Comments on the Form of Equal Loudness Curves

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In the September 2004 issue of New Zealand Acoustics, Vern Goodwin reported on important changes to the equal loudness curves as defined in ISO 226 under the title, "ISO 226 Equal Loudness Curves". He reported that in 2003, the International Standards Organization issued revised equal loudness curves for pure tones in, "ISO 226:2003 Acoustics–Normal equal-loudness-level contours", which replaced ISO 226:1987.

This note comments on the form of the equal loudness curves at low frequencies.

The revised curves (and the previously published curves) are represented in Fig. 1.

The form of the curves between 31.5 Hz and 1000 Hz varies markedly between the threshold of hearing (0 Phon) and the highest loudness curve presented (100 Phon).

Above 1000 Hz the loudness curves closely follow the same form and only vary in level.

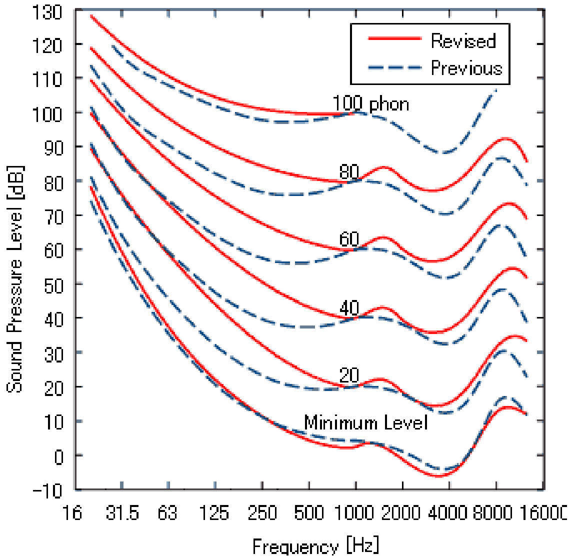

Fig.1 ISO 226: 2003 and ISO 226: 1987 equal-loudness-level contours.

The transition from the non-linear behaviour at the lower frequencies to the linear behaviour at higher frequencies is approximately centred on 1000 Hz.

It appears worth considering whether there is a better way of presenting the non-linear, lower frequency part of the curves, than that used in Fig.1, as a simple equation may suffice rather a series of curves. It may also suggest a possible mechanism for the perception of loudness of lower frequency sounds.

In Fig.2, the data in Fig. 1 is presented as a function of the reciprocal of the square-root of frequency. This data can also be approximated by the equation:

$$L(dB) = \frac{(-3.1P+460)}{f^{0.5}} + (1.1P-17) \quad (1)$$

where L is sound level of a tone giving a loudness level, P, at a frequency, f , between 31.5 and 1000 Hz.

The standard deviation of the difference between the ISO 226: 2003 data presented in Fig.1, and the predictions using equation 1 is 2.1 dB when the values at the six octave band centre frequencies between 31.5 and 1000 Hz, and the six loudness levels

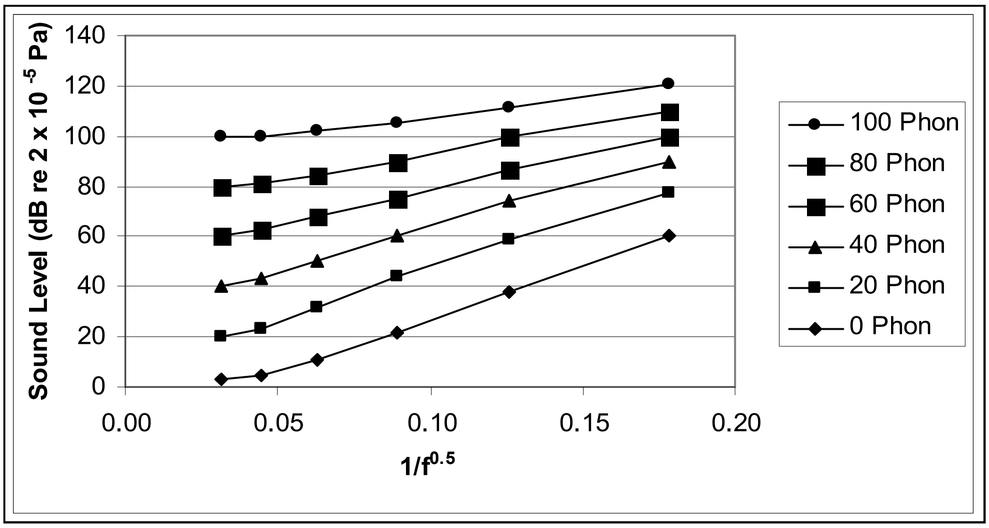

Fig.2 Equal-loudness-contours presented as a function of the reciprocal of the square-root of frequency in the range of 31.5 to 1000Hz.

between 0 and 100 Phon are used. If the data for the hearing threshold are omitted from the calculation the standard deviation is 1.4 dB.

These standard deviation results may seem to be high, but considering that the standard deviation of the difference between the ISO 226:1987 and 2003 data is 5 dB, that it is difficult to measure the loudness of tones at low frequencies and low intensities, and that equation (1) is an approximate one and has not been optimized, the fit is surprisingly good.

From Fig.1 it can be seen that the form of the equal loudness contours below 1000 Hz is dependent on the loudness level.

What is not so apparent is that the product of f^n (where n is a number between 0 and 2) and the pressure amplitude of the sound, for a given loudness level, is approximately constant in the frequency range 31.5 < f < 1000 Hz, for a given loudness contour.

At frequencies above 1000 Hz, the ear is responding to the pressure amplitude of the sound only, at a given frequency.

