HANDBOOK OF NOISE AND VIBRATION CONTROL

4th Edition

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PREFACE

The Fourth Edition of the Handbook of Noise and Vibration Control has been completely revised, up-dated and extended to keep pace with the rapid expansion in this relatively new discipline of engineering and construction. Machinery is the principal cause of noise and vibration. The constant quest for more power, more capacity, more speed, more weight loading, to meet the demands of industry today, and tomorrow, is a portend of greater noise and vibration. Yet all industrialized countries have introduced stringent laws to combat noise in the factory, the office and the environment. To sell at home and abroad, machinery manufacturers must comply with the laws appertaining to the country of origin or importation. It is certain that more man-made laws will be introduced to offset the detrimental effects of man-made machinery. A quiet machine is an acceptable machine; a noiseless machine is an efficient machine. The ultimate in machine efficiency and acceptability precludes noise and vibration completely.

This handbook is fully comprehensive and contains a wealth of technical data and information essentially of a practical nature to help machine designers, architects, public health and municipal authorities, factory managers, and all those concerned with reducing noise and vibration, wherever, whenever and however possible. Cause, effect, measurement, acceptable levels, methods of control, materials to use, working data and sources of specialized assistance and purchase are all incorporated in this one volume.

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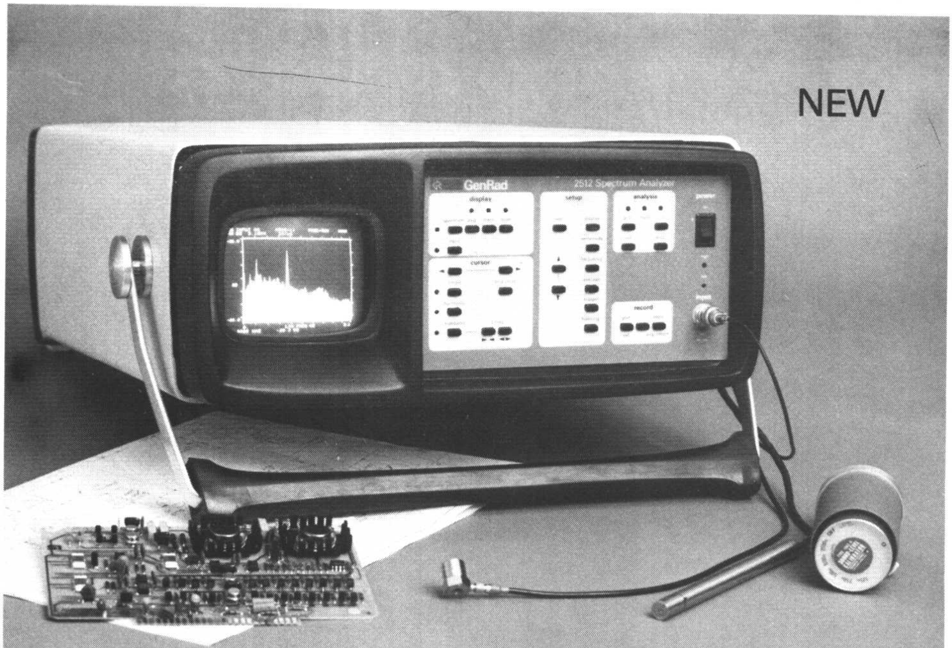
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Sound and Noise Parameters

Sound is a form of energy transmission and the amount of *sound energy* passing through or arriving at unit area in unit time is a measure of the *intensity* of the sound, designated by 1. The minimum intensity which can be detected by the average individual is 10^{-12} watts/m^2, this level defining the *threshold of hearing*. At the other end of the scale an intensity of 1 watt/m^2 produces a change in sensation at the ear from hearing to feeling, this level being known as the *threshold of feeling*. This represents an intensity range of 10^{12} (one million million).

