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Equal Annoyance Contours for Infrasonic Frequencies

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Abstract

Eighteen subjects (age range: 18-25) rated the annoyance of 18 sound stimuli on a graphic scale (four infrasonic frequencies at different intensity levels and four levels of 1000 Hz octave-filtered pink noise for reference). The exposure time for each stimulus was 15 minutes. The order of exposures was determined from a latin square and each subject was exposed to only one stimulus per day. Equal annoyance contours were constructed to connect points that produced the same annoyance rating. The equal annoyance curves demonstrate that the lower the frequency the greater must be the sound pressure to cause a given amount of annoyance. Compared with 1000 Hz the curves lie much closer together in the infrasonic range. The closeness of the curves in the infrasonic region implies that small changes in sound pressure may cause relatively large changes in annoyance.

Based on the experimental results a weighting curve with a slope of 12 dB per octave is suggested for the assessment of annoyance and loudness in the infrasonic range. A curve with the same slope and an attenuation of O dB at 10 Hz is at present under consideration in the International Standardization Organization. For environmental purposes a maximum permitted level of 95 dB is proposed for use with this curve.

1. Introduction

Infrasound, at pressure levels that can be heard, is quite common in our daily surroundings, and may cause considerable annoyance. A few countries have introduced measurement procedures and hygienic limits, but there has been a deplorable lack of experimental facts on which to base such limits.

For audio frequency sound the agreement between annoyance and loudness is usually so good that dB (A) and similar measures developed from loudness investigations can be used as an estimate of the annoyance effect. It might therefore seem a possibility to use the equal loudness curves already described for the infrasound region (1, 2, 3, 4) as a base for an extension downward of existing weighting curves. However, the close relation between annoyance and loudness found at higher frequencies may not exist in the infrasound region, because very low frequencies are perceived as a throbbing sound instead of a tone, and this may have an influence on the degree of annoyance experienced.

Several investigations (5, 6, 7, 8, 9, 10) seem to indicate that the assumed agreement between loudness and annoyance already becomes questionable in the low frequency range 20-100 Hz.

The aim of the present project has therefore been to establish equal annoyance contours in the frequency range 4-31.5 Hz which may be used to determine hygienic limits.

2. Method

2.1 Subjects

Eighteen engineering students participated (15 men and 3 women; age range: 20-25). All were paid volunteers, and all were familiar with infrasonic stimuli from their participation in our work on equal loudness curves for the infrasonic range. An audiometeric test ensured normal hearing.

2.2 Sound conditions

To simplify matters - in our present state of ignorance - we used only pure tones as stimuli and have - for reference - also included a 1000 Hz octave-filtered pink noise. To make comparisons possible we decided to use the same frequencies as in our work on equal loudness. Based on results from the loudness investigation four intensity levels that ensured a satisfactory dynamic range for each frequency were chosen. Because it was not possible to achieve a sufficiently high sound pressure in the test room, we were, however, not able to test reactions to 2 Hz, and for the same reason 4 Hz was only presented at two levels. The 18 stimuli used are shown in Table 1. (see section 3, results)

2.3 Apparatus

The experiments were performed in a 16 cubic metre pressure chamber (11). In order to simulate a living room situation, the test room was fitted with a carpet, cosy lamps and an easy-chair for the subject. The infrasound was generated by 16 electrodynamic loudspeakers, driven by a B & K 2712 power amplifier. The loudspeakers were concealed in the wall behind a screen. The 1000 Hz noise was produced by an equalized high fidelity sound reproduction system with the loudspeaker placed 140 cm from the subject. The sound pressure levels given in Table 1 are levels measured before the experiment, at the point where the subject's head would be during the experiment. An HP 21MX computer controlled the experimental session.
The subjects indicated the degree of annoyance experienced on a 150 mm long graphic scale. The left end was marked "not at all annoying" and the right end "very annoying" (see figure 1). This type of scale has a number of advantages. It leaves the subject greater freedom of discrimination, the problems of interpretation of verbally graduated scales are eliminated, and it is easy to administer.

