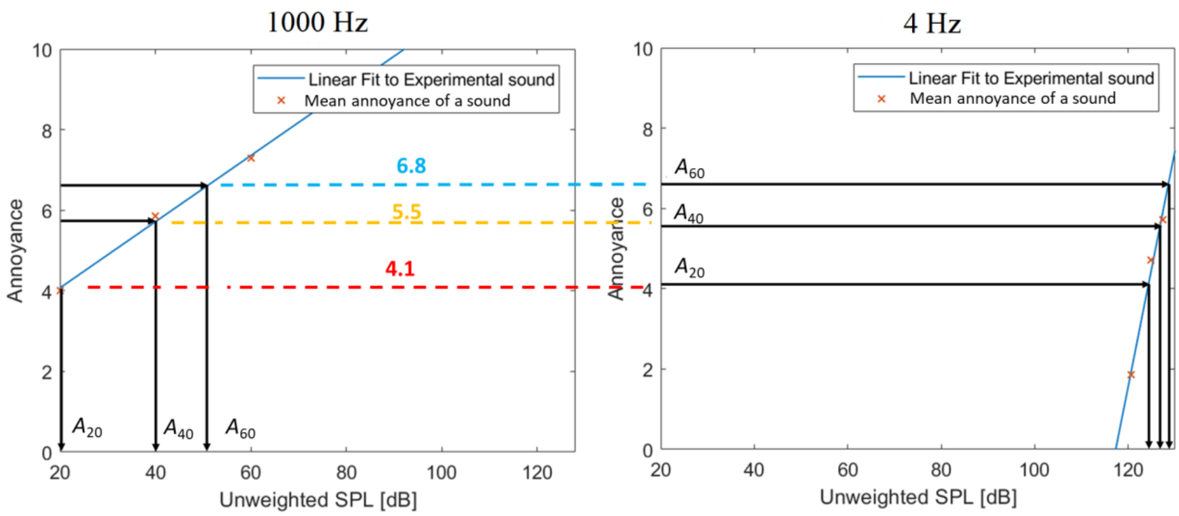

Figure 2 – A visualization of the linear fit to the mean annoyance for frequencies 4 and 1000 Hz. The arrows demonstrate how the SPL corresponding annoyance A_{20}, A_{40}, and A_{50} is calculated. The annoyance values were A_{20} = 4.1, A_{40} = 5.5, and A_{50} = 6.8.

3. RESULTS

The calculated mean annoyance values as a function of frequency are shown in Figure 3a. Figure 3b includes the three EACs in frequency range 4 – 1000 Hz calculated according to the method described in Section 2.6.

4. DISCUSSION

4.1 Findings

High mean annoyance values were achieved for frequencies 2000 Hz onwards. This suggests that in our experiment high frequency sounds were usually perceived more annoying than infrasound.

SPL yielding equal annoyance increases with decreasing frequency. For infrasound our EACs have SPL values over 100 dB. The three EACs are much closer to each other in frequencies below 31.5 Hz than in frequency region 125 – 1000 Hz. This suggest that a small increment in SPL in low frequencies can increase the perceived annoyance rather much.

We only calculated the EACs in frequency range 4 – 1000 Hz because it was not possible to determine EACs reliably above 1000 Hz.