As long ago as the nineteenth century it was established that the minimum increase in stimulus of any sensation which can be perceived (δS) is proportional to the existing stimulus (S), or mathematically

$$\delta T = K \frac{\delta S}{S}$$

where T is the sensation and δT a first perceivable step in sensation
K is a constant

or in integrated form

$$T = K \log S \quad \text{(Weher-Fechner law)}$$

In other words the sensation of sound is proportional to the logarithm of the stimulus. Conveniently, the ratio between two intensities (or powers) may be expressed in *bels* by the simple formula

$$\log 10 \frac{I_1}{I_2}$$

where I_1 is intensity level 1
I_2 is intensity level 2

or *Intensity level* $= \log_{10} \dfrac{I}{I_o}$

where I is the prevailing intensity

I_o is the reference level or threshold of hearing in the case of sound.

A finer scale is given by the use of the *decibel* (or one tenth of a bel), designated dB, when:

$$\text{Intensity level} = 10 \log_{10} \frac{I}{I_o} \text{ dB}$$

$$\text{with } I_o = 10^{-12} \text{ watts/m}^2$$

This gives a range of 120 dB between the threshold of a audibility and threshold of feeling (which can be further upwards if necessary). It also establishes that a doubling of sound intensity corresponds to a change of 3 dB, thus comparing two sound intensities I_1 and I_2.

the relationship is $10 \log_{10} \dfrac{1_1}{1_2}$ dB

If $1_1 = 1_2$, this leaves

$$10 \log_{10} \frac{2}{1} \text{ dB}$$

$$= 3.01 \text{ dB or, practically, 3 dB.}$$

Sound Pressure

The source of energy transmission in a sound wave is sound pressure and it is generally more suitable to deal in this term since it is easier to measure sound pressure than sound intensity. The basic relationship involved is that sound intensity is proportional to the *square* of the associated sound pressure (P), so that for a comparison of *sound pressures* the relationship becomes

$$20 \log_{10} \frac{P_1}{P_2} \text{ dB}$$

It follows that the *sound pressure level* (SPL) of a particular sound is given by

$$\text{SPL} = 20 \log_{10} \frac{P_1}{P_o} \text{ dB}$$

where P_o is the reference pressure level corresponding to an intensity of 10^{-12} watts/m^2 or 2×10^{-5} Newtons/m^2

Hence, $\text{SPL} = 20 \log_{10} \dfrac{P_1}{0.00002}$

In this case a doubling of *sound pressure level* is equivalent to a difference of 6 dB.

Combined Sound Levels

When two or more wave sources are present the combined sound level is determined as the arithmetical sum of each of the *mean square sound pressure ratios*. (Simple addition of sound *pressure* levels gives a meaningless result).

$$\text{The mean square pressure ratio} = \text{antilog}\ \frac{SPL}{10}$$

where SPL = measured sound pressure level

Thus the combined sound pressure level of two or more sources is

$$\text{Combined SPL} = \text{antilog}\ \frac{SPL_1}{10} + \text{antilog}\ \frac{SPL_2}{10} + \text{antilog}\ \frac{SPL_3}{10} + \text{antilog}\ \frac{SPL_n}{10}$$

It is generally more convenient to use a graph for rapid solutions – see Fig 1.

In either case, where the difference in sound pressure levels from different sources is greater than 6 dB, the resultant sound pressure level is substantially the same as that of the loudest sound and so the effect of the lower sound can be ignored.

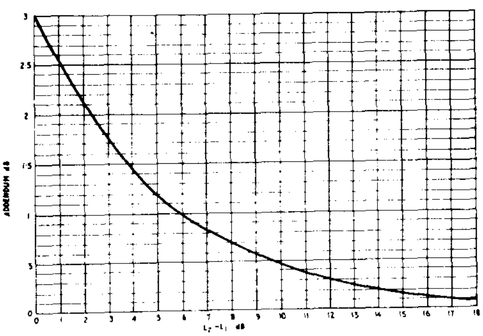


Fig 1

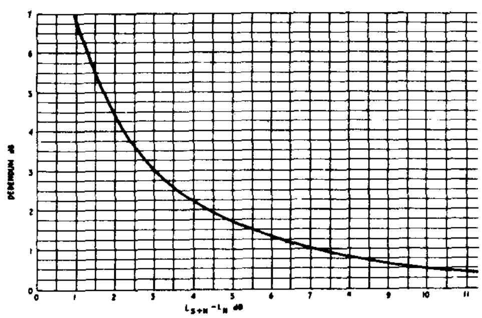


Fig 2

Subtracting Sound Levels

It is also convenient to be able to 'subtract' the effect of one noise from another, eg to be able to subtract background noise from a total noise measurement in order to obtain the actual noise produced by a single source, such as a machine.