2.4 Experimental design

Each subject was exposed to the whole range of stimuli. To balance out possible carry-over effects the order of exposures for each subject was determined from a special 18 × 18 latin square that ensured that no stimulus was preceded by any other stimulus more than once (12). Each subject was exposed to only one stimulus per day for 18 days, and at the same hour every day.

2.5 Procedure

The subjects received a written instruction with a description of the experimental procedure. Each session lasted 20 minutes and during this period the subject was alone in the test chamber. He (or she) was supplied with two newspapers and instructed to read until the end of the session. After five minutes of silence the sound stimulus was presented for 15 minutes, and then, after a delay of 15 seconds, the subject was asked to indicate, on the graphic scale, the degree of annoyance experienced (Question 1). In the instruction the subject was requested to accept the label "not at all annoying" as descriptive of his situation during the five minutes of silence, and to indicate the degree of annoyance during sound exposure in relation to this definition.
After a further delay of 20 seconds the subject was asked to indicate, on the same scale, the degree of annoyance that he would probably feel at home, if his neighbour produced the same sound for two hours (Question 2).
One minute after the sound exposure ended, the subject was requested to adjust the sound of a 1000 Hz octave-filtered pink noise so that is was perceived as equally annoying as the sound heard while reading. This task was primarily incorporated for methodological reasons, and the results will not be discussed in this paper.
When the subjects had been exposed to the series of sound stimuli, they were asked to indicate on the graphic scale where they would place the label "unacceptable annoyance" if the label referred to noise in their home environment (Question 3).
After the termination of each experimental sitting the subjects were allowed - in writing - to comment freely on the stimulus situation.

Figure 1. The graphic scale used by the subjects to indicate degree of annoyance.

3. Results

3.1 Questions 1 and 2

Degree of annoyance was measured in mm, and means and standard deviations for each of the 18 stimuli are presented in Table 1.

Table 1. Means and standard deviations for Question 1 (Annoyance during experiment) and Question 2 (Imagined annoyance at home).

Stimulus		Question 1		Question 2	
Frequency (Hz)	SPL (dB)	Mean* (mm)	SD (mm)	Mean* (mm)	SD (mm)
1000	20	6	7	11	13
	40	25	20	38	26
	60	54	36	71	36
	80	115	33	126	27
31.5	75	17	22	24	33
	84	39	37	56	50
	93	67	37	85	37
	102	93	39	109	33
16	95	21	29	24	31
	102	56	47	65	49
	109	80	38	97	40
	116	114	33	128	27
8	109	34	33	49	46
	114	61	41	69	41
	119	88	41	102	38
	124	102	40	118	29
4	120	24	28	36	46
	124	68	43	83	48

*n = 18 for each mean

The main difference between results from the two questions is that most of our subjects would find the same sound more annoying if heard at home. For both questions the relationship between sound pressure level and annoyance rating is linear for the infrasonic frequencies. The correlation coefficients for 31.5, 16, 8 and 4 Hz were respectively: 0.999, 0.998, 0.991 and 1.000 (Question 1) and 0.998, 0.998, 0 .991, and 1.000 (Question 2). Means for Question 2 are presented graphically in figure 2 together with the regression lines for the infrasonic frequencies.

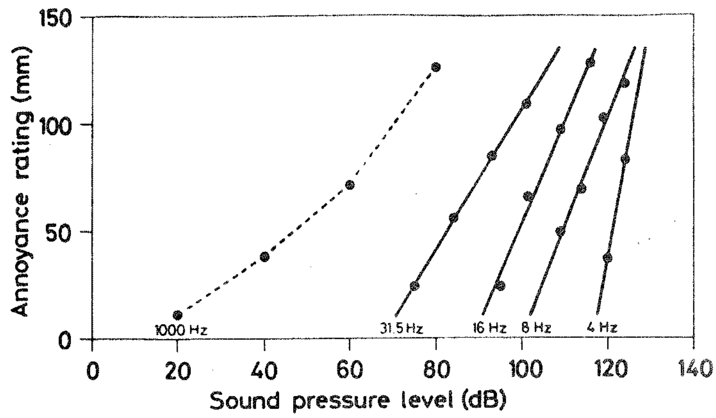

Figure 2. Relation between sound pressure level and annoyance rating (Question 2: Imagined annoyance at home). The filled circles represent the means for each stimulus, and the lines are regression lines for each infrasonic frequency.

