NOISE CONTROL
IN
INDUSTRY
A Practical Guide

by

Nicholas P. Cheremisinoff, Ph.D.

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ABOUT THE AUTHOR

Nicholas P. Cheremisinoff is a private consultant to industry, academia, and government. He has nearly twenty years of industry and applied research experience in elastomers, synthetic fuels, petrochemicals manufacturing, and environmental control. A chemical engineer by trade, he has authored over 100 engineering textbooks and has contributed extensively to the industrial press. He is currently working for the United States Agency for International Development in Eastern Ukraine, where he is managing the Industrial Waste Management Project. Dr. Cheremisinoff received his B.S., M.S., and Ph.D. degrees from Clarkson College of Technology.

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PREFACE

Damage from noise exposure of sufficient intensity and duration is well established and hearing loss may be temporary or permanent. Fortunately, noise exposure can be controlled and technology exists to reduce the hazards. Aside from employer/employee concern with the inherent hazards of noise, added attention has been brought to focus on the subject through regulatory requirements. Under the Occupational Safety and Health Act (OSHA) every employer is legally responsible for providing a workplace free of hazards such as excessive noise. It has been estimated that 14 million U.S. workers are exposed to hazardous noise.

This book is presented as an overview summary for employers, workers, and supervisors interested in workplace noise and its control. We believe that in order to understand and control noise it is not necessary to be highly technical. Noise problems can quite often be solved by the people who are directly affected. It is with these objectives that this book was prepared by the authors/editors and respective contributing experts. Presented are an overview of noise; the regulations concerning its control; an explanation of specific principles and a discussion of some particular techniques. We hope the reader can apply these in his or her workplace.

This book is based upon seminars given by the author during the 1980s. There have been no changes in regulations since that time, and this book is still a valuable reference work for the control of industrial noise.

Nicholas P. Cheremisinoff

CONTENTS

1.

INTRODUCTION TO SOUND AND NOISE

Discordant sound resulting from nonperiodic vibrations in air or, more commonly, unwanted sound, are two definitions of noise. However, noise rarely manifests itself in such definitive terms. Instead, it draws emotional responses on conscious and subconscious levels. It annoys, awakens, angers, distracts, frustrates and creates stresses that result in physiological and psychological problems. It is invisible, yet its effects are clearly evident, and it pervades every facet of life.

EFFECTS OF NOISE

The effects of noise may be categorized as follows [1-5]:

- Noise-induced hearing loss
- Nonauditory health effects
- Individual behavior effects
- Noise effects on sleep
- Communication interference
- Effects on domestic animals and wildlife

It is well established that hearing damage can result from exposure to noise of sufficient intensity and duration. Hearing loss may be temporary or permanent. In general, it is believed that brief exposure to noise, causing significant temporary hearing loss or threshold shift, may lead to permanent hearing loss if the noise exposure is prolonged or recurring. However, the exact relationship between temporary and permanent hearing loss has not yet been clearly defined. Hearing loss in the high frequency ranges seriously affects understanding of speech. Hearing at the higher frequencies is necessary to discriminate the consonants of speech that carry information [6].

While evidence to support nonauditory health effects may not be as complete as the case for hearing loss, there is cause for concern. Noise can alter the normal functions of the endocrine, cardiovascular and neurological systems. It may affect equilibrium and cause a rise in blood pressure, a change in heart rhythm and constriction of blood vessels. Noise may produce effects similar to, or compound effects of, other more common stresses; studies performed on animals prove such phenomena. It is not clear whether changes in physiology due to recurring noise stress are permanent [7].

Behavioral effects may range from a dulling of response to specific auditory signals in noisy environments, which produces frustration, to a sensitizing to annoyances that commonly would be ignored. Noise can magnify the minor aggravations of the work environment. Human performance is affected by noise, especially those tasks requiring information gathering or analyzing processes. Noise simply may be distracting or be so disturbing that it is impossible to think. Further study is required to determine whether behavioral effects are permanent, or to predict annoyance levels.

If sleep is the body's regenerative process, then any interference with sleep will affect emotional and physical health directly. Awakening, or changing the level or pattern of sleep, may affect long-term health and, consequently, human performance.

Noise extends well beyond the workplace. Technological advances have provided subways, engines, and tires. Household noise sources can be as loud as industrial sources. Consider lawn mowers, chain saws, shop tools, stereos, televisions and air conditioners. (See Figure 1 for typical sound levels.) These sources often are left uncontrolled and are usually used by an unprotected and unregulated user. Thus, these noise sources may be as significant in producing hearing loss as is exposure in the workplace. Moreover, when taken as additional high exposure, the ear may not be receiving sufficient "rest" between exposures.

HUMAN EXPOSURE AND RESPONSE [4,8]

Sound is the result of a source setting a medium into vibration. Usually, the medium is air where the receptor is the ear. Based on the sound characteristics, the sensory conclusion drawn by the brain may be noise or sound, i.e., unwanted or wanted sound. As vibrations hit the ear they set into motion the ear drum and ossicles, as shown in Figure 2. The ossicles produce vibrations in the fluid of the inner ear's sensory organ, the cochlea. These vibrations are transduced by sensory hair cells into nerve impulses. The brain translates these impulses into sound. The

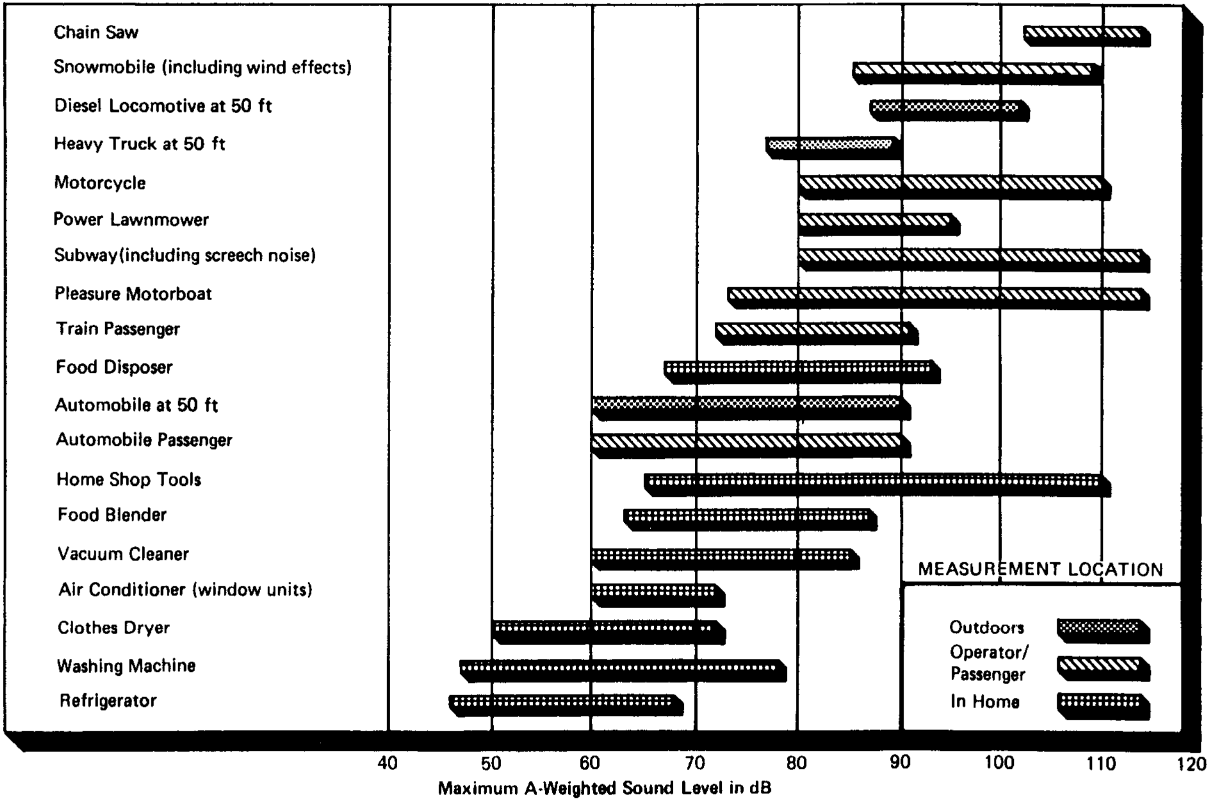


Figure 1. Typical range of common sounds [2].

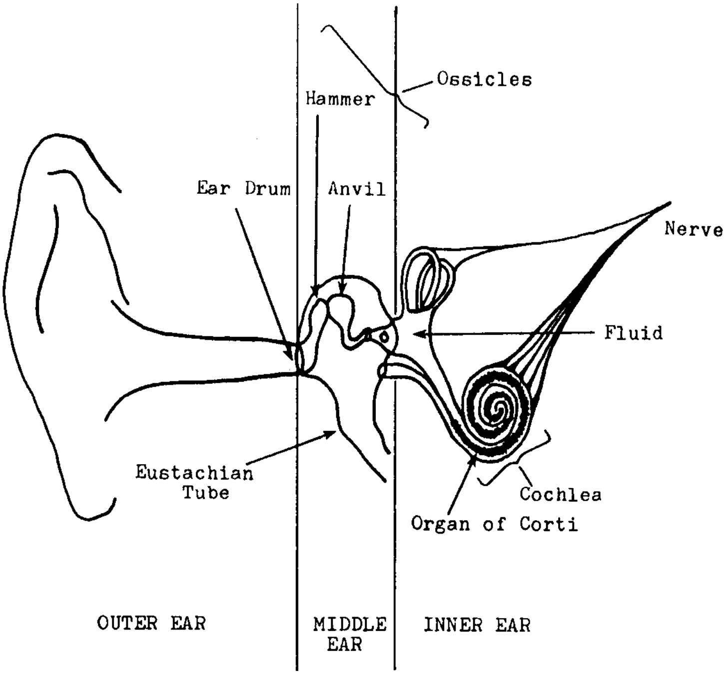


Figure 2. The human ear.

hair cells are nonregenerative; thus, if they are damaged or destroyed, hearing loss will occur.

The ear is less sensitive to low frequencies than to high frequencies. For example, a 50-Hz tone at 70 dB sounds as loud as a 1000-Hz tone at 40 dB. Equal loudness contours (Figure 3) show that as sound levels increase, the ear becomes more uniformly sensitive to all frequencies. The ear is a self-adjusting sound measuring device—within limits [9].

As a sensory organ the ear is second only to the eye with regard to its importance as a means of contact with man's surrounding environment. Yet the human ear can, without pain, discern sound over a dynamic range of ten million to one. The human eye responds to light of intensity range of 105 from threshold to limit.