The procedure to be adopted is:–

(i) Measure the total noise in dB with both sources operating. Call this SPL_T

(ii) Measure the background noise only in dB with the single source shut off – Call this SPL_B

(iii) Calculate the quantity $\left(10^{\frac{SPL_T}{10}} - 10^{\frac{SPL_B}{10}}\right)$ Call this D.

(iv) Find, the numerical value of $SPL_T - 10 \log_{10} D$

(v) Subtract this value from the total noise measurement (SPL_T) to give the value of the single noise source.

Again, graphical solution is preferred for simplicity and quickness — see Fig 2.

Correction for background noise is only applicable where the source to background noise ratio is less than about 20 dB. In other words, for higher source to background noise ratios the effect of background noise will be negligible and so the total noise measurement will be virtually the same as that of the single source.

Noise from Identical Sources

If a number of separate noise sources are present each with an identical sound pressure level at the point of measurement, the total sound pressure level can be calculated from the sound pressure level of one source.

$$\text{dB (total)} = \text{dB}_1 + 10 \log n$$

where dB_1 is the sound pressure level of one source
n is the number of identical sources

Average Sound Pressure Levels

To find the average of a number of separate sound pressure levels in decibels the following formula applies

$$\text{dB (average)} = 10 \log \frac{1}{N} \left(\text{antilog} \frac{\text{dB1}}{10} + \text{antilog} \frac{\text{dB2}}{10} + \ldots\ldots \text{antilog} \frac{\text{dBn}}{10} \right)$$

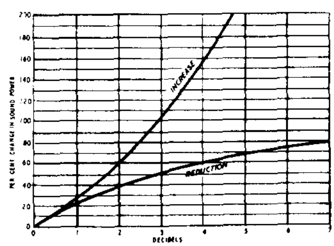
where dB1, dB2, ... dBn are the separate sound pressure level readings
N = number of separate readings to be averaged.

Percentage Change in Sound Level

To express an increase or decrease in sound power as a percentage instead of a difference in decibels the following relationship applies:—

$$\text{percentage increase} = \text{antilog} \frac{\text{dB2} - \text{dB1}}{10} - 1$$

$$\text{percentage reduction} = 1 - \frac{1}{\text{antilog} \dfrac{\text{dB1} - \text{dB2}}{10}}$$



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Solutions can be read directly from the graph given in Fig. 3.

Actual Pressure of Sound Waves

The pressure (P) produced by sound waves is

$$P = 0.0002 \times 10^{-6} \times 10^{\text{dB}/20} \text{ bar}$$

$$= 29.0 \times 10^{-10}\ 10^{dB/20}\ \text{lb/in}^2$$

$$= 29.0 \times 10^{-10}\ \text{antilog}\ \frac{dB}{20}\ \text{lb/in}^2$$

where dB is the sound pressure level.