Equal annoyance points have been determined in the following way: It is assumed that the relation between the sound pressure level and degree of annoyance for a given infrasonic frequency is expressed by the equation for the regression line:

$$y = \hat{\alpha} + \hat{\beta}(x - x_0) \tag{1}$$

$$\text{hence} \quad x = \frac{y - \hat{\alpha}}{\hat{\beta}} + x_0$$

where y is the annoyance in mm, x the corresponding sound pressure level, x_0 the mean of the sound pressure levels used at a given frequency, $\hat{\alpha}$ the mean annoyance for that frequency, and $\hat{\beta}$ the slope of the regression line for that frequency. In order to obtain dB values for equal annoyance points, the mean annoyance found for 1000 Hz at 20, 40, 60, and 80 dB respectively has been inserted in (1) as y.

The inaccuracy of the estimate of the dB values for a given equal annoyance point is a function of the inaccuracy of the observed annoyance value for 1000 Hz and of $\hat{\alpha}$ and $\hat{\beta}$ (x_0 is a constant). The variance for annoyance values at 1000 Hz were calculated from the observations, and estimates of the variances for $\hat{\alpha}$ and $\hat{\beta}$ were obtained from the regression analysis; thus through linearization of (1) as a function of y, $\hat{\alpha}$ and $\hat{\beta}$,an approximate estimate of the SD of the dB values can be calculated from the following equation:

$$\delta(x) = \sqrt{\frac{\delta^2(y) + \delta^2(\hat{\alpha}) + \delta^2(\hat{\beta})(x - x_0)^2}{\hat{\beta}^2}} \tag{2}$$

Means and standard deviation of equal annoyance points calculated for Question 1 and Question 2 are shown in Table 2 .

The resulting equal annoyance contours shown in Figure 3 are determined from answers to Question 2 (imagined annoyance at home), because this question bears a closer resemblance to the task required in similar studies concerned with the annoyance effect of audio frequency sound. As can be seen from Table 2, the differences between pairs of equal annoyance points from the two questions are small and unsystematic, and can therefore be ignored. The equal annoyance curves demonstrate the not very surprising fact that the lower the frequency the greater must be the sound pressure to cause a given amount of annoyance. Compared with 1000 Hz the curves lie much closer in the infrasonic range. This change is already seen at 13.5 Hz, but becomes even more pronounced with decreasing frequency.

Table 2. Mean sound pressure levels in dB (and their standard deviations) for equal annoyance points in the infrasonic range, calculated for Question 1 and for Question 2, with 1000 Hz as reference frequency.

		Reference SPL (dB)			
Question	Frequency (Hz)	20	40	60	80
1	31.5	71.5 (2.8)	78.4 (2.6)	88.5 (3.3)	109.7 (4.3)
	16	91.2 (2.1)	95.7 (1.9)	102.4 (2.3)	116.4 (2.5)
	8	102.3 (2.7)	106.5 (2.3)	112.8 (2.2)	125.9 (2.6)
	4	118.4 (1.1)	120.2 (0.9)	122.8 (1.0)	128.2 (1.9)
2	31.5	70.3 (3.1)	78.9 (2.8)	89.4 (3.0)	106.9 (3.6)
	16	91.8 (1.9)	97.2 (1.8)	104.0 (1.9)	115.2 (1.9)
	8	101.2 (2.8)	106.8 (2.3)	113.7 (2.0)	125.1 (2.2)
	4	117.9 (1.6)	120.2 (1.1)	123.0 (1.0)	127.7 (2.1)

