CHAPTER 23

PHYSICS OF SOUND

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INTRODUCTION

The sensation of sound is produced when pressure variations having a certain range of characteristics reach a responsive ear. These pressure variations may be produced by any object that vibrates in a conducting medium with the proper cycle rate, or frequency, and amplitude. Sound may consist of a single frequency and amplitude; however, common noise spectra have many different frequency components with many different amplitudes.

This chapter is concerned primarily with those practical aspects of sound that are related to its characteristics in a given space and to its propagation through specified media. Basic terminology, noise measurement, and practical calculation procedures such as combining sound levels are emphasized.

BASIC TERMINOLOGY

Amplitude:

The amplitude of sound may be described in terms of either the quantity of sound produced at a given location away from the source or the overall ability of the source to emit sound. The amount of sound at a location away from the source is generally described by the sound pressure or sound intensity, while the ability of the source to emit sound is described by the sound power of the source.

Free Field:

A free field exists in a homogeneous, isotropic medium free from boundaries. In a free field, sound radiated from a source can be measured accurately without influence from the test space. True free-field conditions are rarely found except in expensive anechoic (echo-free) test chambers; however, approximate free-field conditions may be found in any homogeneous space where reflecting surfaces are at great distances from the measuring location as compared to the wavelengths of the sound being measured.

Frequency (f):

The frequency of sound describes the rate at which complete cycles of high and low pressure regions are produced by the sound source. The unit of frequency is the cycle per second (cps) which is also called the hertz (Hz). The frequency range of the human ear is highly dependent upon the individual and the sound level, but a normal-hearing young ear will have a range of approximately 20 to 20,000 cps at moderate sound levels. The frequency of a propagated sound wave heard by a listener will be the same as the frequency of the vibrating source if the distance between the source and the listener remains constant; however, the frequency detected by a listener will increase or decrease as the distance from the source is decreasing or increasing (Doppler effect).[1]

Loudness:

The loudness of a sound is an observer's impression of its amplitude, an impression also dependent on the characteristics of the ear.

Noise and Sound:

The terms noise and sound are often used interchangeably, but generally, sound is descriptive of useful communication or pleasant sounds, such as music, while noise is used to describe discord or unwanted sound.

Period (T):

The period is the time required for one cycle of pressure change to take place; hence, it is the reciprocal of the frequency. The period is measured in seconds.

Pitch:

Pitch is used as a measure of auditory sensation that depends primarily upon frequency but also upon the pressure and waveform of the sound stimulus.

Pure Tone:

A pure tone refers to a sound wave with a single simple sinusoidal change of level with time.

Random Noise:

Random noise is made up of many frequency components whose instantaneous amplitudes occur randomly as a function of time.

Resonance:

Resonance of a system exists when any change in the frequency of forced oscillation causes a decrease in the response of the system.

Reverberation:

Reverberation occurs when sound persists after direct reception of the sound has stopped. The reverberation characteristic of a space is specified by the "reverberation time" which is the time required after the source has stopped radiating sound for the rms sound pressure to decrease 60 dB from its steady-state level.

Root-Mean-Square (rms) Sound Pressure:

The root-mean-square (rms) value of a changing quantity, such as sound pressure, is the square root of the mean of the squares of the instantaneous values of the quantity.

Sound Intensity (I):

The sound intensity at a specific location is the average rate at which sound energy is transmitted through a unit area normal to the direction of sound propagation. The units used for sound intensity are joules per square meter per second.

Sound intensity is also expressed in terms of a level (sound intensity level L_I) in decibels referenced to 10^{-12} watts per square meter.

Sound Power (P):

The sound power of a source is the total sound energy radiated by the source per unit time. Sound power is normally expressed in terms of watts. Sound power is also expressed in terms of a level (sound power level L_P) in decibels referenced to 10^{-12} watts.

Sound Pressure (p):

Sound pressure normally refers to the rms value of the pressure changes above and below atmospheric pressure when used to measure steady-state noise. Short term or impulse-type noises are described by peak pressure values. The units used to describe sound pressures are newtons per square meter (N/m^2), dynes per square centimeter (d/cm^2), or microbars. Sound pressure is also described in terms of a level (sound pressure level L_p) in decibels referenced to 2×10^{-5} newtons per square meter.

Velocity (c):

The speed at which the regions of sound-producing pressure changes move away from the sound source is called the velocity of propagation. Sound velocity varies directly with the square root of the density and inversely with the compressibility of the transmitting medium as well as with other factors; however, for practical purposes, the velocity of sound is constant in a given medium over the normal range of conditions. For example, the velocity of sound is approximately 1130 ft/sec in air, 4700 ft/sec in water, 13,000 ft/sec in wood, and 16,500 ft/sec in steel.

Wavelength (λ):

The distance required for one complete pressure cycle to be completed is called one wavelength. The wavelength (λ), a very useful tool in noise control work, may be calculated from known values of frequency (f) and velocity (c):

$$\lambda = c/f \qquad (1)$$

White Noise:

White noise has an essentially random spectrum with an equal-energy-per-unit frequency bandwidth over a specified frequency band.