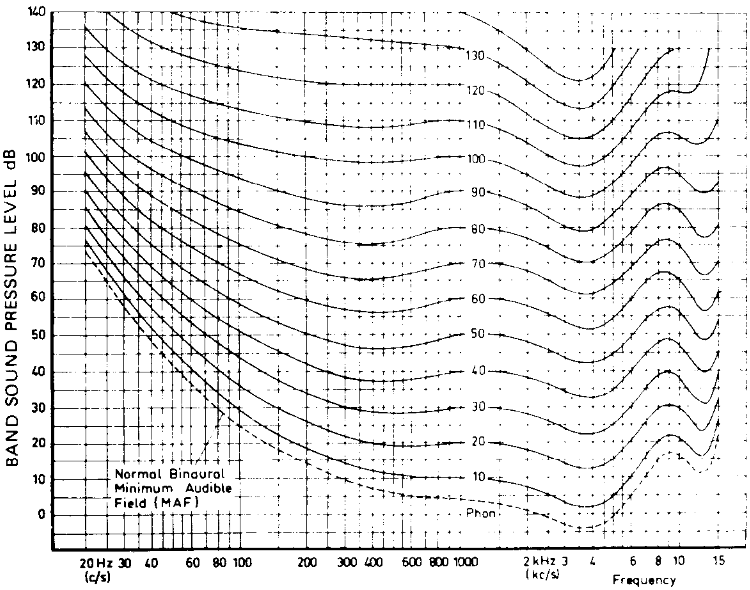


Fig 4 ISO Normal equal-loudness contours for pure tones. They can be applied when: (a) The source of sound is directly ahead of the listener; (b) The sound reaches the listener in the form of a free progressive plane wave; (c) The sound pressure level is measured in the absence of the listener; (d) The listening is binaural; (e) The listeners are otologically normal persons in the age group 18 to 25 years inclusive.

Sound Power Level

The definition of *sound power level* (designated L_W) is identical to that for intensity level, substituting watts for intensity, viz

$$L_W = 10 \log_{10} \frac{W}{W_o}$$

where W is the acoustic power in watts

W_o is the reference power level = 10^{-12} watts/m^2

Since a 10^{-12} power ratio corresponds to −120 dB, this formula can also be written

$$L_W = 10 \log_{10} W + 120 \text{ dB}$$

The sum of sound power levels can be determined from the formula

$$L_W \text{ (total)} = 10 \log_{10} \left(\text{antilog} \frac{L_{W1}}{10} + \text{antilog} \frac{L_{W2}}{10} + \text{.... antilog} \frac{L_{Wn}}{10} \right)$$

Subjective Units

As previously noted, sound pressure level in dB is the parameter most suitable for objective measurement. To project this in a more realistic manner as far as subjective response is concerned various 'weightings' can be associated with the measuring instrument employed – see Table I and chapter: *Measurement of Sound*. Of these, dB(A) is by far the most common form of weighting and is (almost) universally employed for National and International standards for noise legislation, etc.

The apparent loudness of sound, however, is basically a feature of hearing sensation rather than actual sound pressure and is also frequency-dependent. The latter may be taken into account by 'weighting' sound pressure measurements but the resulting data are still objective rather than subjective, and the two have still to be related on a 'response' basis. As a consequence many attempts have been made to establish subjective loudness scales for sound, a number of which have become widely used and a specific application prepared to sound pressure level figures.

The 'basic' subjective units are:—

phon – a measure of 'loudness level'.
sone – a measure of 'subjective loudness'.
noys – a measure of 'perceived noise'.

Loudness Level

Loudness levels are derived as contours of sound pressure levels of simple tones over a range of frequencies, each contour representing a constant apparent loudness. Each contour is designated by a number, representing the loudness level in *phons*. At a specific frequency (1000 Hz) this number is defined by the band sound pressure level in dB. The contours express the frequency dependency of subjective response.

Since these data are essentially subjective different contours can be derived from different techniques or from different sampling methods, although the ISO Normal equal loudness contours shown in Fig 4 are generally accepted. It should be noted, however, that these are only valid when

(i) the listeners are otologically normal persons in the age group 18 to 25 years
(ii) the source of the sound is directly ahead of the listener.
(iii) the sound reaches the listener in the form of a free progression plane wave (free field).
(iv) the sound pressure level is measured in the absence of the listener.
(v) the listener is biaural

Loudness levels may be determined from octave band analysis when values may be expressed as phons (OD); or phons (GF) for loudness levels in a free field, and phons (GD) for loudness levels in a diffuse field.