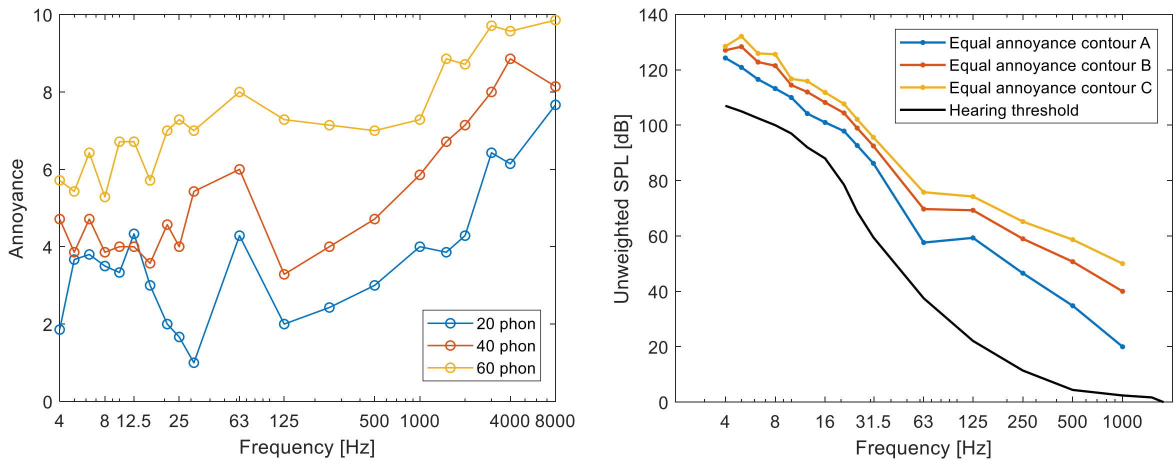

Figure 3 – a) The mean annoyance ratings of all sounds in the experiment as a function of frequency. The annoyance response scale was from 0 to 10. b) Three equal annoyance contours as a function of frequency. Equal annoyance contour describes the SPL where the sounds are perceived equally annoying. The hearing threshold is composed from references (3) and (10).

4.2 Comparison with other studies

Andresen and Møller (5) have published EACs in frequency range 4 – 1000 Hz. They reported annoyance in frequencies 4, 8, 16, 31.5, and 1000 Hz, while we reported annoyance contours by using 15 frequencies. Their EACs with base point at 20 dB and 40 dB in 1000 Hz can be compared to our contours. They found equal relationship that smaller frequencies require higher SPL to be perceived equally annoying as high frequencies. Further, they describe that the EACs are very close to each other in infrasound. We noticed the same phenomenon. However, our curves had higher SPL than those of reference (5). The difference was about 15 dB for some frequencies. Further research is needed to investigate the reason for the difference. One must note that our results involve only seven participants and the uncertainty can be high.

4.3 Future research

Annoyance of infrasound with SPL closer to hearing threshold (under 20 phon) should be examined. EACs are very close to each other in infrasound region. This suggest that small increments in SPL in infrasound can have a significant impact on perceived annoyance. Thus, infrasound with SPL slightly over the hearing threshold can be annoying.

5. CONCLUSIONS

An experiment was conducted to determine equal annoyance contours (EACs) in frequency range 4 – 1000 Hz. EACs were calculated for three levels, having basepoints at SPL of 20, 40, and 50 dB at 1000 Hz. SPL yielding equal annoyance increased with decreasing frequency. From 31.5 Hz and below the EACs were much closer to each other than on higher frequencies, suggesting that small increase in SPL in low frequencies can increase annoyance significantly. The results were produced from data of seven participants and are preliminary. The achieved EACs are preliminary and final contours will be published later involving a larger number of participants, hearing thresholds, and equal loudness contours.

REFERENCES

1. Whittle LS, Collins SJ, Robinson DW. The audibility of low-frequency sounds. J Sound Vib. 1972;21(4):431-48.
2. Sakamoto S, Yokoyama S, Yano H, Tachibana H. Experimental study on hearing thresholds for low-frequency pure tones. Acoust. Sci. & Tech. 2014;35(4):213-8.
3. International Organization for Standardization. ISO 389-7:2005. Acoustics. Reference zero for the

calibration of audiometric equipment. Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions. Geneva, Switzerland: ISO; 2005.
4. International Organization for Standardization. ISO 226:2003(E). Acoustics — Normal equal-loudness-level contours. Geneva, Switzerland: ISO; 2003.
5. Andresen J, Møller H. Equal Annoyance Contours for Infrasonic Frequencies. J Low Freq Noise V A. 1984;3(3):1-9.
6. Møller H. Annoyance of Audible Infrasound. J Low Freq Noise V A. 1987;6(1):1-17.
7. Kurakata K, Mizunami T, Matsushita K. Sensory unpleasantness of high-frequency sounds. Acoust Sci Technol. 2013;34(1):26-33.
8. Møller H, Andresen J. Loudness of pure tones at low and infrasonic frequencies. J Low Freq Noise V A. 1984;3(2):78-87.
9. International Organization for Standardization. ISO/TS 15666:2003. Acoustics – Assessment of noise annoyance by means of social and socio-acoustic surveys. Geneva, Switzerland: ISO; 2003.
10. Watanabe T, Møller H. Low Frequency Hearing Thresholds in Pressure Field and in Free Field. J Low Freq Noise V A. 1990;9(3):106-15.