Machinery Noise Measurement

(Monographs in Electrical & Electronic Engineering 17)

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Preface

This is a general book on machinery noise measurement for engineers. It is intended to be of value to the designers and manufacturers of any machinery or equipment which makes noise—for example, electric and mechanical machinery, office and data-processing equipment, and domestic appliances—with the exception of moving vehicles.

The noise level produced by engineering equipment is growing in importance with increasing emphasis on the reduction of 'noise pollution' as part of governments' efforts to improve the 'quality of life'. Home and overseas purchasers of engineering equipment demand quietness and frequently compare the products of different manufacturers for relative noise production. However, it is often the case that such comparisons are meaningless because they are not based on the same measurement methods. An important indicator of high quality, a vital factor if international trade is to grow, is a careful and valid specification of noise produced. An engineering exporter who does not pay proper attention to the noise of his equipment and cover this feature in his literature and technical specifications does so at his peril.

There is no dearth of bulky scientific books on acoustics. But most seem to have been written for specialists and do not provide much help to an engineer having a specific noise problem to solve. There has been a real need for an up-to-date review of advances in our knowledge of noise and its measurement over the last twenty years, with particular reference to engineering matters. Only a very unaware engineering designer will not have given thought to the need for quietness in his firm's products and appreciated how important it is, if noise figures are to be taken seriously, for the measurements on which they are based to have been made rationally and accurately. An engineer, producing a product for sale against competition, needs advice on acquiring microphones and noise equipment, on how to use it, on how to specify appropriate measurements, and how to deal with the results. And the problem of making measurements of value when no anechoic chamber is available is a common one. It is often not appreciated that perfectly adequate noise measurements can often be made without such an expensive facility.

The authors' intention in producing this book has been to provide soundly based advice for their fellow engineers who are not noise experts, but who have the need to measure and evaluate noise from machinery. We provide this advice in practical form, with worked examples. With international trade in mind we also append a list of national and international standards on machinery noise.

Recently, advances have been made in digital techniques. We therefore cover digital sound-level meters and spectrum analysers in addition to giving a comprehensive cover to the more conventional analogue instruments.

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S. J. Y.
A. J. F.

Contents

1	FUNDAMENTAL TERMINOLOGY	1
1.1	Sound-pressure level	1
1.2	Sound-power level	1
1.3	Sound intensity	2
1.4	Relationship between sound-power level and sound-pressure level	2
1.5	Combining two or more sounds of different frequency	4
1.6	Octave- and one-third-octave-band sound-pressure levels	5
1.7	A-weighted sound level	8
1.8	A-weighted sound-power level	11
2	NOISE AND MAN	13
2.1	Loudness level and loudness	13
2.2	Stevens' method	14
2.3	Noise-induced hearing damage	15
2.4	Perceived noise level	17
2.5	Traffic noise index	18
2.6	Equivalent continuous sound level	19
2.7	Noise pollution level	20
3	SOUND POWER MEASUREMENT	22
3.1	Noise field around a machine	22
3.2	Sound-power measurement in free field	25
3.2.1.	Spherical surface measurement	25
3.2.2.	Hemispherical surface measurement	29
3.2.3.	Conformal and other measurement surfaces	30
3.3	Sound-power measurement in semi-reverberant spaces	35
3.3.1.	Reference sound-source substitution method	35
3.3.2.	'Close-field' measurement method	36
3.3.3.	Method for reflection corrections	37
3.3.4.	Room constant method	40
3.3.5.	Oil Companies Materials Association methods	42
3.3.6.	Corrections for background noise	48
3.4.	Measurement in reverberant rooms	49
3.5.	Averaging sound-pressure levels	52
4	ACCURACY IN SOUND-POWER RESULTS	57
4.1	Error due to finite number of measuring points	57
4.2	Error due to 'far-field' assumption	62

4.3 Error due to ground reflection 65
4.4 Other problems 69
4.4.1. Electrical noise floor 69
4.4.2. Wind noise 71
4.4.3. Microphone alignment 71
4.4.4. Ambient temperature and pressure 73

5 MEASUREMENTS ON NOMINALLY IDENTICAL SMALL MACHINES 75
5.1 Statement of problem 75
5.2 The mathematical model 79
5.3 The confidence limit of the mean sound-power level 81
5.4 Approximate calculating procedures 86