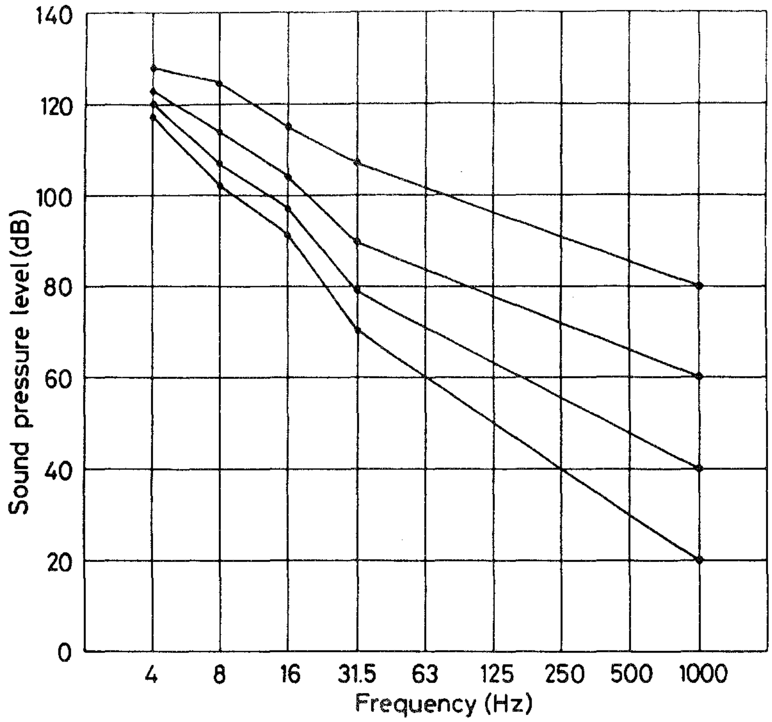

Figure 3. Equal annoyance contours based on results from Question 2 (Imagined annoyance at home).

3.2 Question 3

The mean score for Question 3 (unacceptable annoyance) for the 18 subjects was 50 mm. For each frequency the sound pressure levels that correspond to a 50 mm degree of annoyance were calculated from equation (1). The maximum sound pressure that our subjects would tolerate in home surroundings is 83 dB at 31.5 Hz, 100 dB at 16 Hz, 109 dB at 8 Hz, and 121 dB at 4 Hz. The means are presented graphically in Figure 4.

3.3 Comments

Information extracted from the comments must be treated with caution as subjects were not obliged to make any comments. However some general trends emerged and seem worth mentioning. Exposure to infrasound - in contrast to the 1000 Hz noise - gave rise to physiological complaints such as pressure in the ears, at the eardrum, or in the head - headache or a tendency to headache -

and interference with breathing. Other complaints often mentioned were vibrations of clothes and newspapers, and changes in the perception of the sound caused by body movements or movements of the newspaper.
The comments also reflected that there were large individual differences as to how easily the subjects adapted to the sound exposures.

