Sound Attenuation

INTRODUCTION

In the broadest sense, a sound wave is any disturbance that is propagated in an elastic medium, which may be a gas, a liquid, or a solid. Noise is defined as any unwanted sound perceived by the hearing sense of a human being. Excessive noise can impair hearing, and may also put stress on the heart, the circulatory system, and other parts of the body. Worker exposure to excessive noise over an extended period may result in a permanent loss of hearing. The introduction of a noise source into a given environment can be potentially hazardous, as well as objectionable to nearby tenants and residents – depending on its sound level. Numerous laws have been enacted at both national and local government levels to limit excessive noise. Such regulations are typically grouped together based upon the land use characteristics and the proximity to residential or other sensitive areas.

Every situation in noise control involves a system composed of three basic elements: source, path, and receiver. Before a solution to a complex noise problem can be designed, the dominant source of the noise must be known, the characteristics of the significant transmission path must be understood, and a criterion for the level of noise considered permissible or desirable in this situation must be available.

25.1 BASICS OF SOUND

25.1.1 Concept of sound. A person perceives sound as any vibration of the eardrum in the audible frequency range that results from an incremental variation in air pressure at the ear. A variation in pressure above and below the atmospheric pressure is called **sound pressure** and is measured in units of Pascal (Pa).

The number of pressure variations per second is called the **frequency** of sound, which is measured in cycles per second, called Hertz (Hz). A young person with normal hearing can perceive sound in the frequency range of roughly 20 – 20,000 Hz, defined as the normal audible frequency range. A sound that has only one frequency is known as a pure tone. Pure tones are seldom encountered in practical applications as most sounds are made up of different frequencies. Most industrial noise will consist of a wide mixture of frequencies known as broadband noise. The reciprocal of the frequency of a pure tone is called the **period**. A period is defined as the time required for one complete cycle of the sinusoidal tone, and is measured in seconds.

The **speed of sound** is the rate at which a sound wave propagates through a given medium, and is dependent on the elasticity and density of that medium. For all practical purposes, the speed of sound in air is dependent only on the absolute temperature, which directly affects its density. The equation for the speed of sound in air is $c = 20.05\sqrt{T}$ (m/s), where T is the absolute temperature of air in degrees Kelvin. At room temperature and standard atmospheric pressure, the speed of sound in air is 343 m/s.

Wavelength is defined as the distance a pure tone wave travels during a full period, and is denoted by Greek letter lambda (λ). The wavelength of a pure tone is equal to the speed of sound divided by the frequency of the pure tone $\lambda = c/f$. Knowledge of the tonal wavelength is often used in the design of noise abatement elements to disrupt, or mimic, the offending tone or noise.

25.1.2 The Decibel and Sound levels. Noise control engineering, like any other discipline, has a specialized vocabulary. You may see references to both, sound power and sound pressure level, measured in decibels, in a manufacturers' published test data. Sound levels are described on a logarithmic scale in units called **decibels** (dB). Sound levels are described logarithmically because it compresses the large range of typical sound pressures into a smaller, more practical scale, which incidentally also more closely parallels the human ear's ability to judge the relative loudness of sounds according to the ratio of their pressure. The important thing to remember about the decibel is that it represents a relative measurement or ratio. 'Sound power level' and 'sound pressure level' are typically expressed in terms of decibels, as an indication that they are not absolute values, but rather, measurements relative to a reference quantity.

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The combination of fluctuations in pressure and velocity can be used to form a measure of sound power. The **sound power level** (L_w or SWL) is the total sound power *(W)* radiated from a source with respect to a reference power of $W_{ref} = 10^{-12}$ Watts. Sound power level can be calculated using the following formula:

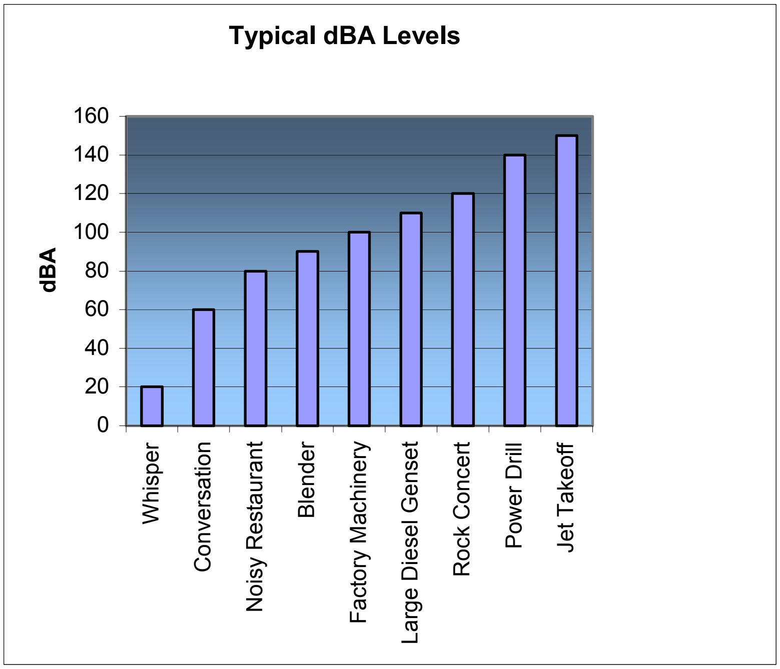
$$L_W = 10\log_{10}\left(W/W_{ref}\right) \qquad (dB) \qquad \text{Eqn. 25-1}$$

It should be noted that the sound power level is a measure of the sound source itself, and is independent on the source's surroundings.

The quantity most often used to measure the "strength" of a sound wave is the **sound pressure level** (*Lp* or SPL) measured with respect to a standard reference pressure of $p_{ref} = 2\times10^{-5}$ Pa. The sound pressure level can be calculated using the following formula:

$$L_p = 20\log_{10}\left(p/p_{ref}\right) \qquad (dB) \qquad \text{Eqn. 25-2}$$

The reference pressure represents the normal threshold of hearing for most individuals. The table below presents overall dBA levels for some environments typically encountered.



25.1.3 Frequency bands and weightings. When detailed information about a complex noise is required, the audible frequency range from 20 Hz to 20 kHz can be divided into contiguous bands. A band has a lower frequency (f_l) and an upper frequency (f_u). The partitioning of a spectrum is considered proportional if ratio (f_u / f_l) is the same for each band. The *center frequency* (f_c) of any such band is defined as the geometric mean $(f_l \cdot f_u)^{1/2}$. An **octave band** is a band for which $f_u / f_l = 2$, and a **1/3 octave band** is one for which $f_u / f_l = 2^{1/3}$. Three contiguous 1/3 octave bands are equivalent to an octave band. The *lower and upper frequencies* may be determined from the center frequency as $f_l = 2^{-1/2n} f_c$ and $f_u = 2^{1/2n} f_c$ (where *n*=1 for octave bands and $^1/_3$ for $^1/_3$ octave bands). Any proportional frequency band can be defined by its center frequency and by *n*. The standard center, lower, and upper frequencies for octave and $^1/_3$ octave bands typically used in noise control and acoustics are given in Table 25-1.

To achieve a meaningful reduction in noise, one must start with accurate information about the source. The human ear is not equally sensitive at all frequencies; it is most sensitive in the 500 Hz to 6000 Hz range, and least sensitive at extremely high and low frequencies outside this range. Three different standardized characteristics called the "A", "B", and "C" weighting networks have been developed to standardize results and comparisons. Each weighting is centered on different sound pressure level curves. A specialized characteristic, the "D" weighting, has been standardized for aircraft noise measurements. The "A" network is widely used as it provides the best correlation to human hearing in subjective tests. Legislation and OEM documentation is most often written with reference to the "A" scale. The three weighting factors for the "A", "B", and "C" networks are provided in Table 25-2. To convert a dB value to a weighted dBA value, simply add the numbers indicted in Table 25-2 to the corresponding octave or $^1/_3$ octave band source data. For example, in the 500 Hz frequency range, an 85 dB sound pressure level will become an 81.8 dBA sound pressure level in the “A” weighted network.