6 SOUND-INTENSITY MEASUREMENT 93
6.1 Sound intensity 93
6.2 Sound-intensity measuring methods 95
6.2.1. Pressure and velocity direct measurement method 95
6.2.2. Two-pressure microphone method 96
6.2.3. Surface intensity method 101

7 NOISE MEASURING EQUIPMENT 105
7.1 Microphones 105
7.1.1. Condenser microphones 105
7.1.2. Electret microphones 105
7.1.3. Piezoelectric microphones 107
7.1.4. Microphone frequency response 108
7.2 Sound-level meters 110
7.2.1. Analogue sound-level meters 111
7.2.2. Impulse sound-level meters 112
7.2.3. Digital sound-level meters and integrating sound-level meters 114
7.3 Frequency analysers 116
7.3.1. Analogue narrow-band frequency analysers 116
7.3.2. Digital real-time frequency analysers (single-channel) 117
7.3.3. Equipment for recording and analysing impulsive noise 121
7.4 Digital sound-power measurement systems 124
7.5 Dual-channel digital spectrum analysers 125

Appendix 1 Room constant and reverberation time 135

Appendix 2 Student's t and the difference between $[(p_i)^2_{av}/p^2_{ref}]_{true}$ and $[(p_i)^2_{av}/p^2_{ref}]_{measured}$ 137
Appendix 3 Derivation of the standard deviation of the total error in the mean-square sound pressure 139
Appendix 4 International and national standards on machinery noise measurements 141

INDEX 160

1. Fundamental terminology

A steady pure-tone sound in air is a sound which exhibits sinusoidal pressure variations in air having a constant frequency and a constant amplitude. The noise, i.e. unwanted sound, around us is usually a combination of a series of components at different frequencies of various mechanical, electromagnetic, and aerodynamic origins. Before examining noise-measurement problems, we shall first introduce some fundamental terminology in the field of acoustic noise.

1.1. Sound-pressure level

In a sound field the sound pressure at a given point is the instantaneous pressure minus the static pressure at that point. The sound pressure is generally expressed as the sound-pressure level in dB (decibel) defined by

$$L_p = 10 \log_{10}\left(\frac{p^2}{p_{ref}^2}\right) \text{dB} \tag{1.1}$$

where p = the r.m.s. sound pressure and p_{ref} = the r.m.s. reference sound pressure.

The reference sound pressure is internationally taken as 2×10^{-5} N m^{-2} (i.e. 20 μPa), which is approximately equal to the r.m.s. sound pressure of a pure tone of 1000 Hz at the normal threshold of hearing. Almost all noise measuring equipment commercially available gives direct readings in sound-pressure level as defined by eqn (1.1) and based on the reference pressure of 2×10^{-5} N m^{-2}.

Example 1.1

A pure tone sound exhibits a r.m.s. sound pressure of 2×10^{-3} N m^{-2}. Calculate the sound-pressure level. The sound-pressure level is

$$L_p = 10 \log_{10}\left(\frac{2 \times 10^{-3}}{2 \times 10^{-5}}\right)^2 = 40 \text{ dB}.$$

1.2. Sound-power level

The sound power emitted by a source is, for ease of comparison, expressed as the sound-power level in dB defined by

$$L_W = 10 \log_{10}\left(\frac{W}{W_{ref}}\right) \tag{1.2}$$

where W = the average sound power emitted by an object in watts and W_{ref} = the reference sound power in watts. The reference sound power W_{ref} is internationally taken as 1×10^{-12} W (i.e. 1 pW). In the older literature, the reference sound power was sometimes taken as 1×10^{-13} W.

Example 1.2

An electric motor emits a sound power of 1×10^{-6} W at 1000 Hz. Determine the sound-power level. The sound-power level is

$$L_W = 10 \log_{10}\left(\frac{1 \times 10^{-6}}{1 \times 10^{-12}}\right) = 60 \text{ dB} \quad \text{re} \quad 1 \times 10^{-12} \text{ W}.$$

1.3. Sound intensity

The sound intensity at a given point in a sound field in a specified direction is defined as the average sound power passing through a unit area perpendicular to the specified direction at that point. For a plane and spherical sound wave propagating in a free field (a field free from reflections) the sound intensity along the direction of wave propagation is given by[1.1]

$$I = \frac{p^2}{\rho c} \text{ W m}^{-2} \tag{1.3}$$

where p = the r.m.s. sound pressure in N m^{-2}, ρ = the constant equilibrium density of the medium in kg m^{-3}, and c = the velocity of sound in the medium in m s^{-1}.