NOISE MEASUREMENT

Steady-state sounds, ones that have relatively constant levels over time, are usually measured with instruments having root-mean-square (rms) characteristics. The time interval over which simple periodic sound pressure patterns must be measured is equal to an integral number of periods of that sound pattern, or the interval must be long compared to a period. If the sound pressures do not follow a simple periodic pattern, the interval must be long enough to make the measured value essentially independent of small changes in the interval length. In all cases, there must be more than 10 peaks per second for the noise to be considered to be steady-state for measurement purposes.

Single prominent peak pressures which may occur over a very short period of time, and peak pressures that are repeated no more than 2 per second, cannot be measured by conventional rms-type instruments because the peaks are not repeated often enough for long-time integrations to be meaningful. These single pressure peaks are normally measured in terms of the maximum instantaneous level that occurs during a specified time interval.

Just as rms measuring instruments cannot be used to measure single or widely spaced peak pressures, peak measuring instruments cannot be used to measure sustained noises unless the waveform is known to be sinusoidal or is otherwise predictable. In most cases, the relationship of the peak reading to the rms reading of common noises with complex waveforms cannot be established in a practical way. Peak pressure value of a sinusoidal waveform is about 3 dB greater than the rms value of that signal; however, as the waveform becomes more complex the differences may exceed 25 dB for common noises.

Noises with peak pressures occurring at rates between 2 and 10 peaks per second are difficult to measure in that they cannot be clearly defined as peak- or sustained-type noises. If the waveforms of the pressure peaks are complex and repeat between 2 and 10 times per second, an oscilloscope should be used to determine the pressure or energy contribution of the noise.

The Decibel (dB)

The range of sound pressures commonly encountered is very wide. For example, sound pressures well above the pain threshold (about 20 newtons per square meter, N/m^2) are found in many work areas, while pressures down to the threshold of hearing (about 0.00002 N/m^2) are also of wide interest. This range of more than 10^6 N/m^2 cannot be scaled linearly with a practical instrument because such a scale might be many miles in length in order to obtain the desired accuracy at various pressure levels. In order to cover this very wide range of sound pressures with a reasonable number of scale divisions and to provide a means to obtain the required measurement accuracy at extreme pressure levels, the logarithmic decibel (dB) scale was selected. By definition, the dB is a dimensionless unit related to the logarithm of the ratio of a measured quantity to a reference quantity. The dB is commonly used to describe levels of acoustic intensity, acoustic power, hearing thresholds, electric voltage, electric current, electric power, etc., as well as sound-pressure levels; thus, it has no meaning unless a specific reference quantity is specified.

Sound Pressure and Sound-Pressure Level

Most sound-measuring instruments are calibrated to provide a reading of root-mean-square (rms) sound pressures on a logarithmic scale in decibels. The reading taken from an instrument is called a sound-pressure level (L_p). The term "level" is used because the pressure measured is at a level above a given pressure reference. For sound measurements in air, 0.00002 N/m^2* commonly serves as the reference sound pressure. This reference is an arbitrary pressure chosen many years ago because it was thought to approximate the normal threshold of young human hearing at

1000 Hz. The mathematical form of the L_p is written as:

$$L_p = 20 \log \frac{p}{p_o} \text{ dB} \quad , \qquad (2)$$

where p is the measured rms sound pressure, p_o is the reference sound pressure, and the logarithm (log) is to the base 10. Thus, L_p should be written in terms of decibels referenced to a specified pressure level. For example, in air, the notation for L_p is commonly abbreviated as "dB re 0.00002 N/m^2."