25.1.4 Addition of sound levels. Decibel levels for two or more sounds cannot be added directly, as the values are logarithmic. It is often necessary to convert sound pressure levels measured in a series of contiguous bands, into a single-band level encompassing the same frequency range. The level in the all-inclusive band is called the *overall level* L(OA) given by;

$$L_p(OA) = 10\log_{10}\sum_{i=1}^{n}10^{L_{pi}/10} \qquad (dB) \qquad \text{Eqn 25-3}$$

The conversion can also be accomplished with the aid of Table 25-3. The combined effect of sounds depends on the difference in their decibel levels.

To calculate an estimated overall dBA level, the technique presented in Table 25-3 may be employed. To use the table, we must first correct the octave band readings to A-weighting sound pressure levels for the various frequencies. To combine these eight levels into an overall dBA, start with the values in any two bands, for example, the 1st and 8th octave bands. From Table 25-3 we see that whenever the difference between two band levels is zero, the combined level is 3 dB higher. If the difference is 5 dB (the 7th band level minus the new level of 68 dB), the sum is 1.2 dB greater than the larger band level (73 dB). This estimating procedure can be followed until an overall level of 93.3 dBA is obtained. It should be noted that fractional dBA levels do not significantly contribute to overall noise levels, and hence, levels should be quoted to the nearest decibel.

Table 25-1. Center, lower, and upper frequencies for standard set of octave and 1/3 octave bands covering the audible frequency range.

Octave Band			1/3 Octave Band		
Lower Frequency (Hz)	Center Frequency (Hz)	Upper Frequency (Hz)	Lower Frequency (Hz)	Center Frequency (Hz)	Upper Frequency (Hz)
22	31.5	44	22.4	25	28.2
			28.2	31.5	35.5
			35.5	40	44.7
44	63	88	44.7	50	56.2
			56.2	63	70.8
			70.8	80	89.1
88	125	177	89.1	100	112
			112	125	141
			141	160	178
177	250	355	178	200	224
			224	250	282
			282	315	355
355	500	710	355	400	447
			447	500	562
			562	630	708
710	1,000	1,420	708	800	891
			891	1,000	1,122
			1,122	1,250	1,413
1,420	2,000	2,840	1,413	1,600	1,778
			1,778	2,000	2,239
			2,239	2,500	2,818
2,840	4,000	5,680	2,818	3,150	3,548
			3,548	4,000	4,467
			4,467	5,000	5,623
5,680	8,000	11,360	5,623	6,300	7,079
			7,079	8,000	8,913
			8,913	10,000	11,220
11,360	16,000	22,720	11,220	12,500	14,130
			14,130	16,000	17,780
			17,780	20,000	22,390

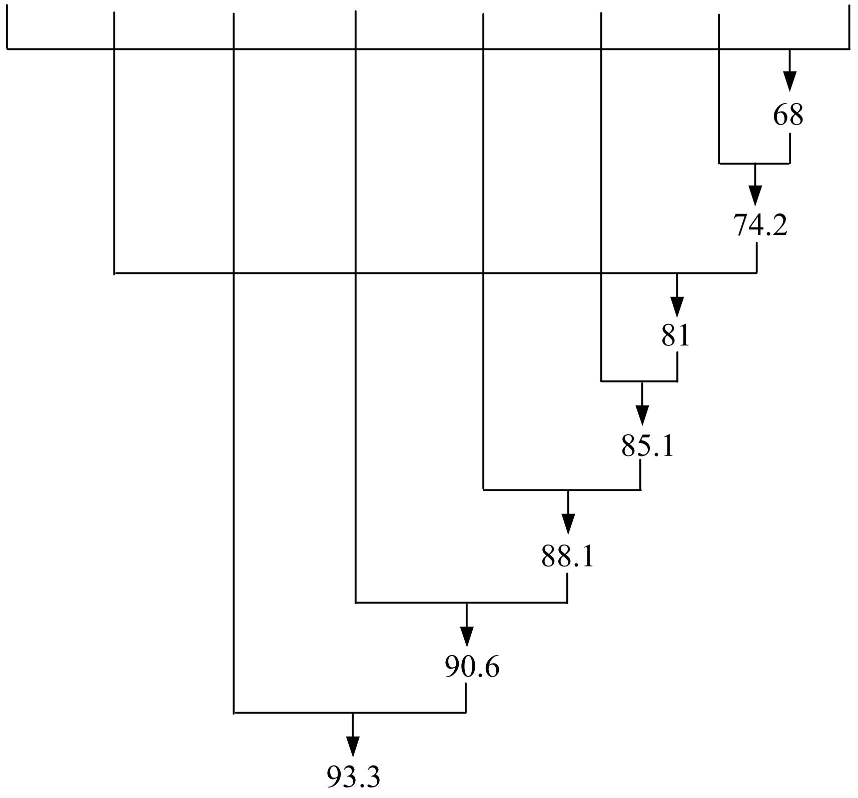
Table 25-2. A, B, and C Electrical Weighting Networks for the Sound-Level Meter. These numbers assume a flat, diffuse-field (random incidence) response for the sound-level meter and microphone