The human ear is functionally a transmitter of all sound vibrations received from the environment. The ear may respond from a low of 16 Hz at birth to a high of 30,000 Hz; however, a range of 20 Hz to 20,000 Hz is considered a broad frequency response. Throughout life frequency perception declines (presbycusis) to a point at which a normal

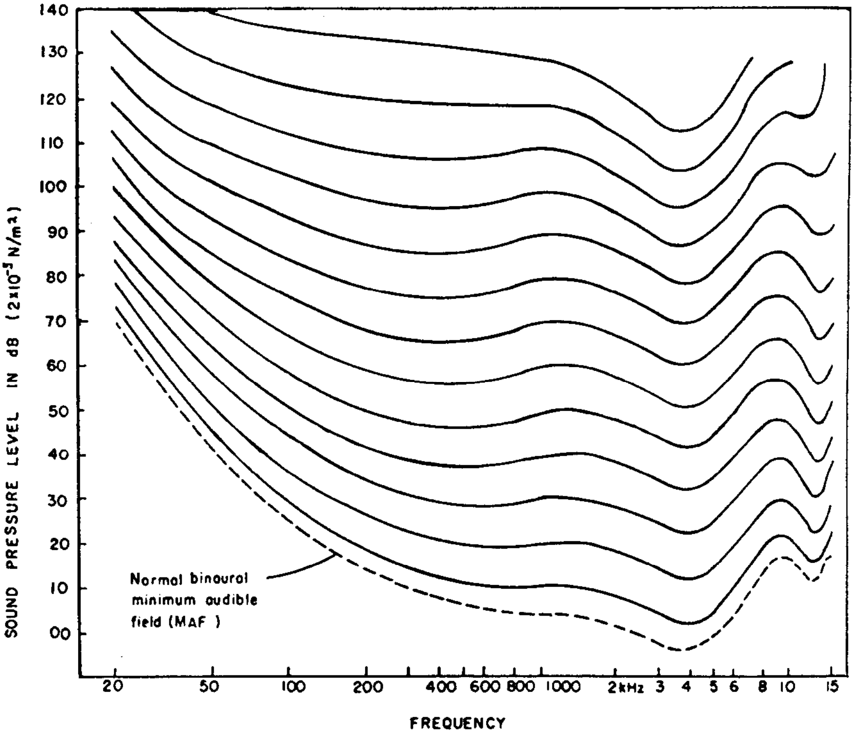


Figure 3. Normal equal-loudness contours for pure tones [9].

adult may have difficulty hearing sounds pitched higher than 12,000 Hz. Speech frequencies are in the range of 20 Hz to 2000 Hz. Needless to say, the process of hearing as related to the work environment is considerably more detailed. These details have been left to others [10,11].

PHYSICS OF SOUND

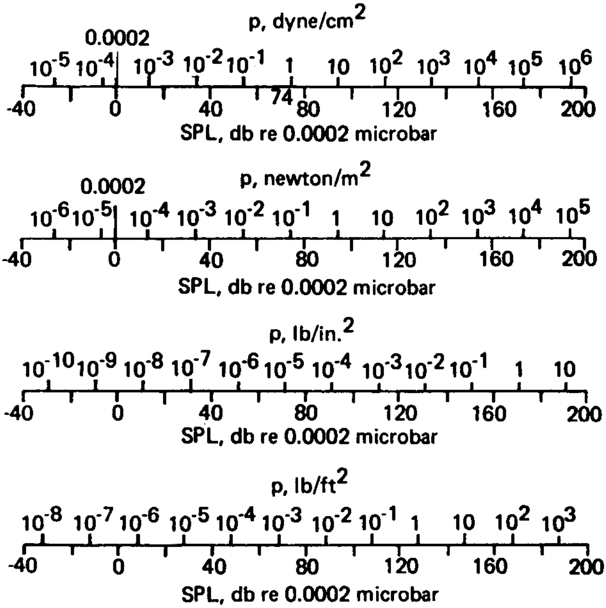
As stated above, vibrations in a medium result in sound. The vibration produces alternating waves of relatively dense and sparse particles—compression and rarefaction, respectively—which travel away from the source as longitudinal waves, much like ripples in water. The resultant variation to normal ambient pressure is translated by the ear and perceived as sound. Like other waveforms, sound waves may be refracted, reflected or scattered. Under normal conditions of temperature, pressure and humidity at sea level, sound waves travel at approximately 344 meter/sec (1100 ft/sec) through air, 1433 meter/sec in water, 3962 meter/sec in wood and 5029 meter/sec in steel. Thus, sound may be transmitted through any media initially and eventually travel through air to a receiver, the ear.

Sound may be described in terms of three variables: (1) amplitude (perceived as loudness), (2) frequency (perceived as pitch) and (3) duration (time).

Amplitude is the measure of the difference between atmospheric pressure (with no sound present) and the total pressure (with sound present). Thus, the amplitude of a given sound wave equates to the sound pressure: the greater the amplitude, the greater the pressure. The common units of pressure are:

- N/m^2 = newtons per square meter
- d/cm^2 = dynes per square centimeter
- μbar = microbars

where 1 μbar = 1 d/cm^2 = 0.1 N/m^2 (see Figure 4).



Note: Charts relate SPL (dB re 0.0002 μbar) to p in dynes/cm^2, newtons/m^2, lb/in.^{2}, and lb/ft^2. For example, 1.0 newton/m^2 equals 1.435×10^{-4} lb/in.^{2}, equals 94 dB.

Figure 4. Relationship of sound pressure to corresponding decibel levels [3].

Sound pressure is used as the fundamental measure of sound amplitude because sound power or sound intensity (energy per unit time and energy per unit area, respectively) are not measurable directly by instruments. However, there are mathematical relationships that relate energy of sound waves and pressure changes. By most instrumentation, sound pressure is measured by providing a reading of root mean square (rms) sound pressure level (Lp) as decibels (dB). Absolute pressure is not measured; instead, the reading is related to a reference pressure. For sound measurement in air the reference pressure is:

- 0.00002 N/m^2,
- 20 μN/m^2,
- 0.0002 d/cm^2,
- 0.0002 μbar.

This level was chosen as the normal threshold of hearing for a frequency of 1000 Hz. The sound pressure level is

$$\text{Lp} = 10 \log \frac{(\text{P1})^2}{(\text{Pr})} \qquad (1)$$

or

$$\text{Lp} = 20 \log \frac{(\text{Pl})}{(\text{Pr})} \qquad (2)$$

where Lp = sound pressure level, dB
Pl = sound pressure rms, usually in N/m^2
Pr = reference sound pressure, in N/m^2
log = logarithm to base 10

Corresponding dB levels are given in Figure 4.

Based on the above equation, it can be noted that for each increase of 20 dB, there is a corresponding tenfold increase in sound pressure. The decibel is a logarithmic unit based on a reference level. Under this relationship sound pressure levels expressed as decibels are not additive. That is, a resultant Lp level of adding two Lps from sources producing the same Lp will not be a doubling of the one in decibels; rather, it will be the dB level of one source plus 3 dB. For example, a source producing an Lp of 80 dB when added to another source producing the same Lp at the same distance will not equal 160 dB, but will result in only a 3 dB increase or 83 dB. Further, if there is a 10 dB difference in sound pressure level of two sources, the resultant dB level will be virtually equal to the higher sound pressure source.

RELATIONSHIP OF SOUND PRESSURE, SOUND POWER AND SOUND INTENSITY

As mentioned earlier, sound power is equal to the amount of acoustical energy produced per unit time. Again, as with sound pressure, sound power is derived using a reference level. Because the range of acoustical power is large, an equation describing the power level is employed:

$$Lw = 10 \log \frac{(W1)}{(Wr)} \tag{3}$$

where Lw = sound power level, dB
$W1$ = power of source, W
Wr = reference power, 10^{-12} W
log = logarithm to base 10

Table I shows some typical noise sources, their acoustical power and corresponding sound power levels.

Under free field conditions, where there are no reflections in sound and sound radiates equally in all directions, the sound propagation wave follows a spherical distribution. The surface area of a sphere, $4\pi r^2$, would be used to define the sphere surrounding a noise source. If sound intensity, defined as the energy per unit area, is multiplied by the surface area, a relationship between sound power and intensity is established:

$$W = IA \tag{4}$$

where W = sound power
I = average intensity at a distance r from noise source
A = spherical area, $4\pi r^2$ under free field conditions, of an imaginary shell surrounding a source at distance, r

From this equation it is clear that the sound intensity will decrease with the square of the distance. The factor A is reduced as obstructions are introduced. Typically, only half of free field is approached; thus, A is reduced to $2\pi r^2$ for hemispherical radiation. (For ¼ spherical radiation $A = \pi r^2$; for ⅛ spherical radiation $A = \pi r^2/2$.) The sound intensity, like sound pressure and sound power, also covers a large range of values. Sound intensity is expressed as a dB level described by the following relationship:

$$L_I = 10 \log I/I_r \tag{5}$$

where L_I = sound intensity level
I = intensity at a given distance
I_r = reference intensity, 10^{-12} W/m^2

Table I. Acoustical Power and Sound Power Levels of Typical Noise Sources [3][a]

Power (W)	Power Level (dB re 10^{-12} W)	Source
1000,000	170	Ramjet Turbojet engine with afterburner
10,000	160	Turbojet engine, 7000 lb thrust
1,000	150	Four-propeller airliner
100	140	75-piece orchestra { Peak rms levels in 1/8-second intervals
10	130	Pipe organ
3	125	Small aircraft engine
1.0	120	Large chipping hammer Piano { Peak rms levels in BB♭ tuba 1/8-second intervals
0.1	110	Blaring radio Centrifugal ventilating fan (13,000 cfm)
0.01	100	Four-foot loom Auto on highway
0.001	90	Vanaxial ventilating fan (1500 cfm) Voice–shouting (average long-time rms)
0.0001	80	
0.00001	70	Voice–conversational level (average long-time rms)
0.000001	60	
0.0000001	50	
0.000,000,01	40	
0.000,000,001	30	Voice–very soft whisper

[a] Space average sound pressure level at 10 meters = power level-28 dB.

From spherical free field conditions, relationships between sound intensity and sound pressure can be established. The sound intensity can be described in terms of the sound pressure, the medium (air) carrying the sound and speed of sound in the medium:

$$I = P^2/\rho V \qquad (6)$$

where P = rms sound pressure, Pa
ρ = density of air at standard conditions 1.2 kg/m^3
I = intensity
V = speed of sound in air, 344 meter/sec

For a given set of conditions, sound power and sound intensity can be defined in terms of sound pressure, and vice versa.

$$\text{Sound intensity} = I = P^2/\rho V \tag{6}$$

in terms of pressure.

$$\text{Sound pressure} = P = (I\rho V)^{1/2} \tag{7}$$

in terms of intensity.

$$\text{Sound power} = W = IA \tag{4}$$

Therefore,

$$\text{Sound power} = W = \frac{P^2 A}{\rho V} \tag{8}$$

in terms of sound pressure.

$$\text{Sound pressure} = P = \left(\frac{W\rho V}{A}\right)^{1/2} \tag{9}$$

in terms of sound power.

For free field conditions under hemispherical radiation conditions, sound pressure would be defined as

$$P = \left(\frac{W\rho V}{2\pi r^2}\right)^{1/2} \tag{10}$$

Two additional relationships exist between sound pressure level and sound power level:

$$Lw = Lp + 10 \log A \tag{11}$$

for distance r between noise source and sound pressure level measurement point, in meters, and

$$Lw = Lp + 10 \log A - 10.5 \tag{12}$$

for r in feet.

A is defined as the surface area of an imaginary shell at distance, r, where Lp would be the measured sound pressure level for any point on the shell.

In the above review, it should be noted that although L_I, Lp and Lw are expressed as dB, they are by no means equivalent. The dB is dimensionless; therefore, it is imperative that dB values be qualified as to origin: intensity, pressure or power.

Example Calculation

A manufacturer of a four-propeller airplane states that the peak acoustical power output is 1000 watts. What would be the sound power level and sound pressure level at 10, 20 and 100 feet?

Sound Power Level:

$$Lw = 10\ W1/Wr = 10 \log (1000/10^{-12}) = 150 \text{ dB}$$

Sound Pressure Level: assuming hemispherical radiation,

$$A = 2\pi r^2$$

$$P = \left(\frac{W\rho V}{A}\right)^{1/2}$$

where $W = 1000$ W
$\rho = 1.2$ kg/m^3
$V = 344$ meter/sec
$r = 10, 20, 100$ ft
ft^2 X $(0.0929) =$ m^2

$$P = \left(\frac{(1000)(1.2)(344)}{2\pi(10)^2(0.0929)}\right)^{1/2}$$

where $P = 84.1$ N/m^2
$Lp = 20 \log (P1/Pr) = 20 \log (84.1/0.00002) = 132.5$ dB

(Check using Equation 12.)

$$Lw = Lp + 10 \log A - 10.5$$

or

$$Lp = Lw - 10 \log A + 10.5$$

where $A = 2\pi r^2$

$$= 150 - 10 \log (2\pi(10)^2) + 10.5$$

$$= 132.5 \text{ dB}$$

For 20 and 100 ft, Lp would be equal to 126.5 and 112.5, respectively. The above example shows that as the sound pressure is halved, due to the increase in distance from 10 to 20 ft, there is a corresponding reduction in the sound pressure level of 6 dB. This relationship holds true for any doubling or halving of the sound pressure. In addition, the example problem also illustrates the inverse square rule, i.e., the sound pressure level will diminish by 6 dB each time the distance is doubled.