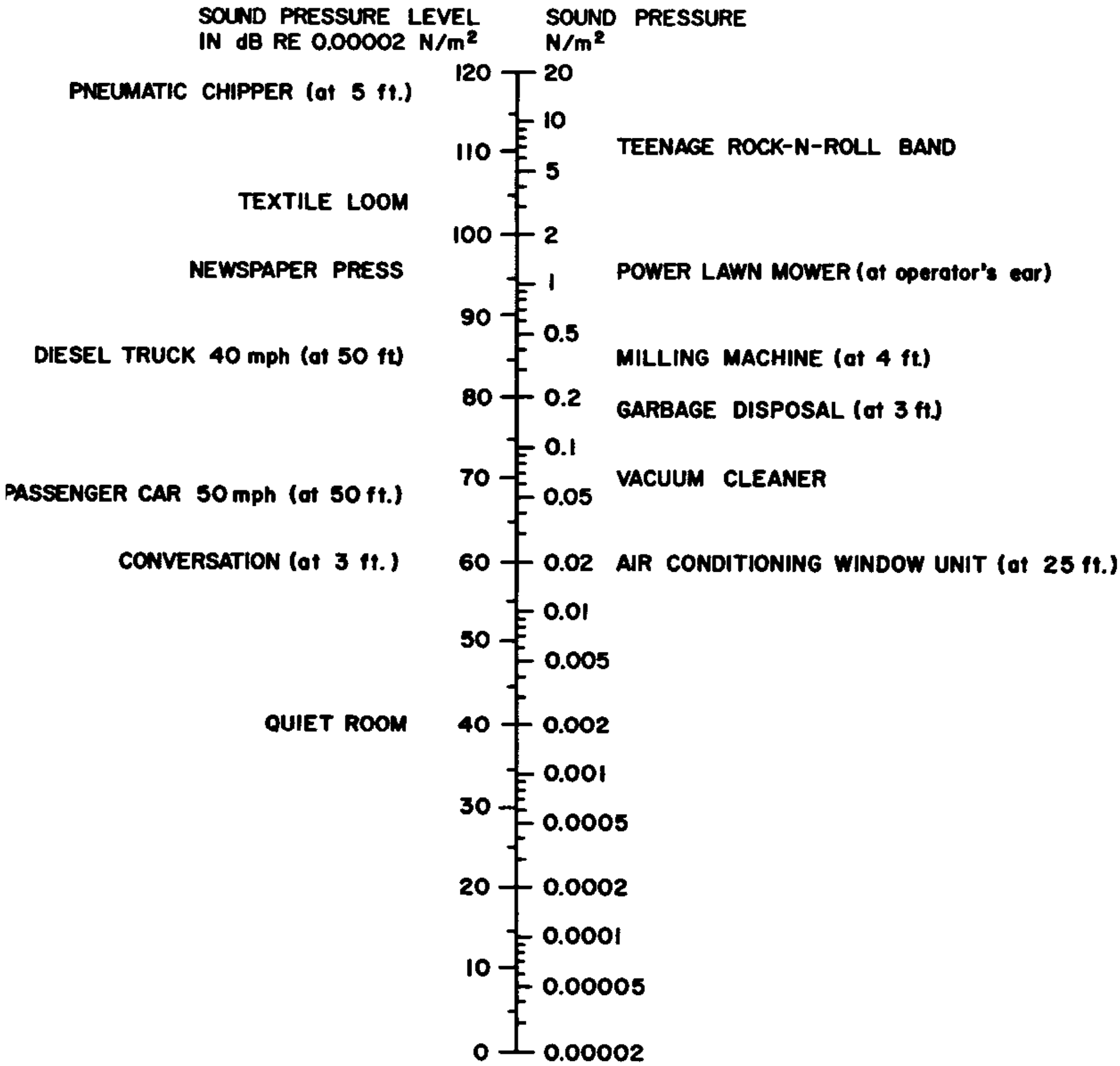

Figure 23-1. Relationship between A-Weighted Sound-Pressure Level in Decibels (dB) and Sound Pressure in N/m^2

Figure 23-1 shows the relationship between sound pressure in N/m^2 and L_p in dB, and illustrates the advantage of using the dB scale rather than the wide range of direct pressure measurements. It is of interest to note that any pressure range over which the pressure is doubled is equivalent to six decibels whether at high or low levels. For example, a range of 0.00002 to 0.00004 N/m^2, which might be found in hearing measurements, and a range of 10 to 20 N/m^2, which might be found in hearing conservation programs, are both ranges of six decibels.

*An equivalent reference 0.0002 dynes per square centimeter is often used in older literature. The microbar is also used in older literature interchangeably with the dyne per square centimeter.

The L_p referenced to 0.00002 N/m^2 may be written in the form:

$$L_p = 20 \log (p/0.00002)$$
$$= 20 \text{ lop } p - \log 0.00002$$
$$= 20 \log p - (\log 2 - \log 10^5)$$
$$= 20 \log p - (0.3 - 5)$$
$$= 20 (\log p + 4.7)$$
$$= 20 \log p + 94 \text{ re } 0.00002 \text{ N/m}^2 \quad . \quad (3)$$

Sound Intensity and Sound-Intensity Level

Sound intensity (I) at any specified location may be defined as the average acoustic energy per unit time passing through a unit area that is normal to the direction of propagation. For a spherical or free-progressive sound wave, the intensity may be expressed by

$$I = \frac{p^2}{\rho c}, \qquad (4)$$

where p is the rms sound pressure, ρ is the density of the medium, and c is the speed of sound in the medium. It is obvious from this definition that sound intensity describes, in part, characteristics of the sound in the medium, but does not directly describe the sound source itself.

Sound-intensity units, like sound-pressure units, cover a wide range, and it is often desirable to use dB levels to compress the measuring scale. To be consistent with Equations (2) and (4), intensity level (L_I) is defined as

$$L_I = 10 \log \frac{I}{I_o} \text{ dB} \quad , \qquad (5)$$

where I is the measured intensity at some given distance from the source and I_o is a reference intensity. The reference intensity commonly used is 10^{-12} watts/m². In air, this reference closely corresponds to the reference pressure 0.00002 N/m² used for sound-pressure levels.

Sound Power and Sound-Power Level

Sound power (P) is used to describe the sound source in terms of the amount of acoustic energy that is produced per unit time. Sound power may be related to the average sound intensity produced in free-field conditions at a distance r from a point source by

$$P = I_{avg} \, 4\pi r^2 \quad , \qquad (6)$$

where I_{avg} is the average intensity at a distance r from a sound source whose acoustic power is P. The quantity $4\pi r^2$ is the area of a sphere surrounding the source over which the intensity is averaged. It is obvious from Equation (6) that the intensity will decrease with the square of the distance from the source; hence, the well-known inverse-square law.

Power units are often described in terms of decibel levels because of the wide range of powers covered in practical applications. Power level L_P is defined by

$$L_P = 10 \log \frac{P}{P_o}, \qquad (7)$$

where P is the power of the source, and P_o is the reference power. The arbitrarily chosen reference power commonly used is 10^{-12} watt. Figure 23-2 shows the relationship between sound power in watts and sound-power level in dB re 10^{-12} watt.