Frequency (Hz)	A-weighting relative response (dB)	B-weighting relative response (dB)	C-weighting relative response (dB)
25	-44.7	-20.4	-4.4
31.5	-39.4	-17.1	-3.0
40	-34.6	-14.2	-2.0
50	-30.2	-11.6	-1.3
63	-26.2	-9.3	-0.8
80	-22.5	-7.4	-0.5
100	-19.1	-5.6	-0.3
125	-16.1	-4.2	-0.2
160	-13.4	-3.0	-0.1
200	-10.9	-2.0	0
250	-8.6	-1.3	0
315	-6.6	-0.8	0
400	-4.8	-0.5	0
500	-3.2	-0.3	0
630	-1.9	-0.1	0
800	-0.8	0	0
1,000	0	0	0
1,250	+0.6	0	0
1,600	+1.0	0	-0.1
2,000	+1.2	-0.1	-0.2
2,500	+1.3	-0.2	-0.3
3,150	+1.2	-0.4	-0.5
4,000	+1.0	-0.7	-0.8
5,000	+0.5	-1.2	-1.3
6,300	-0.1	-1.9	-2.0
8,000	-1.1	-2.9	-3.0
10,000	-2.5	-4.3	-4.4
12,500	-4.3	-6.1	-6.2
16,000	-6.6	-8.4	-8.5
20,000	-9.3	-11.1	-11.2

Table 25-3. Combining two sound levels L_1 and L_2. May be sound power levels or sound pressure levels.

L_1-L_2	0	1	2	3	4	5	6	7	8	9	10
L_{com}-L_1	3.0	2.5	2.1	1.8	1.5	1.2	1.0	0.8	0.6	0.5	0.4

Band Number	1	2	3	4	5	6	7	8
Center Frequency (Hz)	63	125	250	500	1000	2000	4000	8000
SPL (dB)	91	96	99	90	85	78	72	66
A-weighting	-26	-16	-9	-3	+0	+1	+1	-1
Corrected SPL (dBA)	65	80	90	87	85	83	73	65



Overall A-weighted SPL ≈ 93 dBA

Figure 25-1. Determination of overall A-weighting SPL from levels in frequency bands.

25.1.5 Ambient noise. The noise that is present in the environment before the introduction of additional noise sources is referred to as the ambient or background noise level. The ambient noise level should be measured and accounted for, prior to the installation of equipment. As an example, equipment is to be introduced into an environment where the requirement for the completed installation is 65 dBA, measured at point X. Other sources contributing to the ambient noise level at the site dictate that the pre-installation noise level is already 63 dBA at point X. From Table 25-3 we can see that in order to meet the 65 dBA specification, the noise radiated from the newly installed equipment should not exceed 60 dBA. (The difference between the levels is 3 dBA, and 2 dBA should be added to the 63 dBA ambient level.) In general terms, sound abatement solutions need only be introduced in an environment where ambient or auxiliary noise sources will not mask their contributions.

25.2 SOUND TRANSMISSION

If a point source of sound is placed in an environment without any reflecting surfaces (in free field), sound waves will travel out from it in a spherical wave front. If the point source is close to the ground, sound will radiate from it in a hemispherical pattern. Sound radiates from a source in a similar fashion as a pressure front from an explosion. As the area of the hemisphere increases with distance from the source, the sound pressure level decreases correspondingly. Most real sound sources are somewhat directional, and as a result, sound levels at equal distances – but differing orientations - are not necessarily equal. Many OEM data sources will usually reference a measurement standard that may include location averaging, as well as a reference elevation. The directivity index D_I allows for the SPL to be adjusted depending on which direction a sound source is radiating with respect to an observer. As a general rule, if the wavelength of sound is large in comparison to the dimension of the source, it radiates uniformly in all directions. Due to increasingly longer wavelengths, low frequency sounds are typically less directional than high frequency sounds.