FREQUENCY OF SOUND

Frequency can be defined as the number of compressions and rarefactions per unit time (sec) qualified to a given medium, usually air. Units of frequency are hertz, which designate the number of cycles per second. Frequency is independent of the speed of sound in a given medium. All frequencies travel at the same speed. In air, at standard conditions, all frequencies travel at approximately 344 meter/sec. The relationship between the speed of sound and the frequency is defined by

$$V = \lambda f$$

where V = speed of sound, meter/sec
λ = wavelength, meter
f = frequency, Hz

Lambda, or wavelength, is defined as the distance a sound wave travels during one pressure cycle (1 compression and 1 rarefaction). In lay terms, frequency may be equated to pitch. Figure 5 shows some examples of various frequency ranges. Figure 6 shows relationship of frequency and wavelength.

DURATION OF SOUND

Sounds may be classified further as to their duration. Continuous sounds are those produced for relatively long periods. Intermittent sounds are produced for short periods, and impulse sounds are produced for extremely short periods. Table II provides some examples of noise exposure classifications. Impulse noise, such as a gunshot, is defined as lasting less then 500 msec and as having a change in sound pressure level of at least 40 dB during the impulse period. A single impulse may be identified as a discrete

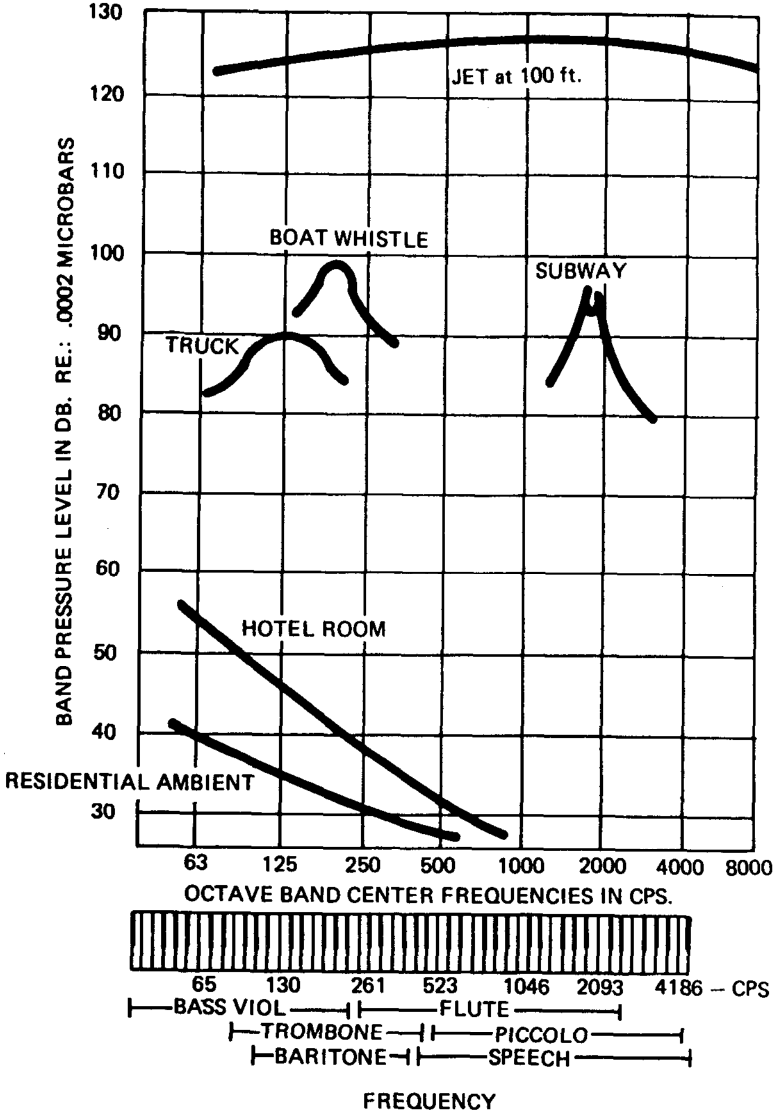


Figure 5. Noise spectra [3].

event or superimposed on a background of steady-state, fluctuating or intermittent noise. Impulse noises can be distinguished as to type and character; however, they may be measured properly only by oscillographic techniques.

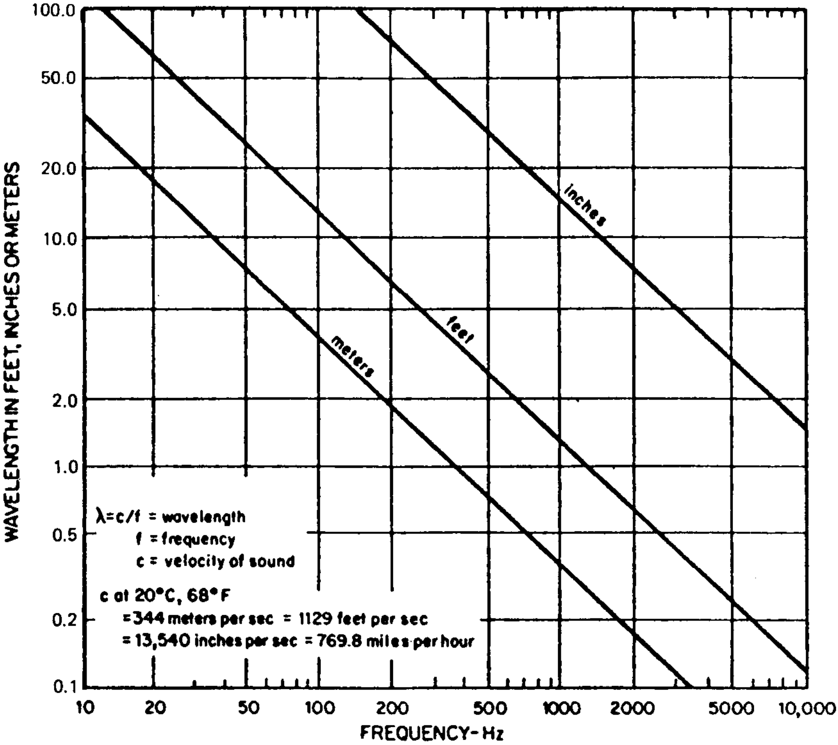


Figure 6. Frequency-wavelength chart for sound in air at normal temperature and pressure [12].

Table II. Classifications of Ongoing Noise Exposure [3]

Type of Exposure	Typical Examples
Steady State	Weaving room noise; sound of a waterfall; shipboard noise; interior of a vehicle or aircraft noise; turbine noise; hum of electrical substation.
Fluctuating Noise	Many kinds of processing or manufacturing noise; traffic noise; airport noise; many kinds of recreational noise (e.g., vehicle racing; radio and television).
Intermittent Noise	Many kinds of industrial noise (especially in construction work, shipbuilding, forestry, aircraft maintenance, etc.); many kinds of recreational noise (e.g., at rock concerts, when using a chain saw); light traffic noise; occasional aircraft flyover noise; many kinds of domestic noise (e.g., use of electrical applicances in the home); school noise.

Characteristics of Impulse Noise

The following are the characteristics of impulse noise [3]:

1. Peak sound pressure level (in dB re 0.00002 N/m^2) (for reasons connected with measurement practice in the English-speaking countries, the overpressures associated with sonic booms in aerospace operations are customarily expressed in lb/ft^2 relative to atmospheric pressure);
2. Duration, msec or μsec;
3. Rise and decay time;
4. Type of waveform (time-course);
5. Spectrum (in case of oscillatory events); and
6. Number of impulses.

NOMENCLATURE

A = area
cps = cycles per second
d/cm^2 = dynes per square centimeter
dB = decibels
f = frequency
I = sound intensity
I_r = sound intensity reference
λ = wavelength
L_I = sound intensity level
L_P = sound pressure level
L_W = sound power level
μbar = microbar
N/m^2 = newtons per square meter
P,p = sound pressure
P_r = sound pressure reference
ρ = density
r = radius, distance between sound source and measurement point
rms = root mean square
SPL = sound pressure level
V,v = speed of sound
W = sound power
W_r = sound power reference

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2.

INDUSTRIAL NOISE CONTROL—AN OVERVIEW

Although the general principles applied in noise control engineering are fairly well established, it is not always possible to predict the results of noise reduction techniques. However, the methods of attacking a given noise control problem provide a procedure through which problem definition and eventual solution can be determined.

Each noise control problem can be broken down into three component parts:

1. the source emitting the sound energy,
2. the path along which the sound energy travels, and
3. the receiver.

From this initial division of the problem it is important to remember that the objective of noise control is not to reduce noise for its own sake, but for the sake of the receiver, usually the human ear. Within this context, controls must be sought that are effective, yet economical. With respect to the three components of a noise problem, the solution will involve:

1. a reduction of the sound energy being released from the source,
2. a diversion or reduction of the sound energy along its path, and
3. protection of the receiver.

LOW-COST SOLUTIONS FOR NOISE CONTROL

Before costly equipment or process design changes are undertaken, the following methods/procedures should be investigated. It should be noted that these controls are usually requisite to proper noise problem analysis.

- Maintenance, regular and preventive
- Operational procedure changes
- Process optimization

- Equipment relocation
- Administrative controls
- Applying room or simple machine treatments
- Equipment replacement

Perhaps the greatest single contribution of unnecessary noise is the lack of proper maintenance and corresponding preventive maintenance intervals. Equipment that is poorly maintained eventually becomes inefficient. One manifestation of inefficiency is noise (misdirected energy), which, ultimately, becomes the subject of replacement. Typical energy wasters and noise producers are:

- Steam leaks
- Slipping belts
- Worn bearings
- Worn gears
- Improperly aligned belts
- Unbalanced or nontrue rotating parts
- Reciprocating striking parts
- Insufficiently lubricated parts
- Misplaced or improperly installed machine guards
- Contact between moving and stationary parts
- Compressed air leaks
- Vibrating sheet metal, such as streamlining
- Improperly adjusted linkages or cams

There are dozens more. Just about every item on a maintenance schedule can be related to a noise producer. Usually, if noise is present, adjustments and/or part replacement are necessary. The latter can be avoided by a preventive maintenance (PM) schedule/program. A PM program will avoid reactionary adjustments and help a maintenance crew become accustomed to anticipating problems. Ultimately, PM will save costly capital expenditures and excessive equipment downtime, as well as give direction in establishing an inventory of parts that are necessary, rather than "nice to have on hand."

The manner in which equipment is operated or an operation is physically performed directly affects employee exposure to noise (operator and nearby co-workers). Where operations are monitored by employees, distance will reduce noise exposure; thus, the work station location is crucial to exposure. If monitoring is intermittent, then "quiet areas," where the employee may find refuge, will reduce exposure time. If monitoring is constant but contact with equipment is intermittent, then a booth located at or near the equipment will provide refuge.

The operational speed of the equipment may be disproportional to the noise output. Employee performance at high speed and high noise, for example, may be equal to slightly lower speed and less noise. A point of marginal return will exist. For a series of parallel or simply adjacent equipment lines, high noise levels may be a result of simultaneous operation. Often, staggering operation schedules reduces the compounded noise level.