Loudness Scale

A loudness scale can be derived as a transfer function from equal loudness contours, the unit for such a scale being the *sone*. As an arbitrary starting point a loudness of 1 sone is equivalent to a loudness level of *40 phons*. The complete relationship is then defined as

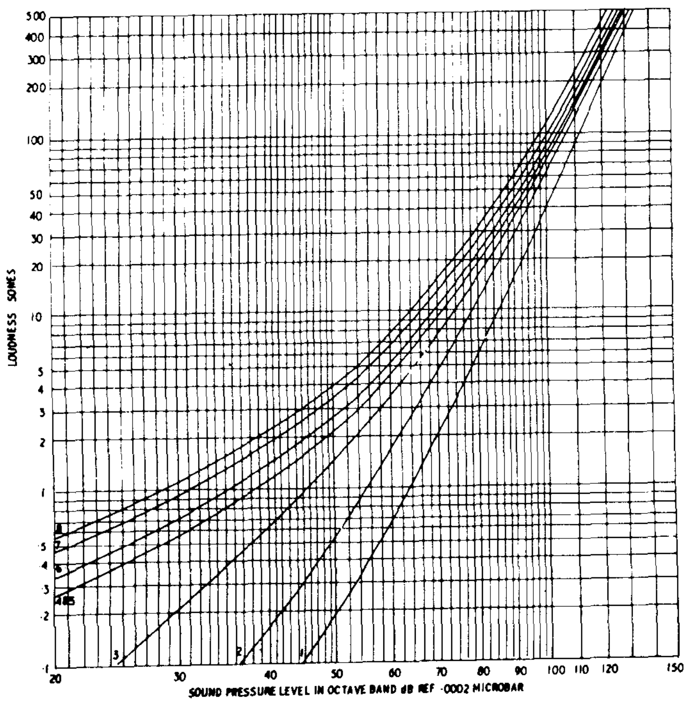
$$\log_{10} L_S = 0.03LL - 1.2$$

where L_S = loudness in sones

LL = loudness level in phons or the sound pressure level of a 1 000 Hz pure tone (which is assessed to be equal in loudness to the sound under comparison).

The *sone* as a unit has the attractive feature that numerical values are substantially linear in expressing loudness levels, eg a reduction in sound level to one half of its original value is equivalent to halving the number of sones. Similarly, well separated components of sound are additive on the sone scale, eg a loudness of 51 sones from one source combined with a loudness of 52 sones from a second source gives a combined loudness of 51 + 52. In the case of two sounds of equal loudness 'S', the combined effect will be equal to 25 sones. By comparison, with loudness *level* two sources of equal loudness will give a theoretical increase of *10 phons*.

Fig 5



Loudness scale values in sones can be obtained directly from octave-band analysis by reference to tables (see Table III) or charts (eg see Fig 5) In the case of charts, the procedure is as follows:-

(i) Tabulate loudness values (sones equivalent) for the measured sound pressure levels in each band.
(ii) Find the highest value given in this tabulation.
(iii) Multiply the loudness value of all *other* bands by 0.3.
(iv) Determine the sum of (ii) and all the other corrected values (iii).
This will give the total loudness of the noise in sones.
(v) The total loudness in sones can then be converted into *Loudness Level* (LL).

A similar procedure is adopted in the case of half-octave or one-third-octave band analysis, the appropriate charts being shown in Fig 6. The only difference (apart from the greater number of bands) is the correction factor value used in step (iii). This is 0.2 for half-octave band analysis, and 0.15 for one-third-octave band analysis data.