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Equation 25-4 is a useful equation for the determination of SPL at a distance *R* from a point source, assuming hemispherical spreading.

$$SPL = SWL - 20\log_{10}(R) - 8 - D_I - other \qquad \text{(dB)} \qquad \text{Eqn 25-4}$$

In the above equation, the "*other*" category represents factors affecting sound propagation such as: atmospheric absorption, ground attenuation, wind or temperature gradients, trees, barriers or buildings, etc. The difference in SPL between two distances, R_1 and R_2, from a point source, can be calculated as follows:

$$SPL_2 = SPL_1 - 20\log_{10}(R_2 / R_1) \qquad \text{(dB)} \qquad \text{Eqn 25-5}$$

As a rule of thumb the SPL will be reduced by 6 dB when the distance from a point source is doubled in free field conditions. As a conservative estimate, a value of 5 dB to 5.5 dB should be used to account for ground reflections. The free field begins at approximately 10 meters from a typical large genset.

In the installation of an electric generating system, many field factors can contribute to deviations of actual SPL values, from theoretically predicted values. A margin of safety should therefore be applied to calculated values, if all field conditions are not fully known. Walls, buildings, signs and auxiliary machinery commonly change the resulting sound field. An obstacle in the sound path will partially reflect, absorb and transmit sound. In general, an object must be larger than one wavelength in order to significantly interfere with sound. A 10 kHz source has a wavelength of 3.4 cm. In this example, even a small object such as a measuring microphone will disturb the sound field locally. At 100 Hz, where the wavelength is 3.4 meters, sound isolation becomes much more difficult.

Sound waves travel not only in air, but also in solids and liquids. Airborne sound is usually caused by vibration in solids or turbulence in fluids. Vibration in solids and liquids can travel great distances before producing airborne sound. One example is the vibration from a train, which can be heard in the rails a great distance away prior to airborne sound transmission. It is this type of sound transmission that sometimes defeats attempts to acoustically isolate generator sets; without adequate vibration isolation of the skid base, vibrations can travel unopposed through the skid, so that much of the noise is not subjected to acoustic dampening systems engineered into the enclosure. Ideally, a generator set should be mounted on isolators, or mounted on a concrete pad, with the enclosure completely surrounding the base. Small leakages can contribute greatly to overall sound levels, and as a result, gaskets should be used to prevent any noise leaks through gaps in an uneven concrete surface, or around enclosure penetrations. Turbulent fluid flow within pipes can also produce radiated sound that can be transmitted to the building, or enclosure structure. Rigid couplings for pipes and electrical connectors can drastically affect the attenuation, and where warranted, connections should be flexible or isolated to prevent transmission of vibration to the enclosure walls.

25.3 SOUND ABSORPTION BY MATERIALS

Sound waves are reflected when they hit a hard surface. Providing an absorbent surface can reduce some of the reflected sound. In a "hard" room, soft materials such as absorbent ceiling panels, carpeting on the floor, and drapes or special absorbent wall coverings, will reduce noise by reducing the reflected sound. Only reflected sound can be treated as described, while direct sound will not be affected.

Porous materials of varying density and composition are generally used as sound absorbers to convert sound energy into heat within the open pores of the material. In order to maintain the best absorption values of the chosen materials, the air channels should all be open to the surface so that sound waves can propagate into the material. If pores are sealed, as in a closed cell foam, the material is generally a poor absorber. Pores should not be sealed by paint, or coverings, and any protective shielding for the absorbing material should generally be perforated.