Process optimization is akin to proper maintenance; however, it goes beyond simple or routine adjustments or replacement. Optimization of process involves the concepts of money, materials, equipment, personnel and energy resources. These five factors used efficiently in the framework of time will achieve optimization. Efficiency of equipment and human factors is measurable as high performance or output. Thus, factors such as noise that affect performance will have a direct effect on optimization potential. Optimization can be pursued only if proper maintenance procedures are instituted first. Optimization procedures may include changing manufacturing procedures to achieve higher yields. Optimization may involve altering equipment or may require substitution of material. In other words, optimization is directed at "curing" the source rather than "curing" the noise emitted by it. To the extent that higher efficiencies will result in a lowering of total monetary outlay, noise control through this option may be low cost. It is worth mentioning that alteration or replacement of equipment will require a new set of specifications to achieve reduced noise. New equipment does not automatically guarantee low noise level.

Equipment relocation may be a viable alternative for noise reduction if clear area is available. However, relatively quiet manufacturing operations may be substituted for open area. The primary objective of relocation is to distribute noisy equipment so that distance can reduce noise levels. If the noisy equipment requires little supervision, isolating such equipment may prove preferable to raising the general noise level.

Administrative controls run the gamut from rescheduling production to employee rotation. Employee rotation is perhaps the most common form of administrative control. Production scheduling involves running production so that actual noise exposure is constantly below accepted limits, rather than noise levels being high one day and low the next. Employee rotation can be effective, but differing labor skills and wages, union contracts, and perhaps employee resistance may be factors that would need to be resolved.

The presence of reflective surfaces, as well as surfaces that amplify noise at the source, increases sound levels. In a room, walls, windows, floors, ceilings, equipment and work surfaces act as reflectors of sound. The reflective sound combines with the source-emitted sound, which results in sound levels higher than the source. By controlling the reflective sound, sound levels can be reduced to those levels approaching the source. Simple treatments include covering the surfaces with sound-absorbent materials and installation of baffles (hung from ceiling or placed in the reflective path). Large surfaces on noisy or vibrating equipment act as noise amplifiers. By covering the surfaces of equipment (usually interior surfaces), the amplification potential will be eliminated or drastically reduced.

In some cases, the most expeditious method to a quieter working area is equipment replacement. Electric motors, compressors, pumps and fans fall into this category; however, these items usually can be justified in the cause of energy efficiency. A premium may be associated with quieter, energy-efficient expenditures, but some estimates of quiet-associated performance increases should be factored into capital approval justifications. It should be realized that new equipment per se will not guarantee less noise; rather, specifications will determine the extent of noise reduction (Table I).

Equipment Specifications [1,2]

Notwithstanding maintenance, possibly the greatest single step toward a quieter work environment is the purchase of quiet equipment. The key to a successful noise control program and consistent purchase practices is the adoption of noise control specifications. Specifications are not ironclad; they must be related to engineering judgment. Thus, "specs" must create the atmosphere for the exchange of ideas, as well as quantitative data. A meaningful spec in the context of noise control will not be abstract, that is,

Table I. Trouble-Shooting Causes of Noise [1]

Noise Caused By	Can Be Reduced By
Aerodynamics–fan intake and discharge, vents, steam jets, etc.	Reducing velocity; using absorbent material and silencer.
Flow in pipes–gas or vapor lines, compressor inlet or discharge pipes, etc.	Reducing velocity and increasing pipe size; avoiding sudden changes of pipe size and direction of flow; avoiding abrupt obstructions.
Metallic contacts–grinders, mills, conveyors, etc.	Substituting other materials, such as wood, rubber or plastic, for metal.
Stamping or blanking–punches, etc.	Changing into shearing action.
Vibration of machine casing–compressors, blowers, engines, etc.	Using sturdier design or damping material.
Blade passing interference–turbines, fans, blowers, etc.	Increasing gap between interfering parts.
Sonic flow in control valve–steam reducing stations, safety relief valves, etc.	Reducing pressure drop or dissipating flow energy.
Sliding or backlashing–conveyors, gears, etc.	Controlling manufacturing tolerance and using proper lubrication.
Amplification due to reflection–pump house, compressor station, etc.	Applying acoustical absorbent to reflecting surface.
Electrical or magnetic force–motors, transformers, etc.	Avoiding resonance between machine parts and frequency of alternating current.

it must be subject to the area where the equipment is to be installed. Clearly, this means the area is part of a master noise level plan where specifications or noise level limits have been set. In this manner, equipment design is more closely related to both its intended environment and situations in which the noise levels before and after equipment installation are predictable.

If current practices leave specifying up to the vendor, as in the case of "vendor shall supply equipment in accordance with the latest OSHA rules," then no specification exists. Current Occupational Safety and Health Act (OSHA) rules on noise control do not establish an absolute noise level. Instead, noise level exposure is a function of noise level and time. A vendor can supply equipment that produces noise levels on the order of 110 dBA and be in compliance with current OSHA rules. OSHA permits a daily exposure of a half hour to noise levels of 110 dBA. Furthermore, sound pressure levels can exceed 130 dB for certain frequency-time intervals. Lastly, the practice of vendor self-specifying ignores the equipment's would-be environment; compounding of sound pressures is discounted.

The location of the equipment and the intended location of employees is critical to economical noise reduction. OSHA's rules apply to noise entering the ear, usually 3–4 feet from the machine. If distance for noise measurement is not specified, the specification sound level will be meaningless because noise levels 1 inch from the machine will not equal those levels at 20 feet. Clearly, testing criteria must accompany the equipment specification. The specification should contain, at a minimum, the following:

- References for specification/test methods
- Noise level specification
- Equipment noise level report/tests
- Deviations from specification
- Guarantee

References for the specification would include, at a minimum, proper terminology, methods for measurement of sound and equipment standards. Standards, methods and terminology may be obtained from the American National Standards Institute (ANSI). Trade organizations also may have developed specific standards. The common standards worth noting are:

ANSI S1.1-1960	Acoustical Terminology
ANSI S1.2-1971	Method for the Physical Measurement of Sound
ANSI S1.4-1971 (R1976)	Specifications for General Purpose
ANSI S1.11-1966	Specifications for Octave Band Analyzers
ANSI S1.13-1971	Methods for the Measurement of Sound Pressure Levels

Additional standards specific to the equipment and its application should be added as necessary.

Noise level specifications should be written for equipment piece and equipment location. Conceivably, two identical pieces of equipment may require differing noise specifications due to their intended location. This specificity can be accomplished through attachments to the specification in the form of data sheets. The data sheet would show equipment location as intended where existing equipment and noise contours are superimposed. Employee locations also can be shown. The noise levels can be designated as A-weighted sound levels or by octave band. Acceptable noise level ranges should be indicated in either case. The levels specified should be qualified to actual in-place conditions.

Verification of testing and format of reporting can be accomplished through a Noise Level Report. The tests and the report should be keyed to the data sheet attachment of the specification. By providing a report format or blank there is little left to judgment regarding the report's content. The report should include the following:

- Equipment type
- Manufacturer
- Purchase order number
- Specification and data sheet number
- Equipment specification/description:
    - Model number
    - Serial number
    - Size/capacity
    - Horsepower/speed rating
- Test conditions:
    - Machine load/speed
    - Test room
        - Dimensions: length, width, height
        - Material: floor, wall, ceiling, % glass
- Background noise levels by noise level: or
    - Octave band (center band frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000 Hz in dB re: 0.00002 N/m^2)
- Monitoring equipment used:
    - Model number and manufacturer
- Location of monitoring equipment in relation to room and equipment (usually measurements in each quadrant approximately 3–5 feet from edge of equipment)
- Test results:
    - Tabular format showing location, A-weighted sound level and octave band levels of center frequencies of 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000 Hz
- Noise contours showing A-weighted sound level or by octave band center frequency levels.

It should be made clear to the supplier that noise data obtained in accordance with the specification are critical to the award. Additionally, the tests and report should be performed at the vendor's cost. If exceptions to the report, test methods, etc., exist on the vendor's part, the vendor should be permitted to so state. The test data may be obtained from: (1) actual measurement in vendor's test room as per specs; (2) duplicate equipment and conditions under in-place conditions; and (3) similar equipment and conditions with unconditional guarantee. The specific type of data will vary, of course, with company policy; however, it should be so specified. In any case, data should be certified.

As mentioned earlier, exceptions to, and deviations and variations from, the specification should be permitted. However, the extent permitted by company policy should be outlined in the specification. The prime objective should remain equivalency of data. Precision and accuracy are paramount. The supplier must detail in the report all circumstances that differ from the specification. Contact between company personnel and the supplier before tests are performed should be encouraged.

Lastly, a guarantee must be provided to ensure that the equipment, as installed, will meet the standards set by the company. In the event remedial action must be taken by the company or the vendor, the guarantee is provided to ensure that such expenses will be absorbed by the supplier.

MASTER PLANS

With the passage of the Quiet Communities Act, the U.S. Environmental Protection Agency (EPA) now can provide direct aid to state and local agencies. Many communities are taking advantage of such federal aid to research and ultimately write noise ordinances with specific levels for property line boundaries [3]. Master plans can help.

A noise master plan is simply a policy and plan in which current noise levels and future goals are detailed. The goals may incorporate future regulatory changes in the framework of current rules. The goals would be company-specific, of course, and the path to reach the goals will be clear only after all existing data have been collected. Data collection is the most time-consuming aspect of planning.

Data collection can be accomplished easily with a team of two technicians—one to read the meter and one to record the information. Data collection should be related to a disciplined process of establishing a grid (by floor, work area, etc.) and taking measurements corresponding to the grid line intersects. Grid line spacing–for example, 20, 15, 10, 5 feet–is determined by the level of detail desired. An alternate approach is to take measurements at "random" locations around specific equipment. In either method, the simplest procedure is to record the raw data directly on a plot plan or plan view of the area being surveyed. These data then can be analyzed preliminarily by connecting similar or 1, 2 or 3 dB intervals to create contours. By establishing contours, data gaps can be identified or data can be verified in the field. Because data, in the form of contours, show noisy areas (not just points) on scaled drawings, engineering solutions can be readily visualized. Directional noise can be identified quickly. Contours may be color coded or overlays can be developed to show changes in noise data as changes are introduced. Simply stated, contouring is a data management tool; it is a natural progression toward computer modeling [4].

Regardless of the data management method used, quality of data is paramount. Information similar to that required for equipment testing (discussed previously) should be gathered. Subsequently, these data can be meaningfully compared to original data. Information should include:

- Machine/Process Data:
    - Type and description of the machine/process
    - Condition of machine: age, maintenance, guarding in-place, etc.
    - Machine operation: speed, cycling, materials processed, etc.
    - Existing noise/vibration controls
- Building Data:
    - Size and shape of room
    - Layout of equipment, work stations, break areas
    - Surface materials: ceiling, walls, floor
    - Existing acoustical treatments

Once existing data are collected, a plan for achieving goals can be developed. Specific target areas can be subject to engineering review and prioritized.

SOUND CONTROL PRINCIPLES

In general, four basic principles are employed to reduce noise: isolation, absorption, vibration isolation and vibration damping. No one approach using any one or a combination of these principles is inherently superior to another. The most effective solution to a noise problem can be developed at a minimum cost if each principle is understood.

Isolation

Simply, isolation is the physical separation of noisy equipment from other equipment or areas. Separation will reduce the compounded noise that results from locating several pieces of noisy equipment in a given area. Enclosures constructed of highly absorbent material with impervious outer walls is one application of isolation.