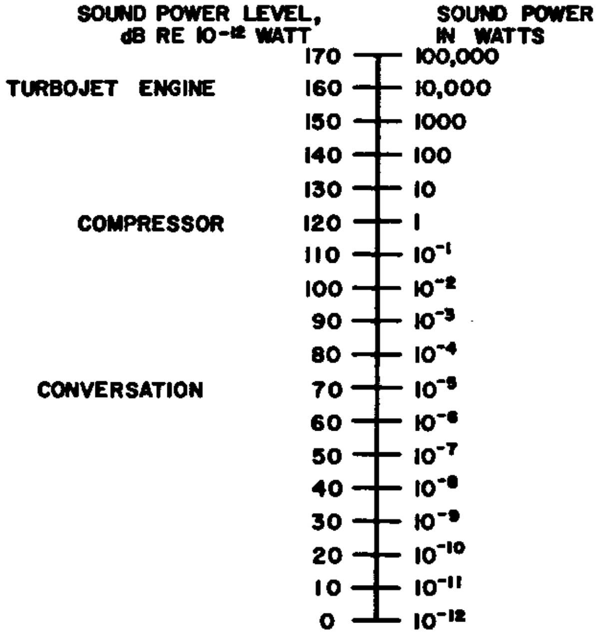

Figure 23-2. Relationship between Sound Power Level in Decibels (dB) and Sound Power in Watts

Relationship of Sound Power, Sound Intensity, and Sound Pressure

Many noise-control problems require a practical knowledge of the relationship between pressure, intensity, and power. An example would be the prediction of sound-pressure levels that would be produced around a proposed machine location from the sound-power level provided for the machine.

Example: Predict the sound-pressure level that would be produced at a distance of 100 feet from a pneumatic chipping hammer. The manufacturer of the chipping hammer states that the hammer has an acoustic power output of 1.0 watt.

From Equations (4) and (6) in free field for an omnidirectional source:

$$P = I_{avg} \, 4\pi r^2 = \frac{p^2 \text{ avg } 4\pi r^2}{\rho c}, \qquad (8)$$

where

$$p_{avg} = \sqrt{\frac{P \rho c}{4\pi r^2}} . \qquad (9)$$

If P is given in watts, r in feet, and p in N/m², then, with standard conditions, Equation (9) may be rewritten as

$$p_{avg} = \sqrt{\frac{3.5p \times 10^2}{r^2}}$$

and, for this example,

$$p_{avg} = \sqrt{\frac{3.5 \times 1.0 \times 10^2}{(100)^2}} = 0.187 \text{ N/m}^2 \quad .$$

The sound-pressure level may be determined from Equation (2) to be:

$$L_p = 20 \log \frac{0.187}{0.00002} = 79.4 \text{ dB re } 0.00002 \text{ N/m}^2.$$

Noise levels in locations that are reverberant can be expected to be somewhat higher than predicted because of the sound reflected back to the point of measurement.

COMBINING SOUND LEVELS

It may be necessary to combine sound-pressure levels (decibels) during hearing conservation or noise-control procedures. For example, it may be necessary to predict the overall levels in an area that will result from existing levels being combined with those of a new machine that is to be installed. The combination of levels in various frequency bands to obtain overall or weighted overall sound-pressure levels is another example.

Sound-pressure levels cannot be added arithmetically because addition of these logarithmic quantities constitutes multiplication of pressure ratios. To add sound-pressure levels, the corresponding sound pressures must be determined and added with respect to existing phase relationships.

For the most part, industrial noise is broadband with nearly random phase relationships. Sound-pressure levels of random noises can be added by converting the levels to pressure, then to intensity units which may be added arithmetically, and reconverting the resultant intensity to pressure and finally to sound-pressure levels in dB. Equations (2) and (4) can be used in free-field conditions for this purpose.

A more convenient way to add the sound-pressure levels of two separate random noise sources is to use Table 23-1. To add one random noise level $L_p(1)$, measured at a point to another, $L_p(2)$, measured by itself at the same point, the numerical difference between the levels, $L_p(2) - L_p(1)$, is used in Table I to find the corresponding value of $L_p(3)$ which, in turn, is added arithmetically to the larger of $L_p(1)$ or $L_p(2)$ to obtain the resultant of $L_p(1) + L_p(2)$. If more than two are to be added, the resultant of the first two must be added to the third, the resultant of the three sources to the fourth, etc., until all levels have been added, or until the addition of smaller values do not add significantly to the total.

Example: The overall sound-pressure level produced by a random-noise source can be calculated by adding the sound-pressure levels measured in octave bands shown in the following table:

Octave Band Center Frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Sound-Pressure Level (dB)	85	88	94	94	95	100	97	90	88

A good procedure for adding a series of dB values is to begin with the highest levels so that calculations may be stopped when lower values are reached which do not add significantly to the total. In this example, the levels of 100 and 97 have a difference of 3 that corresponds with $L_n(3) = 1.8$ in Table 23-1. Thus, 100 dB + 97 dB = 100 + 1.8 = 101.8 dB. Combining 101.8 and 95, the next higher level, gives 101.8 + 0.8 = 102.6 dB which is the total of the first three bands. This procedure is continued with one band at a time until the overall sound-pressure level is found to be about 104 dB.