In evaluating materials for their ability to absorb sound energy, its ability to absorb sound is usually provided in the form of an absorption coefficient (α). The absorption coefficient is defined as the ratio of sound energy absorbed by a given surface, to the sound energy incident upon that surface. The absorption coefficient can vary from 0 to 1; i.e. if α=0.9, then 90% of the sound energy will be absorbed. The absorption coefficient is dependent on the frequency, and is usually published for octave, or 1/3 octave, bands. Most porous absorbers are more efficient at high frequencies, while improving the materials thickness, or mass, can increase low frequency absorption.

Panel absorbers are often an option when low-frequency absorption is required. Thin, flexible panels are mounted away from the wall, creating a shallow air cavity. The air cavity between the panel and the wall provides a means for sound absorption at particular “tuned” frequencies. Incident sound at the frequency of interest produces a resonant response in the panel-cavity that causes the panel to vibrate. Filling the cavity with a porous material can reduce the “sharpness” of the tuning. This type of solution can be cost inhibitive, and is usually employed to treat a specific tone or narrow band of an offending source, when traditional treatments are insufficient.

A traditional approach utilizes a sound absorbing material sandwiched between a perforated lining and an external surface. The perforated lining usually consists of sheeting with a pattern of small, evenly spaced holes that can effectively absorb sound at particular “tuned” frequencies. The perforated facing is mounted on top of the porous material, and, depending on the thickness, hole size and spacing, can partially act as a panel absorber to increase absorption at certain frequencies. Absorption at high frequencies is reduced because of reflections from the solid areas of the facing. A perforated facing with an open area of at least 20% will not significantly degrade the absorption of high frequency sound over the typical range of interest.

25.4 SOUND REDUCTION BY STRUCTURES

25.4.1 Mass law. The mass law relates to the transmission loss of solid panels, and states that within a limited frequency range, the magnitude of the loss is controlled entirely by the mass per unit area of the wall. The law also states that the transmission loss increases 6 decibels for each doubling of frequency, or each doubling of the wall mass per unit area, up to a plateau frequency. For example, lead sheet has a transmission loss of 13 dB at 63 Hz, 19 dB at 125 Hz, 25 dB at 250 Hz, etc. If you double the thickness of the mass from 1/16 in. to 1/8 in. thick, the transmission loss at 63 Hz becomes 13 + 6, or 19 decibels. The combination of lightweight materials, and mass layers, are usually used in combination to provide a composite layer that is sufficient for achieving the required sound attenuation.

25.4.2 Resonance. Every material has a natural mode of vibration known as the resonance frequency, which is dependent upon many characteristics, including mass. Lightweight mounting structures under generators can sometimes result in higher overall noise levels due to excitation of the base by the forcing frequency of the engine, thereby resulting in an amplification of the sound pressure level at that frequency. This can occasionally be seen in paneled buildings, or base structures, where a “drumming” affect is dominant and will actually amplify the sound source. The proper selection of vibration isolators becomes very critical in dampening the forcing frequency of the engine, and isolating it from the adjoining structure. Spring isolators with provision for internal damping may be required to prevent a reinforcement of vibrations at the fundamental frequency.

25.4.3 Enclosures. Acoustical enclosures constitute the most frequently used device to reduce the noise radiated by equipment. Typical enclosure panels are multi-layer composite treatments, consisting of an impervious, exterior layer and a layer of porous sound absorbing material facing toward the interior. As previously described, an impervious mass layer on the exterior surface blocks passage of sound energy radiated by the enclosed sound source. The porous sound absorbing lining will dissipate the retained sound energy, and also provide heat-insulating properties. Sound attenuated enclosures are discussed in Chapter 24.

25.4.4 Wrappings. Many machine components and piping systems require thermal insulation to provide protection for operating personnel, or to prevent excessive heat loss. Equipment such as turbines and generators typically require connecting service piping, which can also be sources of intense noise. It is frequently possible to achieve both thermal and acoustical insulation, by providing a single composite treatment to the exterior of the piping, or component.

25.4.5 Silencers. The noise generated by sources such as engine combustion, blowers, and fans, is generally controlled through the use of silencers. Silencers are typically divided into three types: reactive, absorptive, and a combination reactive/absorptive. Reactive silencers typically provide better noise attenuation at lower frequencies, while absorptive silencers can achieve much greater noise attenuation at higher frequencies. A more flexible solution uses a design that incorporates both reactive and absorptive elements to achieve overall higher noise attenuation throughout the frequency of interest. The proper selection of a silencer will depend upon a number of factors, including: noise spectrum, flow rate, temperature, allowable backpressure, etc. Silencers are presented and discussed in further detail in Chapter 19.