The sound isolation properties of materials are stated in terms of transmission loss. Transmission loss (TL) is the energy transmitted through the material relative to the energy incident on the material. It may be expressed as follows:

$$\mathrm{TL} = 10 \log \frac{\text{(incident energy)}}{\text{(transmitted energy)}} \qquad (1)$$

Measurement of TL has been standardized by the American Society for Testing and Materials (ASTM) by its standard ASTM E90-61T. However, very few laboratories are equipped or qualified to perform the tests [5]. Data on TL, unless qualified to a standard, such as those of ASTM is meaningless. Transmission loss has been defined in more quantitative terms as

$$\mathrm{TL} = 20 \log (fw) - 47.5 \text{ dB} \tag{2}$$

where f = frequency, Hz
w = superficial weight of the material, kg/m^2

From this relationship, TL is more accurately a function of frequency, as well as the mass of the material. The angle of incidence is assumed to be within the range of 0° to 78°. Based on Equation 2, for either a doubling of the frequency or mass the TL will increase 6 dB. Conversely, reducing frequency or mass by half will decrease TL by 6 dB.

Because of the difficulty in testing and the fact that TL varies with frequency, it is desirable to use a single-number rating system. Such a rating has been adapted by manufacturers of TL materials and has been standardized by ASTM (E90-70). The rating system is called Sound Transmission Class (STC). Higher STC values indicate more effective barriers. It should be noted that the STC is useful primarily in assessing the degree to which normal speech is prevented from being transmitted through the material. Thus, for a noise spectrum different than that of speech the STC may not provide an adequate measure of TL. The most accurate method in assessing an application for isolating material is to use the actual TL for each octave band. Table II provides TL values for some commonly used materials. Table III provides STCs for some common building materials.

Absorption

To some extent, absorption occurs in all materials. Sound absorption takes place when sound waves enter a material and a portion of the energy is converted to heat. Materials commonly used are fibrous, lightweight and porous. The materials typically classified as absorptive are: acoustic ceiling tile, reticulated foams, fiberglass and hair felt.

The degree to which absorption occurs in a material, that is, the extent to which acoustical energy is absorbed, is denoted by the material's absorption coefficient. The absorption coefficient is found by using ASTM C 423-66 standard. A value of 1.00 is absolute absorption. Tables IV and V show some average absorption coefficients for various materials [5,8].

Table II. Sound Transmission Losses of Some Common Materials [6]

Material	Transmission Loss (dB) 125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
$^5/_8$-in. plywood	14	20	25	27	24	25
16-gauge steel plate	19	21	27	27	32	39
20-gauge sheet steel	17	20	24	27	32	37
24-gauge sheet steel	15	19	22	26	31	34
8-in. concrete block (lightweight)	33	35	42	46	51	52
8-in. concrete block (dense)	36	40	45	48	55	55
$^5/_8$-in. gypsum wallboard	19	22	28	31	26	28

Table III. Sound Transmission Class of Some Common Building Materials [7]

Material	STC
$^5/_{16}$-inch plywood	25
24-gauge steel	26
$^1/_2$-inch gypsum board	26
$^5/_8$-inch gypsum board	28
$^1/_{16}$-inch lead-vinyl	29
$^1/_8$-inch plate glass	28
$^1/_4$-inch plate glass	30
$^3/_{16}$-inch steel plate	35
1-inch thick wood panel	36
4-inch two-inch concrete block (filled with sand)	43
Two layers of $^5/_8$-inch gypsum board on 2 × 4 feet studs 16 inches O.C.	43
8-inch lightweight hollow concrete block	46
8-inch hollow core concrete block	50
4-inch brick wall with $^1/_2$-inch plaster	50
8-inch brick wall	52
6-inch dense concrete	54
12-inch brick wall	59

The performance of materials is often expressed as sabins. The relationship of sabins to absorption coefficient is

$$\text{sabins} = \alpha \times A \tag{3}$$

where α = absorption coefficient
A = surface area of absorbing material, ft^2

Table IV. Sound Absorption Coefficients of Common Acoustic Materials [5]

Materials[a]	Frequency, Hz 125	250	500	1000	2000	4000
Fibrous Glass (typically 4 lb/ft^3) hard backing						
1-inch thick	0.07	0.23	0.48	0.83	0.88	0.80
2-inch thick	0.20	0.55	0.89	0.97	0.83	0.79
4-inch thick	0.39	0.91	0.99	0.97	0.94	0.89
Polyurethane Foam (open cell)						
¼-inch thick	0.05	0.07	0.10	0.20	0.45	0.81
½-inch thick	0.05	0.12	0.25	0.57	0.89	0.98
1-inch thick	0.14	0.30	0.63	0.91	0.98	0.91
2-inch thick	0.35	0.51	0.82	0.98	0.97	0.95
Hair Felt						
½-inch thick	0.05	0.07	0.29	0.63	0.83	0.87
1-inch thick	0.06	0.31	0.80	0.88	0.87	0.87

[a] For specific grades see manufacturer's data; note that, when used, NCR is a single-term rating that is the arithmetic average of the absorption coefficients at 250, 500, 1000 and 2000 Hz.

Table V. Absorption Coefficients (α) of Common Materials [8]

Material	Octave Band Center Frequencies (Hz) 125	250	500	1000	2000	4000
Brick (unglazed)	0.03	0.03	0.03	0.04	0.05	0.07
Brick (unglazed, painted)	0.01	0.01	0.02	0.02	0.02	0.03
Concrete Block	0.36	0.44	0.31	0.29	0.39	0.25
Concrete Block (painted)	0.10	0.05	0.06	0.07	0.09	0.08
Concrete	0.01	0.01	0.015	0.02	0.02	0.02
Glass (ordinary window)	0.35	0.25	0.18	0.12	0.07	0.04
Plaster	0.013	0.015	0.02	0.03	0.04	0.05
Plywood	0.28	0.22	0.17	0.09	0.10	0.11
2-inch-thick Fiberglass (4 lb/ft^3) on Hard Backing	0.20	0.55	0.89	0.97	0.83	0.79

From Equation 3, 1 ft^2 of material with an absorption coefficient of 0.60 will have a performance rating of 0.60 ft^2 sabins. Therefore, 60% of the sound energy in a wave is absorbed and 40% is reflected.

By summing the individual area-absorption coefficient products for all surfaces of a room, a measure of the acoustical environment for the room can be developed, described by the term room constant (R).

$$R = \alpha_n A_n + \alpha_2 A_2 + \ldots \alpha_n A_n \qquad (4)$$

where α_n = absorption coefficient
A_n = surface area of absorbing surface
R = room constant, ft^2 sabins

The greater the room constant, the greater its ability to absorb sound at a given frequency. Note that R increases with room size.

EXAMPLE

A room 50 ft long by 10 ft high by 20 ft wide is constructed with the following materials: Floor and ceiling = concrete; and walls = painted concrete block. A noise source will be emitting a frequency of 1000 Hz. What will be the room constant under existing conditions and after a 2-in.-thick layer of polyurethane foam has been added to the ceiling. See Tables IV and V for α values. For 1000 Hz:

	A	α Before	Aα Before	α After	Aα After
Floor	1000 ft^2	0.02	20	0.02	20
Ceiling	1000 ft^2	0.02	20	0.98	980
Walls	1400 ft^2	0.07	98	0.07	98
			138 ft^2 sabins		1098 ft^2 sabins

$R = \Sigma\alpha A = 138$ ft^2 – sabins *before treatment*
$R = \Sigma\alpha A = 1098$ ft^2 – sabins *after treatment*

For a given noise source singular frequency emissions are rare. Usually all octave bands are involved. For such an application the room constant would have to be calculated for each frequency.

In the real world it would be useful to relate the room constant to sound pressure level changes. By knowing projected changes in dB, various material applications can be evaluated, at the very least on a relative basis. Figure 1 provides a family of curves relating room constants, relative sound pressure level and distance from a noise source. In the example above, room constants of 138 ft^2 sabins and 1098 ft^2 sabins were found before and after room treatment, respectively. Suppose an operator worked around a machine in such a room so that his average distance from the machine was 4 ft. From measurement, a sound pressure level of 90 dB was found for 1000 Hz. The effect of the room constant change can be found by finding the relative change in dB for a corresponding distance–room constant intersect (see Figure 1). For a room constant of 138 ft^2 sabins and an operator location of 4 ft from the noise source, a relative dB level of −4 dB is found. For a

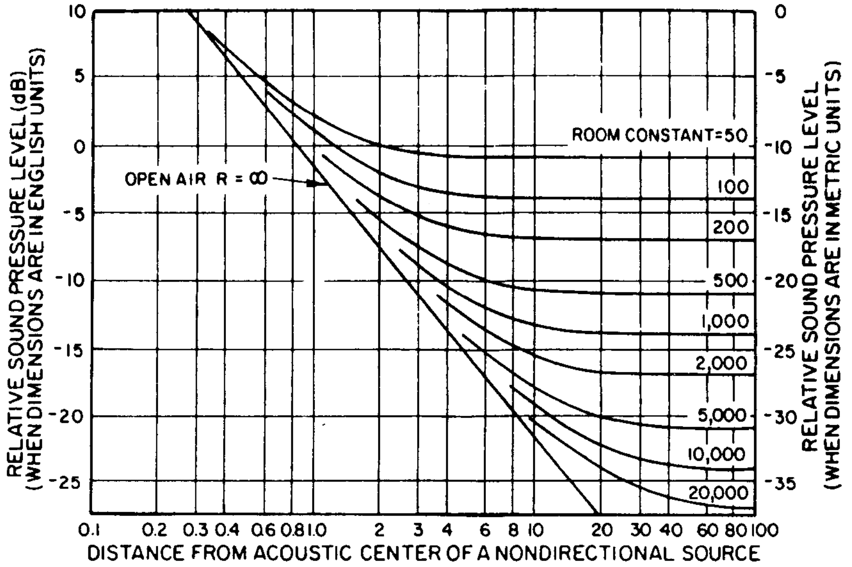

Figure 1. Sound level distribution in spaces with various room constants [5].

room constant of 1098 ft^2 sabins and the same operator location, relative level change of −11 dB is found. Therefore, a reduction of 7 dB for a frequency of 1000 Hz is projected. In reality, each frequency would be subject to the analysis above, then an A-weighted sound pressure level would be calculated for each band.

Another method for estimating the reduction in sound levels due to treatment is by the following equation:

$$\text{Sound level reduction} = 10 \log \frac{(\text{R before})}{(\text{R after})} \tag{5}$$

Note from Figure 1 that for distances below 2 ft from the acoustical source no reduction in noise level is foreseen. The above review shows the value of sound-absorbing material and distance in reducing noise level exposures.

Vibration Isolation

Because airborne noise can be caused by any vibrating surface, vibration control is concerned with noise control at the source. Simply, vibration isolation is aimed at dissociating the vibrating member from its energy source. The entire subject of control may involve machine redesign or improved maintenance to eliminate imbalance or contact between moving and stationary parts, for instance.

Isolation generally involves the separation of vibrating members from energy source by compressible-elastic materials. Common materials for vibration isolation are cork, neoprene, felt, glass fiber, other elastomers, steel springs, etc. The selection of materials involves specifying the weight of the item to be supported, the deflection required and the lowest vibration frequency for the item. The primary function of the isolator is to limit the transmissibility of the vibratory energy. The ratio of the lowest vibration frequency (f) to the natural resonant frequency of the isolator (f_n) under load provides a measure of the isolator's effectiveness.

f/f_n	Explanation
1	Isolator acts as an amplifier.
2	Isolator begins to act as an amplifier.
>2	Isolator acts as an isolator.

As a general rule, a machine on a rigid heavy foundation is well isolated when the resonant frequency is ⅕ the lowest vibratory frequency—$f/f_n = 5$ [5].

The natural frequency may be found under a static deflection analysis of the isolator, since the system's natural frequency and the static deflection depend on the stiffness of the isolator:

$$f_n = 1/2\pi \sqrt{\frac{Kg}{W}} \tag{6}$$

where f_n = natural frequency
K = support stiffness, lb/in.
W = weight of the body,
g = gravitational constant, 386 in./sec^2

Also,

$$d = W/K \tag{7}$$

where d = static deflection, in. By combining Equations 6 and 7,

$$f_n = 1/2\pi \sqrt{g/d} \tag{8}$$

and substituting,

$$f_n = 1/2\pi\sqrt{\frac{386}{d}} = 3.13\sqrt{1/d}\ \text{Hz} \qquad (9)$$

This relationship holds true for deflections that are strictly proportional to the load, i.e., linear systems [5,9]. Figure 2 provides some typical isolators and their natural frequencies and static deflection.

