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The Audibility of Low Frequency Sounds

by

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Introduction

The first classical determination of equal loudness relations for pure tones by Fletcher and Munson in 1933 was followed in 1937 by that of Churcher and King. In 1956 Robinson and Dadson[1] at the National Physical Laboratory redetermined the equal loudness contours, extending these down to 25 Hz. The resulting curves have since been incorporated in an ISO recommendation R226 (1961).

Recently there has been an increasing interest in sounds of even lower frequency. These sounds are propagated in the atmosphere with low loss, are poorly attenuated by normal walls and partitions and their long wavelength makes conventional absorbent treatments ineffective. Sources of low frequency sound range from multi-stage rockets used in space projects, large turbojet engines, diesel engines used in road rail and sea transport, to oil burners and ventilating systems.

The work to be described was aimed at providing some extension to the existing equal loudness and threshold contours down to 3.15 Hz, with an overlap covering the range 25 to 50 Hz. Cross checking of the results by means of direct magnitude estimation is in progress and will be reported later.

Condition of Listening

The ISO equal loudness contours relate to binaural, free-field, frontal incidence conditions which, however, are very difficult to provide at low frequencies. On the other hand the absence of diffraction effects means that the configuration of the sound field is then relatively unimportant. Accordingly we adopted whole body immersion in a uniform sound pressure generated in a pressure cabinet. This preserves the binaural requirements whilst avoiding the disadvantages inherent in the use of earphones at low frequencies, namely the elevation of the threshold in the latter case, due to physiological noise.

Apparatus

(a) Pressure cabinet This was a prism with trapezoidal base of internal dimensions 1.2 m by 0.6 m by 1.48 m high, just large enough to accommodate a seated subject in comfort, constructed of concrete blocks rendered on both sides and equipped with double wooden doors having highly effective seals. A heavy steel pipe of internal diameter 65 mm and length 465 mm was set through the narrow end wall.

(b) Loudspeakers No single sound source was suitable for all frequencies and intensities used in the investigation and various combinations of direct radiator loudspeaker were used. One arrangement was a pair of 457 mm dia. 50 watt loudspeakers, having rubber edge terminations, and long throw magnetic systems, feeding into a rigid box of about 0.12 m^3. The box was attached to the flange of the pipe entering the cabinet by a flexible bellows of length 535 mm and internal dia. 70 mm. The arrangement acted as a low-pass acoustic filter, and resulted in a useful reduction in the harmonic distortion produced by the loudspeakers, the requirements being particularly stringent due to the slope of the threshold curve.

(c) Electronic apparatus This consisted basically of low-distortion oscillators, various 1 dB step attenuators, a two channel electronic switch giving tone bursts starting and finishing at zero crossing, or having any desired rise or fall time, and a DC coupled power amplifier of about 150 watts r.m.s. per channel. A low-pass filter in the loudspeaker line was effective in reducing circuit noise to well below audibility in the booth.

Physical measurements

Measurements of sound pressure were made with a 1 inch condenser microphone calibrated to below 2 Hz using an optical pistonphone. Distortion measurements were made on the acoustical stimuli using a 1/3-octave band analyser (discrimination 50 dB at $\pm$ 1 Octave) in conjunction with a variable high-pass active filter having a cut off rate of 96 dB per octave. The results in Table I show the level of the 2nd, 3rd and 4th harmonics relative to the fundamental for sound pressure levels ranging from 17 to 33 dB above mean threshold.

TABLE I

Hz	Fundamental SPL (db re 2.10^{-5} N/m^2)	Relative level of harmonic dB 2	3	4
3.15	139	- 33	- 32	- 57
6.3	136	- 41	- 43	- 66
12.5	125	- 52	- 61	- 72
25	108	- 52	- 63	- 66

Reference to Table II shows that even at the high sound pressure levels used in the investigation the distortion products are well below the hearing threshold.

Psychophysical method

Threshold measurements were made using a Békésy attenuator. In order to offset the effect of the rapid increase in sensation with sound pressure, expected at low frequencies, the instrument was set to give a slower rate (1.6 dB/s) than that normally used. For 6.3, 12.5, and 25 Hz three forms of stimulus were used: continuous tones, pulsed tones with slow rise and decay ('slow'), and pulsed tones with start and finish at a zero crossing ('fast'). At 3.15 Hz only the continuous test tone was used. Test sessions were in general limited to 10 to 12 minutes per visit, and during this time for example, a subject would complete thresholds for the three conditions of test tones ('continuous', 'fast', 'slow'), together with a repeat determination in the same order. The order of presentation was randomised amongst subjects. For each condition some 1½ minutes of threshold tracing was obtained and this was sufficient for most subjects to reach a condition apparently free from artifact. Direct measurements of the threshold sound pressure levels were made at the end of each subject's test. The introduction of the subject into the booth increased sound pressures by about ½ decibel.