25.5 SOUND MEASUREMENT

25.5.1 Devices. The sound level meter is the most common instrument used in measuring noise sources. A sound level meter works by using a microphone to sense sound pressure, and electronic circuitry to convert the sound pressure to an SPL reading. There are many different kinds of sound meters with a variety of available options. A basic meter can calculate an instantaneous overall SPL, give A-weighting only, and usually has an arbitrary time constant (the rate at which the meter responds to sound). Optional features include selections for different weighting networks (A, B, C, D, or Linear), different time constants (fast – 1/8 *sec*; slow – 1 *sec*; impulse – *fast rise*, *slow decay*), integrating capability with average sound levels over a given time, statistical/histogram results presentation, logging or memory features, and octave band filtering (which can process the sound in one band at a time).

A real-time analyzer is an all-purpose sound-measuring device that uses multiple processors to measure and analyze various sound levels at the same time. Using a real-time analyzer, an individual can observe sound properties over the entire spectrum of interest in real time (i.e.

without the loss of data). A real-time analyzer can perform the work of many sound level meters by simultaneously measuring all octave, or 1/3 octave bands, instead of just one band at a time. Optional features of a typical real-time analyzer include Fast Fourier Transform (FFT) measurements for discrete frequency analysis, and sound intensity measurements using a sound intensity probe. A sound intensity probe has two microphones separated by a spacer, and estimates the instantaneous sound intensity by simultaneously measuring pressures at both microphones. A sound intensity analysis is useful in determining the contributions of individual source elements to an overall sound level, in a multi-source environment.

25.5.2 Guidelines. Various authorities at national, regional and municipal levels publish noise control guidelines and limits. Noise guidelines are often enforced through legislation such as the Environmental Protection Act. A wide variety of standards exist for the measurement and calculation of SPL, SWL, and other more complex acoustical parameters. ISO standard *8528-10 Measurement of Airborne Noise by the Enveloping Surface Method,* can be referenced as a standard procedure for determining overall SPL values.

When taking noise measurements, the height of the microphone should be consistent. The measurement height should be recorded along with the distance from the source, direction of the microphone, and all ambient conditions such as temperature, humidity, wind speed, and ambient noise levels. The directions accompanying the sound level meter should be read to determine whether the microphone should be pointed directly at the noise source, or whether the microphone tip should be at a 90° angle, thus permitting the sound to graze the front of the microphone.

The sound level meter should be carefully handled in order to give valid results. Every meter should be calibrated before, and after, a set of readings is made. The microphone should be fitted with a windscreen when taking measurements outside. One frequently overlooked condition is temperature. The microphone must have ample time to adjust to ambient conditions prior to the commencement of testing. For example, if outdoor testing is to be done in summer, one should not take a sound level meter that has been kept in an air-conditioned office, and immediately start taking measurements outside. It is best to allow several hours for the instrument to heat or cool to ambient temperature. Microphones are extremely sensitive to temperature, and even the operator's body heat can interfere with readings by reflecting sound waves back to the microphone. It may be advisable to mount the microphone on a tripod at the test location, and distance both the meter and operator from the sound field using an extension cable.

Another very important factor influencing the accuracy of measurements is the level of background noise, compared with the noise signal to be measured. Obviously, the background noise must not overwhelm the signal of interest. In practice, the level of the sound source being investigated must be at least 3 dB higher than the background noise in order to obtain significant measurement data. Noise level metering must be performed when the noise source is operational, and when it is not, and these values must be compared. If the difference between the two readings is less than 3 dB, the background noise level is too high for an accurate measurement. It is recommended that the ambient noise be measured as referenced in section 25.1.5 in order to avoid overestimating the severity of the noise problem, and over-designing a solution, as a consequence. If the difference between the ambient and combined noise level is between 3 dB and 10 dB, a correction to the reading is necessary. If the specification calls for octave band readings, ambient noise should be read at each octave band, and corrections made to the noise level readings as necessary.

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