Vibration Damping

Damping materials are absorbents for solid-borne sound. The material absorbs the vibration and converts the energy into heat, thereby reducing

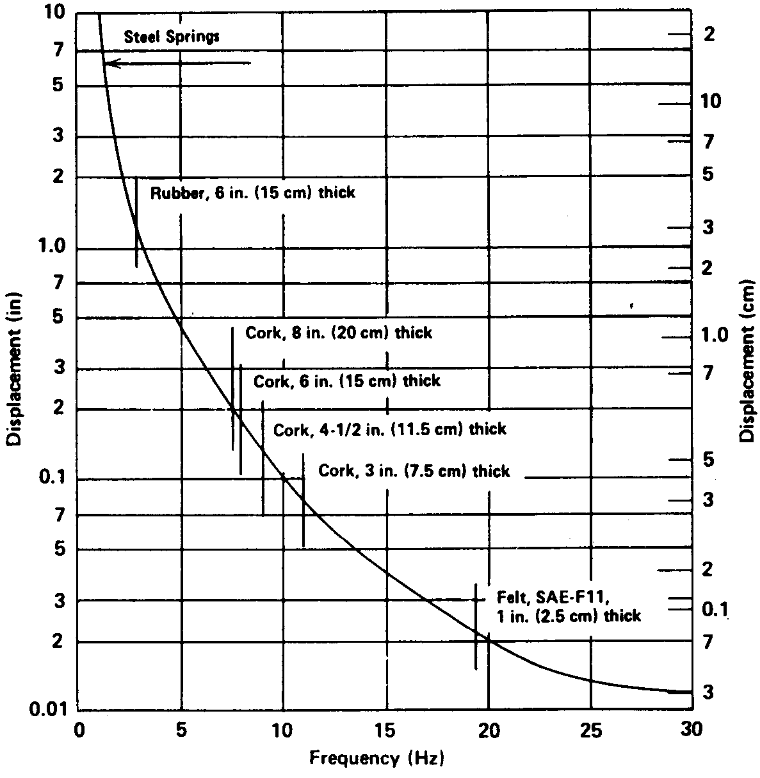

Figure 2. Relationship between static deflection and natural frequency. Typical natural frequencies of some practical isolators are shown [7].

the resonance effect. Typically, vibrating surfaces, such as panels, are subject to damping as a control method. Other applications include reduction of impact noise, such as from pellets thrown against sheet metal chutes, or hoppers. Through the application of viscoelastic damping compounds, reductions of 10–15 dBA can be achieved. A rule of thumb indicates that damping material thickness should be at least as thick as aluminum and twice the thickness of steel [10]. Damping is often accomplished through structural stiffening. Materials that can be glued, painted, taped or sprayed are often used.

MATERIAL SELECTION

Material selection may not be as simple as calculating the optimum noise reduction circumstance. Selection may be influenced by environmental and regulatory factors, as well as by noise reduction:

Environmental

- Exposure
- Moisture
- Solvents
- Vibration
- Dirt
- Oil and grease
- Temperature
- Corrosive materials
- Erosive conditions

Regulatory

- Restrictions on lead-bearing materials in food and drug areas
- Restrictions on materials contacting food and drug products
- Requirements for disinfection/cleaning
- Firebreak requirements, ducts, shafts, etc.
- Restrictions on shedding fibers
- Elimination of inspectable areas, where vermin may hide
- Requirements for anchoring equipment
- Guarding equipment

A review of some common materials and the above factors is provided in Tables VI and VII.

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Table VI. Comparison of Material Properties for Various Types of Acoustical Treatments [7]

	Foams	Fiberglass	Rigid Tiles
Flammability	Can be made self-extinguishing but not generally suitable for architectural purposes.	Good fire resistance.	Good fire resistance.
Acoustical Properties	Excellent absorption in mid-to-high frequencies.	Excellent absorption in mid-to-high frequencies.	Fair absorption in mid-to-high frequencies.
Environmental Considerations	Nontoxic, vibration resistant, deteriorates at high temperatures.	Fiber contamination can be hazardous. Poor vibration resistance. Good high temperature properties.	Nonhazardous. Good high temperature properties. Good vibration properties.
Susceptibility to Acoustical Degradation	Little susceptibility if faced and edge sealed.	Little susceptibility if faced and edge sealed.	Poor in adverse environment.
Major Applications	Machinery enclosures, floor pads, wall treatments.	Machinery enclosures. High-temperature environments.	Architectural.

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Table VII. Review of Typical Noise and Vibration Control Materials [9]

Noise Absorptive Materials	Noise Barrier Materials	Vibration Damping	Vibration Isolation
Curtain Walls	Asphalted felt and fiberboard	Adhesives	Elastomers
Felt and Cloth–Woven and Nonwoven	Foam composites with plastics	Elastomers	Foams
Fiberboard	Glazing	Master sheet and tile	Pads
Formboard	Gypsum board	Semiliquid compounds	Fibers
Glass Foam and Fiber	Lead sheet	Mastic base	Blankets
Metal Felt	Loaded plastic sheet	Plastic base	Boards
Mineral Wool	Loaded rubber sheet	Tapes	Flexible pipe connectors
Partitions with Absorptive Facing	Mastic-cellulose composites		Flexible shaft couplings
Perforated Ceramic Tile	Particle board		Floating floor systems
Perforated Sheet Metal	Sealants and seal tapes		Machinery mounts
Porous Metals	Sheet metal composites		Shock mounts
Slotted Masonry Units	Mineral wood		Vibration dampers
Spray-On Coatings	Plastic foam		Vibration isolators
Wood Fiber			

3.

NOISE CONTROL REGULATIONS

Recently, a poll conducted by the U.S. Bureau of the Census showed that noise is considered one of the most undesirable neighborhood conditions. The poll also showed that the number of people affected by noise is increasing. Similar conclusions have been drawn by the Occupational Safety and Health Administration (OSHA), the National Institute of Occupational Safety and Health (NIOSH) for working environments, the Federal Aviation Administration (FAA) for airplane-related noise and, most importantly, by the U.S. Congress for the population in general.

In the early 1970s Congress reacted to the apparently deteriorating conditions of the workplace and the general environment. Through the passage of the Occupational Safety and Health Act and the Noise Control Act of 1972, Congress gave the federal government the regulatory tools to control noise. With the amendment of the Noise Control Act by the Quiet Communities Act, control of noise through regulatory authorities now exists at every level of government: federal, state and local. A comprehensive review of all the facets for each level of noise control regulation would be well beyond the scope of this report; therefore, the reader is invited to review other sources [1-3].

THE NOISE CONTROL ACT AS AMENDED BY THE QUIET COMMUNITIES ACT

The Noise Control Act created the federal noise abatement and control effort. The Act gave the U.S. Environmental Protection Agency (EPA) the authority to develop noise control methods and carry out the policy of the Act. Congress found that inadequately controlled noise presents a growing danger to the health and welfare of the nation's population, and that federal action is essential to control major sources of noise in commerce and other areas where national uniformity of treatment is required. Major sources of noise are:

- Transportation vehicles and equipment
- Machinery
- Appliances

Congress found that primary enforcement responsibility rests with state and local government except where federal control is necessary. EPA is to carry out the policy of the Act

> to promote an environment for all Americans free from noise that jeopardizes their health or welfare. To that end, it is the purpose of this Act to establish a means for effective coordination of Federal research and activities in noise control, to authorize the establishment of Federal noise emission standards for products distributed in commerce, and to provide information to the public respecting the noise emission and noise reduction characteristics of such products [4].

Federal programs are directed in Section 4 of the Act to control noise:

1. Federal agencies are directed to administer programs to reduce noise consistent with their authorities.
2. Each federal agency must comply with federal, state, interstate and local noise control, unless exempted by the President.
3. EPA is required to coordinate all federal programs related to noise control and noise research.
4. Other agencies are required to consult EPA before prescribing noise regulations. EPA may require public review of any regulations thought insufficient by EPA to protect the public health and welfare.
5. EPA is required to report periodically on the status and progress of federal noise control activities.

Identification of major noise sources, noise criteria and control technology is outlined in Section 5 of the Act:

1. EPA is required to publish (within 9 months) criteria that reflect the kind and extent of all identifiable effects on the public health or welfare resulting from differing quantities and qualities of noise.
2. EPA is required to publish (within 12 months) information on levels of environmental noise, which, in defined areas under various conditions, are requisite to protect the public health and welfare with an adequate margin of safety.
3. EPA is required to publish (within 18 months) a report identifying major sources of noise and giving information on techniques for control of noise.

In Section 6, EPA is given authority to prescribe and amend standards limiting noise generation characteristics. This authority extends to any product or class of products that has been identified as a major source of noise and that falls in the following categories: construction equipment, transportation equipment (including recreational vehicles), any motor or engine, and electrical or electronic equipment. EPA may issue regulations for products in other categories if it is necessary to protect the public health or welfare. The standards must be

> "based on criteria published under Section 5," and requisite to protect the public health and welfare, taking into account the magnitude and conditions of use of such product (alone or in combination with other noise sources), the degree of noise reduction achievable through application of the best available technology, and the cost of compliance.

The manufacturer of regulated products must warrant that his product is designed and built to conform with such regulation at the time of sale. The cost of this warranty cannot be passed on by the manufacturer. States and political subdivisions are prohibited from setting noise emission levels different from those promulgated by EPA, but remain able to regulate use, operation or movement of products.

Under Section 7, EPA is given authority to review and recommend changes to aircraft noise standards. EPA is required to study the adequacy of present aircraft noise emissions standards (including recommendations on retrofit); implications of achieving levels of cumulative noise exposure around airports; and additional measures available to airport operators and local governments to control noise. The FAA's power to prescribe and amend aircraft noise measurement and noise emission regulations under Section 611 of the FAA Act of 1958 is preserved. However, EPA is required to submit to the FAA recommendations for regulations that EPA feels are necessary to protect the public health and welfare. A detailed process for public dissemination of information regarding FAA's action on EPA's recommendations is specified.

EPA may require labeling of products under Section 8. For any product that (1) emits noise capable of adversely affecting the public health or welfare, or (2) is sold wholly or in part on the basis of its effectiveness in reducing noise, the EPA must require the manufacturer to give notice to the consumer of the noise level or its effectiveness in reducing noise. EPA's regulations must indicate the form of such notice, and the method and unit of measurement must be prescribed.

The Secretary of the Treasury shall, in consultation with EPA, issue regulations to carry out the provisions of this Act with respect to new products imported or offered for importation, as provided under Section 9.

Prohibited acts are outlined in Section 10. Manufacturers are prohibited from distributing products that do not conform to applicable labeling standards or noise emission regulations after the effective date of the regulation. All persons are prohibited from removing a noise reduction device from a product in compliance with a noise emission regulation before sale to the ultimate purchaser. All persons are prohibited from refusing to comply with an order from EPA under Section 11 authority, or refusing to provide required information to EPA, or importing a product violating Section 9. EPA may exempt certain products for specified periods of time.

Enforcement actions (Section 11) may be brought against any person who willfully or knowingly violates certain prohibited acts of Section 10. Manufacturers or importers of nonconforming or mislabeled products are subject to fines of up to $25,000 per day for each violation and imprisonment for up to one year. The penalties may double for subsequent convictions. EPA may issue orders specifying relief deemed necessary to protect the public health and welfare.

Citizen suits may be brought against EPA, FAA, the United States or any person for failure to perform under the Act. Reporting and recordkeeping requirements include access and copying of records; violations carry penalties of $10,000 per day and imprisonment for up to 6 months. EPA is authorized to conduct research and provide technical assistance and public information.