The overall sound-pressure level calculated in the above example corresponds to the value that would be found by reading a sound level meter at this location with the frequency weighting set so that each frequency in the spectrum is weighted equally. Common names given to this frequency weighting are flat, linear, 20 kc, and overall.

The corresponding A-weighted sound-pressure level (dBA)* found in many noise regulations may also be calculated from octave band values such as those in the above example if the adjustments given in Table 23-2 are first applied. For example the octave band levels with A-weighting corresponding to the above example would be:

Octave Band Center Frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Sound Pressure Level (A-Weighted) (dB)	45.8	61.9	77.8	85.4	91.7	100	98.2	91.0	86.9

These octave band levels with A-frequency weighting can be added by the procedure described above to obtain the resultant A-weighted level which is about 103 dBA.

A large majority of industrial noises have random frequency characteristics and may be combined as described in the above paragraphs. However, there are a few cases of noises with pitched or major pure-tone components where these calculations will not hold, and phase relationships must be considered. In areas where pitched noises are present, standing waves will often be recognized by rapidly varying sound-pressure levels over short distances. It is not practical to try to predict levels in areas where standing waves are present.

*The A-weighted frequency weighting approximates the ear's response characteristics for low level sound, below about 55 dB re 0.00002 N/m^2.

TABLE 23-1

Table for Combining Decibel Levels of Noises with Random Frequency Characteristics

Sum (L_R) of dB Levels L_1 and L_2

Numerical Difference Between Levels L_1 and L_2	L_3: Amount to be Added to the Higher of L_1 or L_2
0.0 to 0.1	3.0
0.2 to 0.3	2.9
0.4 to 0.5	2.8
0.6 to 0.7	2.7
0.8 to 0.9	2.6
1.0 to 1.2	2.5
1.3 to 1.4	2.4
1.5 to 1.6	2.3
1.7 to 1.9	2.2
2.0 to 2.1	2.1
2.2 to 2.4	2.0
2.5 to 2.7	1.9
2.8 to 3.0	1.8
3.1 to 3.3	1.7
3.4 to 3.6	1.6
3.7 to 4.0	1.5
4.1 to 4.3	1.4
4.4 to 4.7	1.3
4.8 to 5.1	1.2
5.2 to 5.6	1.1
5.7 to 6.1	1.0
6.2 to 6.6	0.9
6.7 to 7.2	0.8
7.3 to 7.9	0.7
8.0 to 8.6	0.6
8.7 to 9.6	0.5
9.7 to 10.7	0.4
10.8 to 12.2	0.3
12.3 to 14.5	0.2
14.6 to 19.3	0.1
19.4 to ∞	0.0

Step 1: Determine the difference between the two levels to be added (L_1 and L_2).

Step 2: Find the number (L_3) corresponding to this difference in the Table.

Step 3: Add the number (L_3) to the highest of L_1 and L_2 to obtain the resultant level $L_R = (L_1 \text{ or } L_2) + L_3$

TABLE 23-2

A-Frequency Weighting Adjustments

f(Hz)	Correction
25	−44.7
32	−39.4
40	−34.6
50	−30.2
63	−26.2
80	−22.5
100	−19.1
125	−16.1
160	−13.4
200	−10.9
250	− 8.6
315	− 6.6
400	− 4.8
500	− 3.2
630	− 1.9
800	− 0.8
1000	0.0
1250	+ 0.6
1600	+ 1.0
2000	+ 1.2
2500	+ 1.3
3150	+ 1.2
4000	+ 1.0
5000	+ 0.5
6300	− 0.1
8000	− 1.1
10000	− 2.5
12500	− 4.3
16000	− 6.6
20000	− 9.3

When the sound-pressure levels of two pitched sources are added, it might be assumed that the resultant sound-pressure level $L_p(R)$ will be less, as often as it is greater, than the level of a single source; however, in almost all cases the resultant $L_p(R)$ is greater than either single source. The reason for this may be seen if two pure-tone sources are added at several specified phase differences (see Figure 23-3). At zero phase difference, the resultant of two like pure-tone sources is 6 dB greater than either single level. At a phase difference of 90°, the resultant is 3 dB greater than either level. Between 90° and O°, the resultant is somewhere between 3 and 6 dB greater than either level. At a phase difference of 120°, the resultant is equal to the individual levels; and between 120° and 90°, the resultant is between 0 and 3 dB greater than either level. At 180°, there is complete cancellation of sound. Obviously, the resultant $L_p(R)$ is greater than the individual levels for all phase differences from O° to 120°, but less than individual levels for phase differences from 120° and 180° — a factor of 2:1. Also, most pitched tones are not single tones but combinations thereof: thus, almost all points in the noise fields will have pressure levels exceeding the individual levels.