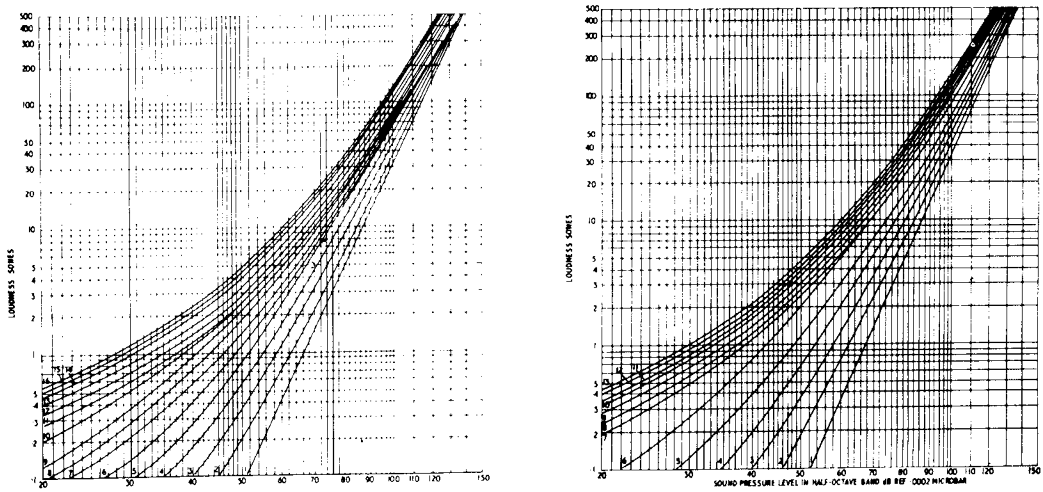


Fig 6

Determination of loudness in this manner is applicable only to a diffuse sound field and is accurate only for steady noise with a broad band spectrum.

Loudness scale values derived from octave band analysis may be referred to as sones (OD) and sones (GF) for loudness in a free field or sones (GD) for loudness in a diffuse field.

Loudness Index

The *loudness index* (LI) is an alternative method of expressing loudness levels in the form of a series of curves established with a slope of –3 dB per octave through the 1000 Hz reference frequency. The curves are thus rendered in straight line form; although above 9000 Hz the slope changes to a constant 12 dB per octave and below a certain frequency each curve changes to a slope of –6 dB per octave – see Fig 7. The diagonal line which defines this lower frequency change point passes through the 10 dB pressure level at 1000 Hz.

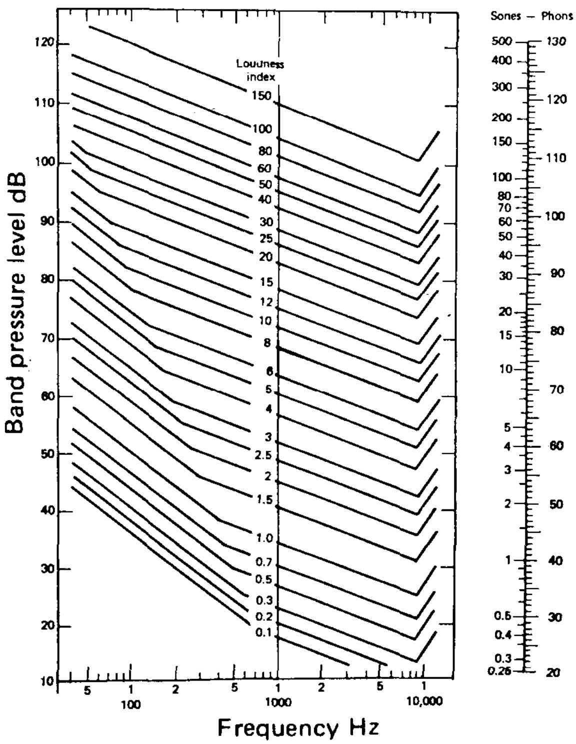


Fig 7 Loudness index curves (Stevens)

Unlike equal loudness contours where the band pressure level at 1000 Hz designates the loudness level (phons), loudness index values have the relationship shown in Table IVA. Expanded tabular values over the full frequency range are given in Table IVB. Corresponding values of dB, phons or sones are determinable graphically, or again from tables (see Tables VA, B and C).

Again loudness index can be determined from octave band analysis. The procedure is:

(i) Determine the LI for each band.

(ii) Calculate the total loudness (in terms of LI value) from the formula –

$$LI(total) = LI_{max} + 0.3\,(LI_{sum} - LI_{max})$$

where LI_{max} is the greatest numerical value of LI found in (i)

LI_{sum} is the sum of all the values found in (i)

A similar method of conversion can be used to find the total loudness from half-octave and one-third-octave band measurements. The factor 0.3 is replaced by 0.2 or 0.15 respectively, in these cases. (Note: half-octave analysis is obsolete and no longer used).

Thus the general formula for LI is

$$LI \text{ (in sones)} = Sm + K\ [\Sigma S - Sm]$$