Under Sections 17 and 18, EPA is authorized to promulgate regulations for railroad and motor carriers. After consultation with the Department of Transportation (DOT), EPA is required to promulgate regulations for surface carriers engaged in interstate commerce, including regulations governing noise emission from the operation of equipment and facilities of such carriers. The effective date for such regulations must permit the development and application of the requisite technology. The Secretary of Transportation has the responsibility of assuring compliance with EPA's regulations. State and local governments are prohibited from establishing operational noise emission limits different from applicable federal standards, but EPA may allow a different standard if it determines in consultation with the Secretary of Transportation that local conditions necessitate such different regulations.

The provisions of Section 18 are nearly identical to Section 17 except that they apply to a "common carrier by motor vehicle, a contract carrier by motor vehicle, and a private carrier of property by motor vehicle as those terms are defined in the Interstate Commerce Act (49 U. S. C. 303(a))."

The Noise Control Act was amended by the Quiet Communities Act on November 8, 1978. The amendments are outlined below:

- Section 6: States may petition for stricter product standards.
- Section 11: Civil penalties are prescribed as not to exceed $10,000 per day.
- Section 14: Authorizes EPA to provide direct assistance to communities and states in the form of grants, training programs, seminars, a clearinghouse

on noise information, technical assistance, research and development programs.

Additional provisions deal with airport noise and effects on surrounding communities. Regulations promulgated under the Noise Control Act are listed in Table I with the corresponding federal citation [4].

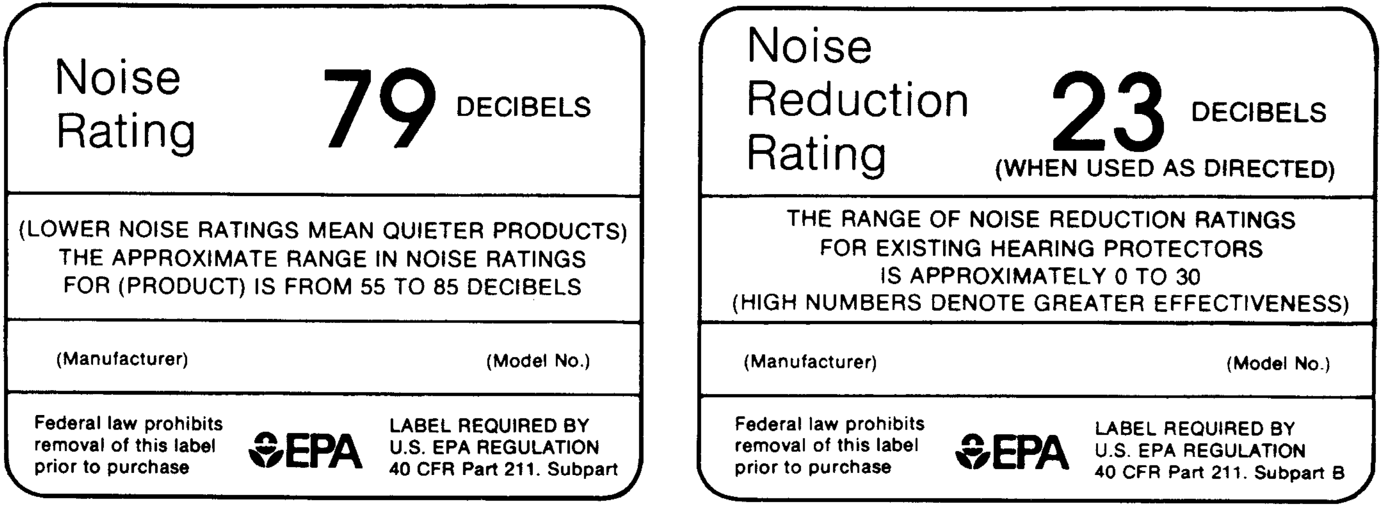
Under Section 8 of the Act, EPA recently promulgated a rule requiring noise reduction ratings (NRR) on all hearing protection devices manufactured on or after September 27, 1980, the effective date of the rule. The NRR will take the form of a decibel value. The number will approximate the A-weighted sound pressure level attenuation provided by the device. For example, for noise levels of 100 dBA, the noise level the individual's ears are exposed to while wearing a device with a NRR of 30 dBA would be 70 dBA. See Figure 1 for example of a typical NRR label.

Also under Section 8, EPA's authority extends to product noise labeling. For products designated by EPA, manufacturers would have to test and label the noise level range found, as well as competitive products. Although no products have been designated yet, EPA is poised to regulate the following [5]:

- Lawn and garden power equipment
- Refrigerators
- Washing machines
- Sewing machines

Table I. Major Noise Control Regulations

Citation		Subject
40 CFR		
Part 201 - Subpart	B	Interstate rail carrier operations
	C	Measurement criteria
202	B	Interstate motor carrier operations
203		Low-noise emission products
204	B	Portable air compressors
205	B	Medium and heavy trucks
	F	Truck-mounted solid waste compactors
209		Rules of practice governing proceedings under the Noise Control Act of 1972
210		Citizen suits
211	B	Hearing protective devices



Noise Rating **79** DECIBELS

(LOWER NOISE RATINGS MEAN QUIETER PRODUCTS)
THE APPROXIMATE RANGE IN NOISE RATINGS
FOR (PRODUCT) IS FROM 55 TO 85 DECIBELS

(Manufacturer) (Model No.)

Federal law prohibits
removal of this label
prior to purchase

EPA

LABEL REQUIRED BY
U.S. EPA REGULATION
40 CFR Part 211. Subpart

Noise Reduction Rating **23** DECIBELS
(WHEN USED AS DIRECTED)

THE RANGE OF NOISE REDUCTION RATINGS
FOR EXISTING HEARING PROTECTORS
IS APPROXIMATELY 0 TO 30
(HIGH NUMBERS DENOTE GREATER EFFECTIVENESS)

(Manufacturer) (Model No.)

Federal law prohibits
removal of this label
prior to purchase

EPA

LABEL REQUIRED BY
U.S. EPA REGULATION
40 CFR Part 211. Subpart B

Courtesy of Environmental Protection Agency

Figure 1. A typical NRR label.

- Vacuum cleaners
- Typewriters
- Hair dryers
- Air conditioning and ventilation equipment
- Acoustic ceiling tiles and panels
- Acoustic wall tiles and panels

Tables II–IV review some areas of research sponsored by various federal agencies through the Noise Control Act. These activities are coordinated by EPA [6].

STATE ENVIRONMENTAL NOISE PROGRAMS

State environmental noise programs have gained momentum in recent years in the area of new product sound level limits. Table V presents a state listing for noise emitters. In use, sound level limits for on-the-road motor vehicles are in effect for the same states listed in Table V, with the addition of Connecticut, Hawaii, Idaho, Illinois, Indiana, New York and Pennsylvania. Property line sound level limits for industrial and commercial operations have been adopted in seven states (Connecticut, Illinois, Maryland, Minnesota, New Jersey, Oregon, Washington), and an additional 10 states are contemplating similar laws. In some cases, local ordinances can be stricter than state law [7].

Table II. Summary of Federal Agencies' Current Involvement in Noise Research [6][a]

	Area of Involvement			
Agency	Noise Effects	Aircraft	Surface Vehicles	Stationary Machinery
NASA	X	X		
DOT	X	X	X	
HEW	X			X
DOD	X	X	X	X
NSF	X		X	X
DOI	X			X
DOC/NBS	X			X
USDA			X	X
CPSC				X
HUD	X			
EPA	X	X	X	X

[a] Full names of these federal agencies are listed in the section entitled Abbreviations, at the end of this chapter.

Table III. Current Agency Involvement in Noise Effects Research Categories [6][a]

Agency	Research Category							
	Noise-Induced Hearing Loss	Nonauditory Health Effects	Individual Behavior Effects	Noise Effects on Sleep	Communication Interference	Community or Collective Response	Domestic Animals and Wildlife	Measurement Methodology and Calibration
HEW/NINDS	X				X			
HEW/NIEHS	X	X						
NEW/NIOSH	X	X	X					X
DOD	X	X	X		X	X		X
NASA				X		X		X
DOT			X			X		
DOC/NBS			X					
HUD						X		X
EPA	X	X	X	X	X			X
NSF	X							
DOI/BOM					X			X

[a] Full names of these federal agencies are listed in the section entitled Abbreviations, at the end of this chapter.

Table IV. Current Agency Involvement in Areas of Machinery Noise R&D [6][a]

	Area of Involvement		
Agency	Source Noise Control Technology	Building and Structural Noise Transmission and Control	Measurements and Measurement Methodologies
BOM	X		X
NIOSH	X	X	X
NSF	X	X	X
DOD	X	X	X
NBS		X	X
EPA	X		X
USDA			X

[a] Full names of these federal agencies are listed in the section entitled Abbreviations, at the end of this chapter.

Table V. New Product Sound Level Limits [7]

On-Road Motor Vehicles	CA, CO, FL, MI, MN, NE, NV, OR, WA
On-Road Motorcycles	CA, CO, FL, MD, MI, MN, NV, OR, WA
Off-Road Motorcycles	CA, CO, MI, OR
Off-Road Vehicles	CA, CO, MA, OR
Snowmobiles	CA, CO, CT, IA, ME, MD, MA, MI, MN, MT, NH, NM, NY, OH, OR, PA, RI, UT, VT, WA, WI
Motorboats	CA, CT, NH, NJ, TN

OCCUPATIONAL SAFETY AND HEALTH ACT

Exposure to noise in the workplace is governed by rules promulgated by OSHA (see p. 68). The OSHA standard for noise, 29 CFR 1910.95, establishes permissible noise exposure in terms of duration (hours per day) and exposure as measured on the "A" scale of a standard sound level meter at slow response. Table VI shows the permissible noise exposures based on duration of exposure. For sound levels (L) not shown in Table VI, the allowable exposure (T) may be calculated using the following relationship:

$$T = \frac{8}{2^{(0.2(L-90))}} \qquad (1)$$

Table VI. Permissible Noise Exposure Times [8]

A-Weighted Sound-Level (slow response)	Exposure (hr/day)
90	8
92	6
95	4
97	3
100	2
102	1.5
105	1
110	0.5
115	0.25 or less

OSHA regulations require that protective measures be instituted when sound level exposures exceed those shown in Table VI. The standard decreases the allowable exposure time by half with each increase of 5 dB. When employees are exposed to different sound levels of varying durations, the following formula is used to calculate the mixed exposure:

$$\frac{C1}{T1} + \frac{C2}{T2} + \frac{C3}{T3} + \ldots \frac{Cn}{Tn} = D \qquad (2)$$

where C = actual exposure time at a given noise level
T = permitted exposure time (see Tables VI and X)
D = noise dose

The sum of the fractions will determine whether exposure has exceeded the standard. If the sum of the exposures is equal to, or exceeds, unity, then the mixed exposure is considered to exceed the limit value. If the sum is less than one, then exposure has been within the limit of the standard.

Example

An employee is exposed to several noise levels during the workday. The following is a review of his exposure:

dBA	Time (C)	Allowable Time (T)
95	2.5	4
100	1	2
110	0.25	0.5
75	4.25	No Limit

Using Equation 1, the sum of the fractions is as follows:

$$\frac{0.25}{0.5} + \frac{1}{2} + \frac{2.5}{4} = 1.625$$

Because the sum is greater than one, the employee has been exposed to noise in excess of the standard. If one is considered equivalent to 100% of the allowable exposure, then 1.625 would be equivalent to an exposure of 162.5% of the standard. Table VII provides a conversion from percent noise exposure to equivalent sound pressure level [9]. The example problem resulted in an excess exposure of 162.5%. The equivalent sound pressure level is approximately (through interpolation) 93.5 dBA.