FREQUENCY ANALYSES

General purpose sound-measuring instruments are normally equipped with three frequency-weighting networks, A, B, and C,[2] that can be used to adjust the frequency response of the instrument. These three frequency weightings shown in Figure 23-4 were chosen because: 1) they approximate the ear's response characteristics at different sound levels, and 2) they can be easily produced with a few common electronic components. Also

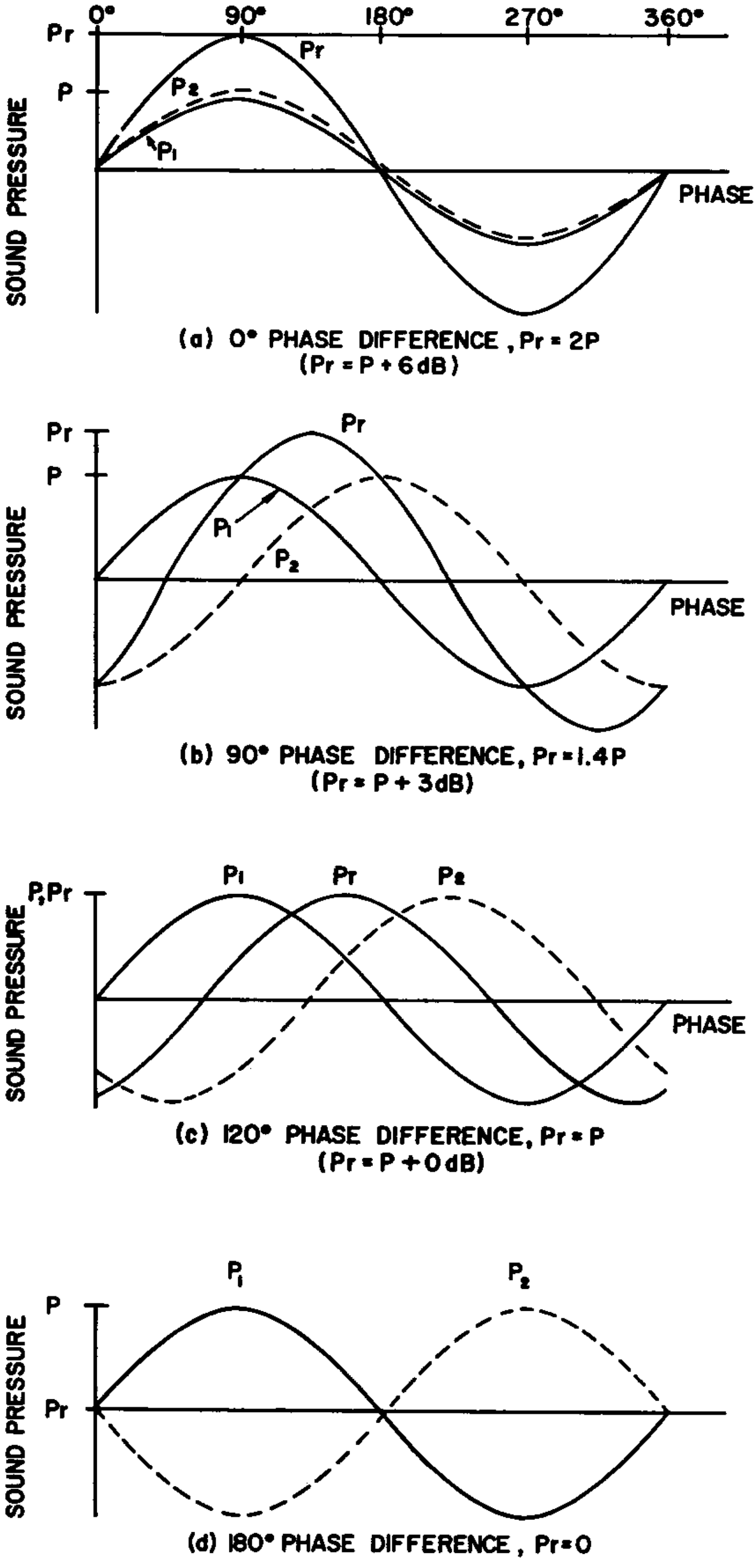

Figure 23-3. Combinations of Two Pure Tone Noises (p_1 and p_2) Phase Differences