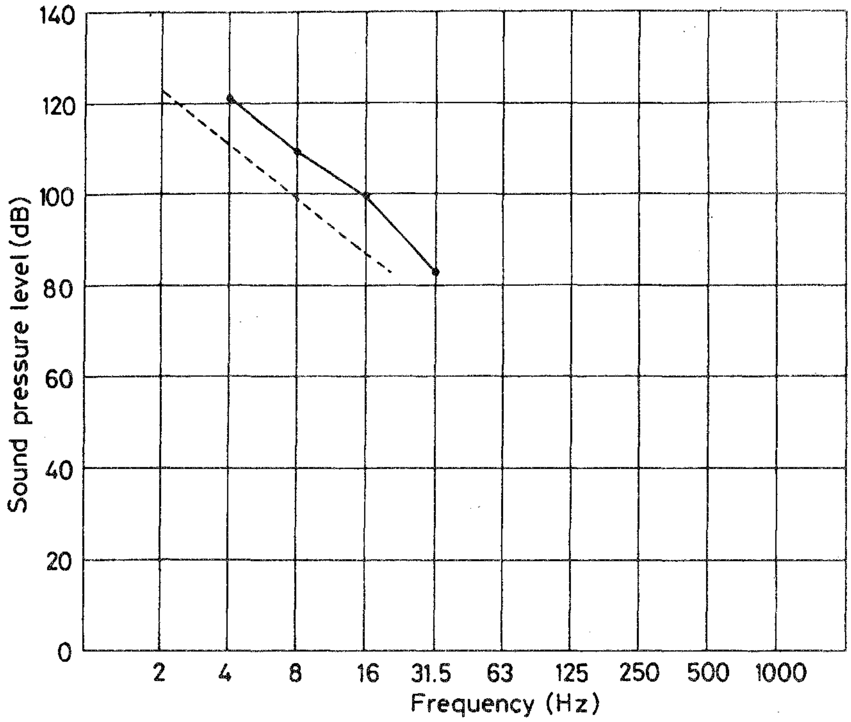

Figure 4. The filled circles represent means for Question 3 (unacceptable annoyance) converted to sound pressure levels. The broken line has a slope of 12 dB per octave and passes 95 dB at 10 Hz; thus the line represents the upper limit of exposure that will result if our suggested criterion of 95 dB is used in connection with the ISO P-weighting curve.

4. Discussion

The closeness of the curves in the infrasonic region implies that small changes in sound pressure may cause relatively large changes in annoyance. From an environmental point of view this is important because a modest reduction in sound pressure will, in some cases, be enough to alleviate annoyance caused by infrasonic noise. It also means that accuracy is crucial when measuring infrasound, and that specific demands must be made on the measuring equipment.
Several investigations (5, 6, 7, 8, 9, 10) have shown that dB(A) values are unsatisfactory for the assessment of annoyance from sounds containing a considerable amount of low frequency energy. It has been found that: 1) Very annoying sounds sometimes have rather low dB(A) values and 2) Sounds that differed only slightly when measured with the A-curve often were far apart in annoyance rating. The disagreement between dB (A) values and the experience of annoyance is a consequence of the level - dependent slopes of the annoyance curves in the low frequency region, and the closeness of the curves at the lowest frequencies. The following two examples illustrate the problem: 1) A 112 dB 20 Hz tone is rated as annoying as an 80 dB noise band at 1000 Hz (see Figure 3) although the sound level is as low as 62 dB (A). 2) Two 20 Hz tones with dB (A) values of 41 and 49 will have sound pressure levels of 91 and 99. From Figure 3 it can be seen that these two tones will lie on two different annoyance curves and that the difference in annoyance will be as large as the difference between 40 and 60 dB at 1000 Hz.

4.1 Comparison with equal loudness curves

The disagreement between dB (A) values and ratings of annoyance has often been interpreted as a difference between the experience of loudness and the experience of annoyance. In Figure 5 the equal loudness curves described by us (3, 4) are shown together with the equal annoyance curves. The two sets of curves are remarkably similar in their general shape, especially when one considers that they have been established by two very different methods, and that the number of subjects used in the two studies is rather small. Thus the relation between loudness and annoyance found at higher frequencies seems to hold for the low and infrasonic regions too, and the explanation of the disagreement between dB (A) values and annoyance ratings could equally well have been given on the basis of the shape of the loudness curves.