The equal loudness tests were made using the constant stimulus method, with sequence patterns AOBOAOB and BOACBOA where A represents the fixed and B the variable stimulus, 0 being a period of silence. Both the order of presentation and the levels of the variable stimuli were randomised. A warning light alerted the subject just before the sequence commenced. 50 Hz was chosen as the starting point. Taking into account the threshold of our group at this frequency, starting levels for the loudness balances of 60, 73, and 86 dB were chosen to simulate approximately the loudness levels 20, 40 and 60 phon. Loudness balances were made in successive octave steps. The mean sound pressure levels at 25 Hz judged to be equal in loudness to the 50 Hz tones became the reference levels for the 25 Hz to 12.5 Hz comparison, and so on.

In order to check that the stepwise procedure was not introducing progressive errors we made triangular comparisons, one covering the two-octave interval 50 Hz to 12.5 Hz and one covering the three-octave interval 25 Hz to 3.15 Hz.

The subject groups were 23 experienced observers, mean age 30 years and 42 paid subjects (predominantly female), mean age 46 years. All were otoscopically normal and had received conventional pure-tone audiometry.

Results of the measurements

Threshold of hearing The results are given in Table II for the continuous condition only. This gave the least acute threshold, whilst, as would be expected, the 'fast' condition gave the most sensitive thresholds. At 25 Hz the mean difference is 1.5 dB, at 12.5 Hz, 1.3 dB and at 6.3 Hz the difference has disappeared. None of the differences are statistically significant. Similarly the mean difference between the first and second determinations of the threshold at one sitting whilst always showing a small improvement of 0.6 to 0.8 dB, are non-significant.

TABLE II

Frequency (Hz)	Mean Threshold SPL	Standard Error of Mean	No. of Subjects
50	51.3	1.60	23
40	58.2	1.60	23
31.5	64.5	1.63	23
25	74.6	1.35	23
	79.9	1.20	42
12.5	95.2	1.45	23
	94.6	1.23	23*
	97.2	1.00	42
6.3	107.1	1.71	16
	106.8	1.10	42
3.15	121.6	1.86	16
	122.7	1.24	34

* Replication

Comparison with a recent determination by Yeowart, Bryan and Tempest[2] of the moneural threshold of hearing, using a somewhat different technique, shows reasonable agreement after an allowance is made for the monaurel/binaural difference. In both determinations the slope of the threshold curve apparently changes at 12.5 Hz.

Loudness balances The results of the equal loudness determinations are given in Table III in terms of mean sound pressure levels.

TABLE III

Frequency (Hz)	'20' phons	'40' phons	'60' phons	No. of subjects
50	60	73	86	20
25	78.0 (1.2)	87.7 (1.2)	97.8 (1.2)	20
12.5	97.7 (1.2)	104.7 (1.3)	112.6 (1.1)	20
	96.1 (1.3)	105.2 (1.4)	114.8 (1.3)	20(a)
6.3	110.9 (0.64)	118.0 (0.45)	125.6 (0.57)	20
	110.3 (0.50)	117.7 (0.44)	125.2 (0.48)	20
3.15	125.8 (0.67)	131.8 (0.47)	136.1 (0.31)	18
	126.5 (0.38)	132.9 (0.24)	137.6 (0.24)	32
		130.9 (1.3)	135.7 (1.1)	12(b)

(a) 50 v 12.5 Hz (b) 25 v 3.15 Hz

The bracketed figures are standard errors of the mean, the smallness of which well reflect the rapid growth of sensation with SPL at low frequencies. At 6.3 Hz a complete replication was made several days after the first determination. The excellent agreement further shows the high reliability of the determinations. At 3.15 Hz the group of 32 paid female subjects was new to loudness balancing and their results show that even for unpractised observers the variability is very small.

Conclusions

Measurements of threshold and equal loudness at low frequencies are difficult to achieve mainly from physical causes. For threshold measurements down to 3 Hz tones free from distortion at sound pressure levels greater than 122 dB are necessary, and for equal loudness we generated levels of 143 dB. The data obtained will facilitate an extension of the equal loudness and threshold contours of ISO R226; the necessary numerical smoothing process has yet to be undertaken. The work has been limited mainly for the reason that we were unwilling to submit our subjects to sound pressure levels greater than 143 dB at 3.15 Hz. In common with other experimenters we noticed the apparent change in modality of the sensation as the frequency is lowered, but the relative continuity of the curves with frequency indicate that the change is not abrupt and that "loudness" still has a meaning at the lowest frequencies.

References

1. D.W. Robinson and R.S. Dadson "A redetermination of the equal-loudness relations for pure tones", Brit. J. Appl. Phys. 7, 166 (1956)

2. N.S. Yeowart, M.E. Bryan and W. Tempest "The monaural M.A.P. threshold of hearing at frequencies from 1.5 to 100 c/s." J. Sound Vib. 6, 335 (1967)