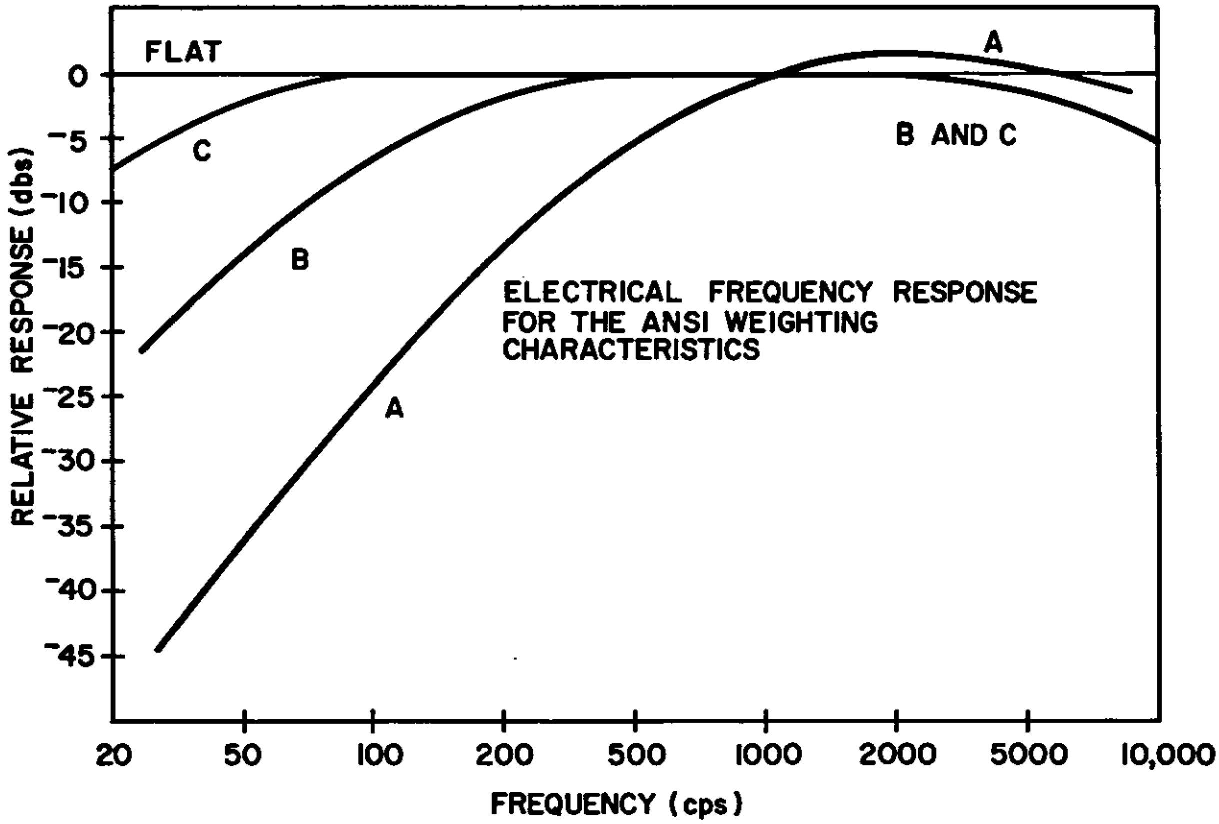

Figure 23-4. Frequency-Response Characteristics for Sound Level Meters (4)

shown in Figure 23-4 is a linear, overall, or flat response that weights all frequencies equally.

The A-frequency weighting approximates the ear's response for low-level sound, below about 55 dB re 0.00002 N/m². The B-frequency weighting is intended to approximate the ear's response for levels between 55 and 85 dB, and the C-frequency weighting corresponds to the ear's response for levels above 85 dB.

In use, the frequency distribution of noise energy can be approximated by comparing the levels measured with each of the frequency weightings. For example, if the A- and C- weighted noise levels are approximately equal, it can be reasoned that most of the noise energy is above 1000 Hz because this is the only position of the spectrum where the weightings are similar. On the other hand, if there is a large difference between these readings, most of the energy will be found below 1000 Hz.

In many cases, such as in noise control procedures, the information supplied by the A, B, and C frequency weightings do not provide enough resolution of frequency distribution of noise energy. Hence, more detailed analyses are needed from analyzers having bandwidths ranging from octaves to only a few cycles in width.

Frequency Bandwidths

The most common frequency bandwidth used for industrial noise measurements is the octave band. A frequency band is said to be an octave in width when its upper band-edge frequency f_2 is twice the lower band-edge frequency f_1:

$$f_2 = 2f_1 \quad . \qquad (10)$$

Octave bands are commonly used for measurements directly related to the effects of noise on the ear and for some noise-control work because they provide the maximum amount of information in a reasonable number of measurements.

When more specific characteristics of a noise source are required, such as might be the case for pinpointing a particular noise source in a background of other sources, it is necessary to use narrower frequency bandwidths than octave bands. Half-octave, third-octave, and narrower bands are used for these purposes. A half-octave bandwidth is defined as a band whose upper band-edge frequency f_2 is the square root of 2 times the lower band-edge frequency f_1:

$$f_2 = \sqrt{2\, f_1} \quad . \qquad (11)$$

A third-octave bandwidth is defined as a band whose upper band-edge frequency f_2 is the cube root of 2 times the lower band-edge frequency f_1:

$$f_2 = \sqrt[3]{2\, f_1} \quad . \qquad (12)$$

The center frequency f_m of any of these bands is the square root of the product of the high and low band-edge frequencies (geometric mean):

$$f_m = \sqrt{f_2 f_1} \quad (13)$$

It should be noted that the upper and lower band-edge frequencies describing a frequency band do not imply abrupt cut-offs at these frequencies. These band-edge frequencies are conventionally used as the 3-dB-down points of gradually sloping curves that meet the American Standard Specification for Octave, Half-Octave, and Third-Octave Band Filter Sets, S1.11-1966.[3]

Comparing Levels Having Different Bandwidths

Noise-measurement data (rms) taken with analyzers of a given bandwidth may be converted to another given bandwidth *if* the frequency range covered has a continuous spectrum with no prominent changes in level. The conversion may be made in terms of sound-pressure levels by

$$L_p(A) = L_p(B) - 10 \log \frac{\Delta f(B)}{\Delta f(A)}, \quad (14)$$

where $L_p(A)$ = the sound-pressure level, in dB, of the band having a width $\Delta f(A)$ Hz.

where $L_p(B)$ = the sound-pressure level, in dB, of the band having a width $\Delta f(B)$ Hz.

Sound-pressure levels for different bandwidths of flat continuous spectrum noises may also be converted to spectrum levels. The spectrum level describes a continuous-spectrum wide-band noise in terms of its energy equivalent in a band one-hertz wide, assuming that no prominent peaks are present. The spectrum level $L_p(S)$ may be determined by

$$L_p(S) = L_p(\Delta f) - 10 \log \Delta f \quad , \quad (15)$$

where $L_p(\Delta f)$ = the sound-pressure level of the band having a width of Δf Hz,

Δf = the bandwidth in Hz.