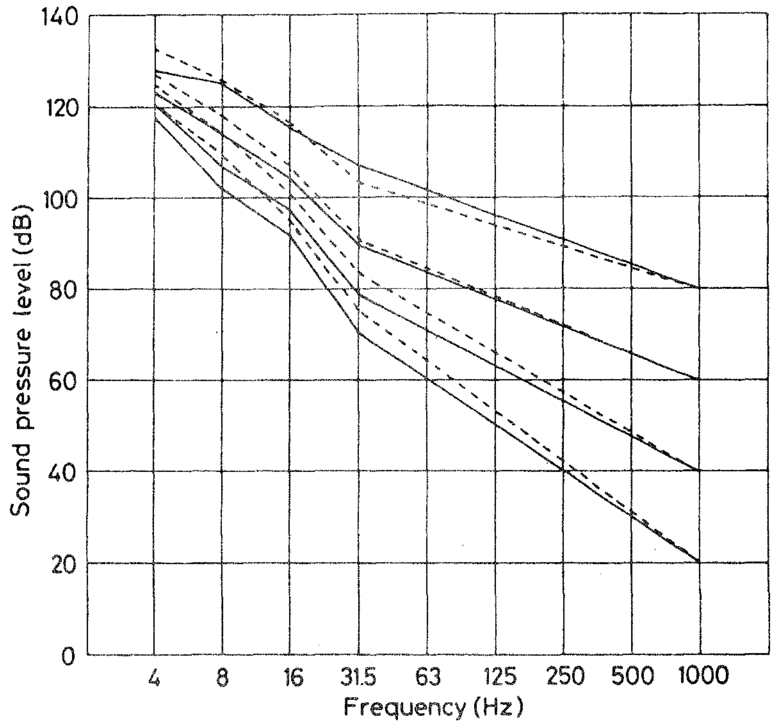

Figure 5. Comparison of equal loudness contours from Møller and Andresen (3,4) (broken) and the equal annoyance contours found in this investigation. Notice: equal loudness points not comparable with equal annoyance points have been omitted from the loudness curves.

It should be mentioned that although the two sets of curves are similar in shape, the annoyance curves lie slightly lower than the loudness curves; a preliminary statistical analysis seems to indicate that this difference is significant; a more thorough analysis will, however, be pulished later.

4.2 Weighting Curves

For practical applications it would be convenient if one weighting curve could cover both the audio and the infrasonic frequency ranges. However, the fact that the annoyance and the loudness curves show a decreasing steepness in the low frequency region with increasing level implies that a number of curves with different relative weightings of medium, low and infrasonic frequencies would be necessary.

As the slopes of the equal loudness and equal annoyance curves are reasonably independent of the sound pressure level within the infrasonic range, a single weighting curve for this frequency region would be a better solution (possibly covering a part of the lower audio frequency range too).

The Technical Committee 43 of the International Standardization Organization is considering a proposal for procedures to be used when measuring noise in the infrasonic range (13). The proposal comprises two weighting curves with different slopes, namely 6 dB per octave (G2-weighting) & 12 dB per octave (G1-weighting). The mean slopes found in our investigation were 12.3 dB per octave for the loudness curves (2-31.5 Hz) and 11.7 dB per octave for the annoyance curves (4-31.5 Hz). It is clear that the curve with a slope of 12 dB per octave will give the best estimate of loudness or annoyance.

4.3 Hygienic limit

The results discussed so far only refer to the relative annoyance experienced when exposed to certain stimuli, and give no information as to acceptable exposure levels in real life. Question 3 (unacceptable annoyance) was designed to obtain information about this, and it would be interesting to use the ISO 12 dB per octave weighting curve in connection with the results obtained from this question. The ISO curve would have an attenuation of O dB at 10 Hz, and if the levels given in Figure 4 are measured with the G1-curve, a value around 105 dB will result. However, the means here reported camouflage the great individual differences in sensitivity to infrasound, and a limit based on means will in many cases be too high. A better criterion would probably be around 95 dB (G1). The broken line in Figure 4 connects points that will give values of 95 dB when measured with the G1-curve.

5. Projected Experiments

Because so little is known about annoyance caused by infrasound this study has been very limited in scope i.e. only pure tones have been used as stimuli and only young students as subjects. To extend the validity of the reported results it will be necessary to use non-sinusoidal infrasonic stimuli, and to use older persons and different occupational groups as subjects. Outside the laboratory infrasound frequently occurs at places of work and is normally mixed with higher frequencies, thus it has also been planned to study the effect of infrasound on certain performance tasks, and investigate reactions to various combinations of infrasound and audio frequency sound.

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