The product of ρ and c is defined as the characteristic impedance of the medium. At 20 °C and standard atmospheric pressure, the characteristic impedance of air is

$$\begin{aligned}(\rho c)_{air} &= (1.21 \text{ kg m}^{-3})(343 \text{ m s}^{-1}) \\ &= 415 \text{ kg m}^{-2} \text{ s}^{-1}.\end{aligned}$$

In acoustics, the unit in kg m^{-2} s^{-1} is also called a rayl. (The c.g.s. rayl is sometimes used also.)

1.4. Relationship between sound-power level and sound-pressure level

Let us consider the case of a machine completely enclosed by a surface. Assuming that the direction of wave propagation at any point on the surface is perpendicular to the surface and that the sound wave can be regarded as either a plane or a spherical wave, the total sound power emitted by the machine is

$$W = \int_A I_i \, dA_i = \int_A \frac{p_i^2}{\rho c} \, dA_i \tag{1.4}$$

where the integration is over the whole surface area A and p_i is the sound pressure on the ith elementary area dA_i. If the whole surface area is divided into n equal parts dA and the value of n is sufficiently large, eqn (1.4) becomes

$$W = \sum_{i=1}^{n} \frac{p_i^2}{\rho c} dA$$

$$= n(dA)\left(\frac{1}{n}\sum_{i=1}^{n}\frac{p_i^2}{\rho c}\right) = A\frac{p_{av}^2}{\rho c} \tag{1.5}$$

where p_{av} = the average r.m.s. sound pressure over the whole surface area.

Dividing both sides of eqn (1.5) by W_{ref} and taking logarithms, we have the sound-power level

$$L_W = 10 \log_{10} \frac{W}{W_{ref}} = 10 \log_{10} A + 10 \log_{10}\left(\frac{p_{av}^2}{W_{ref}\rho c}\right). \tag{1.6}$$

Based on the definition of the sound-pressure level, the value of p_{av}^2 can be expressed in terms of the sound-pressure levels on the surface by

$$p_{av}^2 = p_{ref}^2\left(\frac{1}{n}\sum_{i=1}^{n} 10^{0.1L_{p,i}}\right) \tag{1.7}$$

where $L_{p,i}$ is the sound-pressure level at the ith elementary area.

Combining eqns (1.6) and (1.7),

$$L_W = 10 \log_{10} A + 10 \log_{10}\left(\frac{p_{ref}^2}{W_{ref}\rho c}\right) + 10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{0.1L_{p,i}}\right). \tag{1.8}$$

The second term of eqn (1.8) is approximately equal to zero when $p_{ref} = 2\times 10^{-5}$ N m^{-2}, $W_{ref} = 1\times 10^{-12}$ W, and $\rho c = 415$ kg m^{-2} s^{-1}. Thus the sound-power level can be expressed as

$$L_W = 10 \log_{10} A + \bar{L}_p \tag{1.9}$$

where A = the whole surface area enclosing the machine in m^2 and

$$\bar{L}_p = 10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} 10^{0.1L_{p,i}}\right). \tag{1.10}$$

The value of $\bar{L}_p$ is called the *mean sound-pressure level* or the *level of mean-square sound pressure.*

Equation (1.9) gives a simple approximate relationship between the sound-power level and the mean sound-pressure level and enables us to determine the sound-power level from sound-pressure level measurements made over an 'imaginary' surface enclosing the machine. Strictly speaking, eqn (1.9) is valid only when the sound-pressure level measurements are made in a free field, e.g. in an anechoic chamber. However, for many practical cases, eqn (1.9) can be used for measurements made in an ordinary laboratory if suitable corrections are made (see Chapter 4).

1.5. Combining two or more sounds of different frequency

Let us assume that there are two pure tones at frequencies f_1 and f_2 ($f_1 \neq f_2$) in a sound field. Let the r.m.s. sound pressure of these two sounds be p_1 and p_2, respectively. Based on the summation of the two sinusoidal waves, the total r.m.s. sound pressure is

$$p_{tot} = (p_1^2 + p_2^2)^{1/2}. \tag{1.11}$$

The above equation can be rewritten as

$$\frac{p_{tot}^2}{p_{ref}^2} = \frac{p_1^2}{p_{ref}^2} + \frac{p_2^2}{p_{ref}^2}.$$

Taking logarithms and multiplying both sides by 10, we have

$$10 \log_{10} \frac{p_{tot}^2}{p_{ref}^2} = 10 \log_{10}\left(\frac{p_1^2}{p_{ref}^2} + \frac{p_2^2}{p_{ref}^2}\right),$$

i.e.

$$L_{p,tot} = 10 \log_{10}(10^{0.1L_{p,1}} + 10^{0.1L_{p,2}}). \tag{1.12}$$

If the two pure tones have the same r.m.s. sound pressure, hence the same sound-pressure level, the combined total sound-pressure level is, based on eqn (1.12), only 3 dB more than the sound-pressure level of one pure tone alone.