It should be emphasized that accurate conversion of sound-pressure levels from one bandwidth to another by the method described above can be accomplished only when the frequency bands have flat continuous spectra.

NOISE PROPAGATION CHARACTERISTICS

The sound-power level supplied by the manufacturer of noise-making equipment can be used to predict sound-pressure levels that will be produced by the equipment in surrounding work areas if the acoustical characteristics of the work area are known. These calculations are complex if all factors are considered, but simple approximate solutions to general cases are often helpful to estimate levels.

Noise Source in Free Field

A free field has been defined as one in which the sound pressure decreases inversely with the distance from the source. These ideal acoustical conditions are rarely found in work environments because of the reflecting surfaces of equipment, walls, ceilings, floors, etc.; however, free-field conditions may sometimes be approached outdoors or in very large rooms. For standard free-field conditions, the sound-pressure level L_p at a given distance r from a small omni-directional noise source can be written in terms of the sound-power level L_P of the source as

$$L_p = L_P - 20 \log r - 0.5 \quad , \quad (16)$$

where r is in feet, L_p is in dB referenced to $0.00002 N/m^2$, and L_P is in dB referenced to 10^{-12} watts.

Many noise sources have pronounced directional characteristics; that is, they will radiate more noise in one direction than another. Therefore, it will be necessary for the equipment manufacturer to provide the directional characteristics of the source, as well as the power levels, to predict the sound-pressure levels. The directional characteristics of the source are generally given in terms of the directivity factor Q. Q is defined as the ratio of the sound power of a small, omnidirectional, imaginary source to the sound power of the actual source where both sound powers produce the same sound-pressure level at the measurement position. The directivity factor may be added to Equation (16) in the form

$$L_p = L_P - 20 \log r - 0.5 + 10 \log Q \quad , \quad (17)$$

where 10 log Q is called the directivity index.

Example: Predict the sound-pressure level that will be produced in a free field at a distance of 100 feet directly in front of a particular machine. A directivity factor of 5 is provided by the machine manufacturer for this location. The noise source has a continuous spectrum and a sound power of 0.1 watt.

From Equation (17):

$$L_p = 10 \log \left[\frac{0.1}{10^{-12}}\right] - 20 \log 100 - 0.5 + 10 \log 5$$

$$= 10 (\log 0.1 - \log 10^{-12}) - 20(2) - 0.5 + 10(0.7)$$

$$= 10(-1 + 12) - 40 - 0.5 + 7$$

$$= 76.5 \text{ dB re } 0.00002 \text{ N/m}^2.$$

Noise Source in Reverberant Field

In reverberant fields where a high percentage of reflected sound energy is present, the sound-pressure levels may be essentially independent of direction and distance to the noise source. Levels in these reverberant areas depend upon room dimensions, object size, and placement in the room, and upon the acoustical absorption characteristics of surfaces in the room. Additional complications may be present in the form of regions of enforcement and cancellation of sound pressure, standing waves, caused by strong pure-tone components being reflected. Thus, it is extremely difficult to predict sound-pressure levels at a particular point in a reverberant area.

Sound Absorption

The acoustical characteristics of a room are strongly dependent upon the absorption coefficients of its surface areas. A surface that absorbs all energy incident on its surface is said to have an absorption coefficient of one, while a surface that reflects all incident energy has an absorption coefficient of zero. The absorption coefficient depends upon the nature of the material, the frequency characteristics of the incident sound, and the angle of incidence of the sound. The absorption coefficient is expressed in terms of the fraction of the energy absorbed by the material under the conditions described.

A rule of thumb that may be used to determine the amount of noise reduction possible from the application of acoustically absorbent material on room surfaces is as follows:

$$\text{dB reduction} = 10 \log \frac{\text{absorption units after}}{\text{absorption units before}},$$

where the absorption units are the sum of the products of surface areas and their respective noise absorption coefficients.[4, 5, 6] Absorption units are commonly expressed in terms of the sabin, which is the equivalent of 1 square foot of a perfectly absorptive surface.

Transmission Loss (TL) of Barriers

Sound transmission loss (TL) through a barrier may be defined as ten times the logarithm (to the base 10) of the ratio of the acoustic energy transmitted through the barrier to the incident acoustic energy. TL of a barrier may also be defined in terms of the sound pressure level reduction afforded by the barrier. Unless otherwise specified, the sound fields are diffuse on either side of the barrier. The TL of a barrier is a physical property of the material used for a given wall construction. The TL for continuous, random noise commonly found in industry increases about 5 dB for each doubling of wall weight per unit of surface area, and for each doubling of frequency.

Multiple wall construction with enclosed air spaces provides considerably more attenuation than the single-wall mass law would predict.[7, 8, 9] However, considerable care must be taken to avoid rigid connections between multiple walls when they are constructed or any advantages in attenuation will be nullified.[10, 11]

Noise leaks which result from cracks or holes, or from windows or doors, in a noise barrier can severely limit noise reduction characteristics of the barrier. In particular, care must be exercised throughout construction to prevent leaks that may be caused by electrical outlets, plumbing connections, telephone lines, etc., in otherwise effective barriers.

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