Over most of the loudness level range and frequencies below 1000 Hz, the curves appear to be approximately of the form:

$$f^2 10^{(L/20)} = constant$$
$$(ie\ d^2 p / dt^2 = constant) \quad (2)$$

while at high loudness levels and frequencies below 1000 Hz the curves are approximately of the form:

$$10^{(L/20)} = constant$$
$$(ie\ p = constant) \quad (3)$$

Phon	Expression for Constant	31.5	63	125	250	500	1000	SD (dB)
0	10 Log(f^2 x $10^{(L/20)}$)	60	55	53	54	57	62	3.5
20	10 Log(f^2 x $10^{(L/20)}$)	69	66	64	64	66	70	2.5
40	10 Log(f^2 x $10^{(L/20)}$)	73	73	72	73	76	80	2.9
60	10 Log(f^2 x $10^{(L/20)}$)	80	80	79	82	86	90	4.2
80	10 Log(f^2 x $10^{(L/20)}$)	85	86	87	91	95	100	5.8
80	10 Log($10^{(L/20)}$)	55	50	45	43	41	40	5.9
100	10 Log($10^{(L/20)}$)	61	56	53	51	50	50	4.1

Table 1. Demonstration of a possible hearing mechanism to account for the non-linearity of loudness contours at low frequencies. The expressions for the constant are those that give the lowest standard deviation (SD) when f is either 0, 1 or 2.

where L is the sound level at a given frequency, f, and loudness level, P, p is the pressure amplitude of the pure tone, and t is time.

Table 1 gives an example of the best results (smallest Standard Deviations) from calculations of constants using 10 Log (f^2 x $10^{(L/20)}$), 10 Log (f x $10^{(L/20)}$) and 10 Log ($10^{(L/20)}$).

It should be emphasised that these are not sound levels, and that the important issue is how constant the values are at a given loudness level over the frequency range 31.5 to 1000 Hz. This constancy is indicated by the standard deviation (SD) of the values.

The standard deviations show that the expression containing f^2 is best for all loudness levels up to and including 80 Phon. If the 31.5 Hz data is omitted, the standard deviations for the first five lines in Table 1 would be 2.8, 1.8, 1.5, 2.6 and 3.9.

Can the data in Fig. 2 be collapsed onto a single curve or be represented by a single simple equation?

While 10 Log (f^2 x $10^{(L/20)}$) gives the best form of fit for most of the curves shown in Fig. 1, it is not useful for calculating values of loudness from information on sound level and frequency. Equation 1 can be used for this purpose, but there are alternatives which could be more simple and accurate.

If equation 4 is used to calculate sound levels, the difference between these and the ISO 226:2003 values have a Standard Deviation of 4.4 dB.

$$10\ Log\ (f^2\ x\, 10^{((L-P)/20)}) = 53.2 \quad (4)$$

Another form of a simple equation representing these trends is:

$$10\ Log\ (f^{(2-P/60)}\ x\, 10^{(L/60)}) = 59.4 \quad (5)$$

Phon	31.5	63	125	250	500	1000	SD (dB)
0	60.0	55.0	52.9	53.5	56.5	61.5	3.5
20	63.5	59.5	56.9	56.0	57.0	60.0	2.8
40	65.0	61.0	58.0	57.0	57.5	60.0	3.0
60	65.0	61.5	58.5	58.0	58.5	60.0	2.7
80	65.0	62.0	59.0	58.5	58.5	60.0	2.6
100	65.5	61.5	59.5	59.0	59.0	60.0	2.5

Table 2. Calculated values of the constant in equation 5

The calculated values, at each frequency and loudness level, of the constant on the RHS of equation 5 are given.

The standard deviation of the difference between the actual (ISO 226:2003) sound levels and the sound levels calculated using equation 5 for the octave band centre frequencies from 31.5 to 1000 Hz and for the loudness levels from 0 to 100 Phon is 6.0 dB.

If the two most difficult to measure conditions (31.5 Hz values and the hearing threshold values) are ignored, the standard deviation of the difference between the actual and the calculated values is 3.1 dB.

This standard deviation is not as good as that obtained using equation 1, but again it should be recognized that the standard deviation between the 1987 and 2003 curve values is approximately 5 dB. Also, no attempt has been made to optimise this equation, but it is doubtful if a significantly better fit could be obtained without a more complex relationship.

Other equations can be shown to achieve lower standard deviations but they are more complex and the significance of their form is less open to interpretation.

In summary, the ISO equal loudness contours can be well represented by equation 1, and it appears that there is a possible explanation for the different form of the loudness contours in the frequency range 31.5 to 1000 Hz which is that the ear may be responding to rates of change of acoustic pressure while at higher frequencies the ear is responding to the intensity of the sound. ❑

Fish come back for water music

New Zealand researchers have helped to prove that dead coral can be restocked with fish, using artificial noise to mimic a living reef.

Experiments at Lizard Island on Australia's Great Barrier Reef showed that underwater speakers emitting high- and low-frequency sounds could attract fish to patch reefs of dead coral dropped on the sea floor.

The chair of marine science at Auckland University, Professor John Montgomery, said earlier work at the Leigh marine reserve, north of Auckland, had shown that young fish were attracted to sound.

"We then had to go up to the Tropics to do work on coral reefs to show it was a genuine phenomenon and establish the amount of settlement."

The research has implications for regenerating failing coral reefs and identifying potential adverse effects of man-made noise in the marine environment, such as that from recreational boating, ships, wharves and coastal industry.

If it was known what sort of noise a healthy reef made its condition could be monitored, or artificial noise could be used to help re-populate reefs that had been fished out.

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Angela Gregory (Edited)