The above procedure can be generalized to include any number of pure tones, each of which has a frequency different from the rest. The combined sound-pressure level of n components of different frequencies is

$$\begin{aligned} L_{p,tot} &= 10 \log_{10}\left(\frac{p_1^2}{p_{ref}^2} + \frac{p_2^2}{p_{ref}^2} + \cdots + \frac{p_n^2}{p_{ref}^2}\right) \\ &= 10 \log_{10}(10^{0.1L_{p,1}} + 10^{0.1L_{p,2}} + \cdots + 10^{0.1L_{p,n}}). \end{aligned} \tag{1.13}$$

It should be emphasized that the combination of two or more sound waves of different frequencies does not depend on the phase angle of the sound pressure of these waves. However, the combination of two sound waves of the same frequency does depend on the phase angle. Let us consider the case of two sound waves of the same frequency in a noise field. The combined total r.m.s. sound pressure at a given point in the field is, based on the addition of two phasors,

$$p_{tot} = (p_1^2 + p_2^2 + 2p_1p_2 \cos\theta)^{1/2} \quad (1.14)$$

where p_1 and p_2 are the r.m.s. sound pressures of the two sound waves, and θ is the phase angle between the two sound waves at a given point. If $p_1 = p_2$ and the two sound waves are in antiphase at a particular point, i.e. $\theta = 180°$, then the total sound pressure becomes zero at that point. On the other hand, if the two sound waves are in phase with each other at another point, i.e. $\theta = 0$, then the total sound pressure at that point is doubled, resulting in an increase of 6 dB in the sound-pressure level.

1.6. Octave- and one-third octave-band sound-pressure levels

Sound-measuring equipment is usually equipped with a number of bandpass filters and the final reading of the equipment gives the total sound-pressure level in a particular frequency band. The frequency response of a typical octave bandpass filter is shown in Fig. 1.1. The general relationship between the upper cut-off frequency f_2 and the lower cut-off frequency f_1 is

$$f_2 = 2^a f_1 \quad (1.15)$$

where a is an arbitrary constant. For the most common filters used in

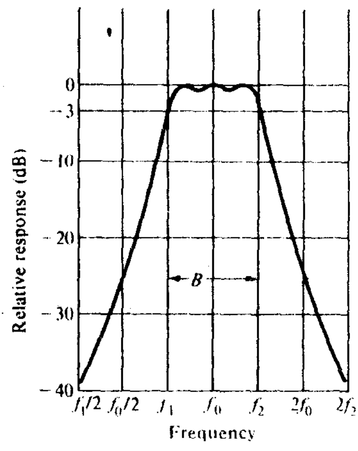

Fig. 1.1. Frequency response of an octave-band filter showing lower cut-off frequency and the upper cut-off frequency. f_1 = lower cut-off frequency; f_0 = centre frequency; f_2 = upper cut-off frequency; B = pass band bandwidth.

noise-measuring equipment, a is 1 or $\frac{1}{3}$. When $a = 1$, the filter is called an octave-band filter and when $a = \frac{1}{3}$ the filter is a one-third octave-band filter. The bandwidth of the passband, i.e. the width between two -3 dB points (see Fig. 1.1), is

$$B = f_2 - f_1. \tag{1.16}$$

The centre frequency f_0 of a filter is defined as

$$f_0 = \sqrt{(f_1 f_2)}. \tag{1.17}$$

TABLE 1.1. Centre and approximate cut-off frequencies for octave- and one-thord octave-band filters[1.3]*

Octave bands			One-third-octave bands		
Centre frequency f_0 (Hz)	Approximate lower cut-off frequency f_1 (Hz)	Approximate upper cut-off frequency f_2 (Hz)	Centre frequency f_0 (Hz)	Approximate lower cut-off frequency f_1 (Hz)	Approximate upper cut-off frequency f_2 (Hz)
16	11	22	16.0	14.1	17.8
			20.0	17.8	22.4
			25.0	22.4	28.2
31.5	22	44	31.5	28.2	35.5
			40.0	35.5	44.7
			50.0	44.7	56.2
63	44	88	63.0	56.2	70.8
			80.0	70.8	89.1
			100.0	89.1	112.0
125	88	177	125.0	112.0	141.0
			160.0	141.0	178.0
			200.0	178.0	224.0
250	177	355	250.0	224.0	282.0
			315.0	282.0	355.0
			400.0	355.0	447.0
500	355	710	500.0	447.0	562.0
			630.0	562.0	708.0
			800.0	708.0	891.0
1 000	710	1 420	1 000.0	891.0	1 122.0
			1 250.0	1 122.0	1 413.0
			1 600.0	1 413.0	1 778.0
2 000	1 420	2 840	2 000.0	1 778.0	2 239.0
			2 500.0	2 239.0	2 818.0
			3 150.0	2 818.0	3 548.0
4 000	2 840	5 680	4 000.0	3 548.0	4 467.0
			5 000.0	4 467.0	5 623.0
			6 300.0	5 623.0	7 079.0
8 000	5 680	11 360	8 000.0	7 079.0	8 913.0
			10 000.0	8 913.0	11 220.0
			12 500.0	11 220.0	14 130.0
16 000	11 360	22 720	16 000.0	14 130.0	17 780.0
			20 000.0	17 780.0	22 390.0

* (Extracts from ISO Standards are reproduced by permission of the British Standards Institution, 2 Park Street, London, from whom complete copies of the publication can be obtained.)

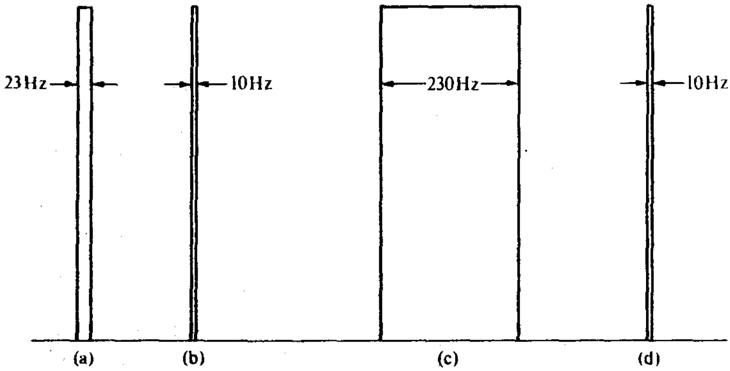

Fig. 1.2. Bandwidths of a constant 23 per cent bandwidth filter and a constant 10-Hz bandwidth filter. (a) Bandwidth of 23 per cent filter at 100 Hz; (b) bandwidth of 10-Hz filter at 100 Hz; (c) bandwidth of 23 per cent filter at 1000 Hz; (d) bandwidth of 10-Hz filter at 1000 Hz.

The centre frequency and frequency band of each of the internationally standardized octave- and one-third octave-band filters are shown in Table 1.1. In addition to octave-bands, and one-third octave bands, some noise analysers used for identifying the predominant frequency components of a noise are equipped with narrow-band filters. The bandwidth of narrow-band filters is either expressed as a constant percentage of the tuned-in centre frequency or as a fixed value in hertz, regardless of the tuned-in centre-frequency value. These are described as constant-percentage bandwidth filters and constant bandwidth filters, respectively. The octave- and one-third octave-band filters are constant 71 per cent and 23 per cent bandwidth filters respectively. Figure 1.2 shows the bandwidths of a one-third octave-band filter at 100 and 1000 Hz, compared with that of a 10 Hz constant bandwidth filter.

If the narrow-band sound-pressure levels of all important frequency components within the passband of a one-third octave-band are known, the corresponding one-third octave-band sound-pressure level can be found by using eqn (1.13). Similarly, one-third octave-band sound-pressure levels can be combined to give the octave-band sound-pressure level (see Ex. 1.3).

Example 1.3

The one-third octave-band sound-pressure levels with centre frequencies of 50, 63, and 80 Hz are 27.9, 24.8, and 23.3 dB, respectively. Calculate the octave-band sound-pressure level with a centre frequency of 63 Hz. Based on eqn (1.13), the required octave-band sound-pressure level is

$$L_p = 10 \log_{10}(10^{2.79} + 10^{2.48} + 10^{2.23}) = 30.5 \text{ dB}.$$