Additional interpretation of the noise standard as shown in Table VI indicates that exposures of above 115 are not permissible for any length of time, Table VI presumes that exposures are of a continuous nature and not impact or impulse noise. Impulse or impact noise exposure must not exceed a 140 dB peak sound pressure level.

An alternative method of determining noise levels is through octave band analysis. Figure 2 is used to convert an octave band sound pressure level

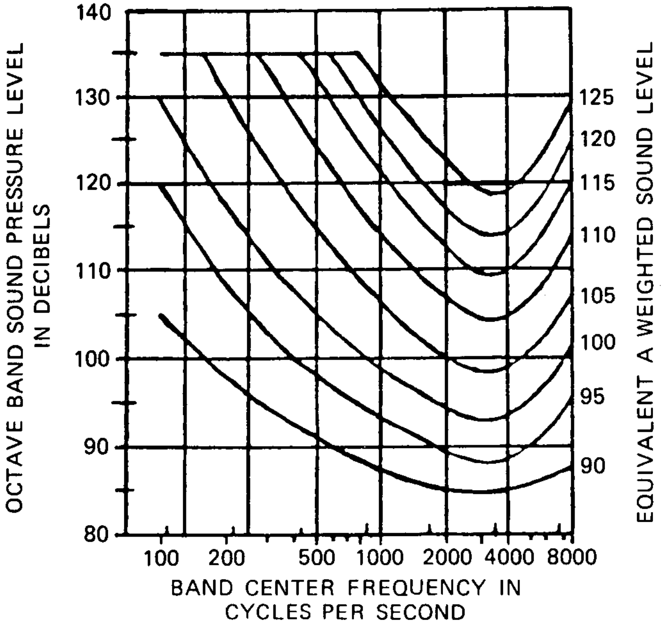


Figure 2. Sound level vs frequency.

Table VII. Conversion from Percent Noise Exposure to Equivalent Sound Pressure Level

Percent Noise Exposure	Equivalent SPL (dBA)	Percent Noise Exposure	Equivalent SPL (dBA)	Percent Noise Exposure	Equivalent SPL (dBA)
10	73.4	111	90.8	400	100.0
15	73.6	112	90.8	410	100.2
20	78.4	113	90.9	420	100.4
25	80.0	114	91.0	430	100.5
30	81.3	115	91.1	440	100.7
35	82.4	116	91.1	450	100.8
40	83.4	117	91.2	460	101.0
45	84.2	118	91.3	470	101.2
50	85.0	119	91.3	480	101.3
55	85.7	120	91.3	490	101.5
60	86.3	125	91.6	500	101.6
65	86.9	130	91.6	510	101.8
70	87.4	135	92.2	520	101.9
75	87.9	140	92.4	530	102.0
80	88.4	145	92.7	540	102.2
81	88.5	150	92.9	550	102.3
82	88.6	155	93.2	560	102.4
83	88.7	160	93.4	570	102.6
84	88.7	165	93.6	580	102.7
85	88.8	170	93.8	590	102.8
86	88.9	175	94.0	600	102.9
87	89.0	180	94.2	610	103.0
88	89.1	185	94.4	620	103.2
89	89.2	190	94.6	630	103.3
90	89.2	195	94.8	640	103.4
91	89.3	200	95.0	650	103.5
92	89.4	210	95.4	660	103.6
93	89.5	220	95.7	670	103.7
94	89.6	230	96.0	680	103.8
95	89.6	240	96.3	690	103.9
96	89.7	250	96.6	700	104.0
97	89.8	260	96.9	710	104.1
98	89.9	270	97.2	720	104.2
99	89.9	280	97.4	730	104.3
100	90.0	290	97.7	740	104.4
101	90.1	300	97.9	750	104.5
102	90.2	310	98.2	760	104.6
103	90.3	320	98.4	770	104.6
104	90.4	330	98.6	780	104.8
105	90.4	340	98.9	790	104.9
106	90.5	350	99.0	800	105.0
107	90.6	360	99.2	810	105.1
108	90.6	370	99.4	820	105.2
109	90.7	380	99.6	830	105.3
110	90.8	390	99.8	840	105.4

Table VII, continued

Percent Noise Exposure	Equivalent SPL (dBA)	Percent Noise Exposure	Equivalent SPL (dBA)	Percent Noise Exposure	Equivalent SPL (dBA)
850	105.4	900	105.8	950	106.2
860	105.5	910	105.9	960	106.3
870	105.6	920	106.0	970	106.4
880	105.7	930	106.1	980	106.5
890	105.8	940	106.2	990	106.5
				999	106.6

for a given frequency to its equivalent A-weighted sound level. The resultant dBA is then compared to the levels given in Table VI to determine compliance.

Example

An employee is exposed to a frequency of 250 cps for 1.75 hours at an octave band sound pressure level of 115 dB. Determine whether the OSHA standard 1910.95 has been violated.

From Figure 2, the equivalent A-weighted sound level for an octave band sound pressure level of 115 dB at a frequency of 250 cps is 100 dBA. From Table VI, the allowable exposure to a 100 dBA sound level is 2 hours; therefore, the standard has not been violated. This presumes that no other contributing noise sources are present.

When employees are subject to noise exceeding the levels listed in Table VI, controls must be instituted. OSHA's current standard calls for the use of administrative or engineering controls. If these measures fail, then personal protective devices, such as hearing protection, must be used. When exposure exceeds the levels given in Table VI, then the employer also must begin an "effective hearing conservation program."

A recently issued amendment to the OSHA *Industrial Hygiene Manual* provides compliance officers with such guidance [9]:

> For compliance purposes, a minimally effective hearing conservation program consists of the following items:
>
> 1-A baseline audiogram for all employees exposed to noise levels equal to or in excess of the standard.
>
> 2-Periodic audiograms for each overexposed employee.
>
> 3-Analysis of audiogram results with retesting and/or referral to an otolaryngologist or qualified physician when a significant threshold

shift occurs. A significant shift will be considered to be equal to or greater than 20 dB at any test frequency.

NOTE: If hearing loss has been determined to be occupationally related, the loss is required to be recorded on the OSHA Form 200.

4-Where insert ear plugs or custom-molded devices other than self-fitted, malleable plugs are utilized, individual employee fitting shall be conducted by a trained person, and employees shall be instructed in the care and use of the devices.

A compliance strategy depicted in flowchart form is provided in Figure 3 [10]. Current OSHA rules and the *Field Operations Manual's* noise chapter are provided as appendixes.

1974 OSHA PROPOSAL TO AMEND NOISE STANDARD

In 1974 OSHA proposed amendments to the current noise standard [11]. The proposal continues the current 90 dBA level for 8 hours, but exposure to 85 dBA noise levels would be limited to 16 hours. Current exposure to levels of 85 dBA is unlimited. Table VIII shows the permissible exposure limits under such a standard. Where sound levels (L) are not provided by Table VIII, the allowable exposure (T) may be calculated using the following relationship:

$$T = \frac{16}{2^{(0.2(L-85))}} \qquad (3)$$

Each employee exposed to a daily noise level dose of 0.5 or above must be identified. For continuous noise, Table IX shows the duration and sound level that would qualify as 0.5 dose (50% of the allowable limit). Monitoring would have to be repeated annually and within 30 days of any equipment or process modification affecting the noise level.

Under the proposal, employees receiving a daily noise dose equal to, or exceeding, a 0.5 noise dose or required to wear hearing protection (because of exposure to 0.5–1.0 noise dose and evidence of "significant" threshold shift), must be covered by a hearing conservation program [11]:

1-The hearing conservation program shall include at least an annual audiometric test for affected employees at no cost to such employees.

2-If no previous baseline audiogram exists, a baseline audiogram shall be taken within 90 days for each employee (A) who receives a daily noise dose of 0.5 or above; or (B) who is required to wear hearing protectors pursuant to paragraph (f) of this section (threshold shift).

3-Each employee's annual audiogram shall be examined to determine if any significant threshold shift in either ear has occurred relative to the baseline audiogram.

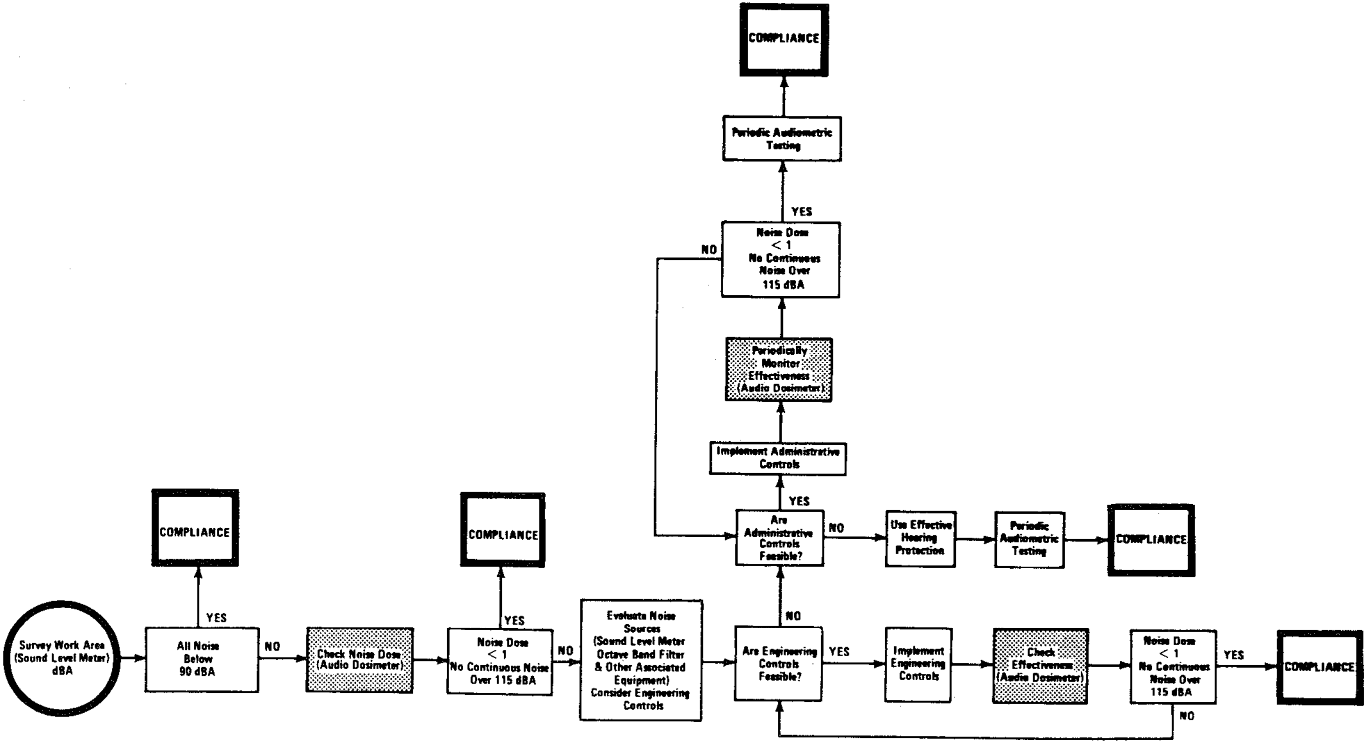


Figure 3. Noise measurement steps in complying with Section 1910.95 of the Occupational Safety and Health Act. Steps do not include 140-dB impact measurement. (Courtesy of E.I. du Pont de Nemours and Company, Inc., Wilmington, Delaware.)

Table VIII. Permissible Exposure Limits

Sound Level (dBA)	Time Permitted (hr - min)
85	16 - 0
86	13 - 56
87	12 - 8
88	10 - 34
89	9 - 11
90	8 - 0
91	6 - 58
92	6 - 4
93	5 - 17
94	4 - 36
95	4 - 0
96	3 - 29
97	3 - 2
98	2 - 50
99	2 - 0
100	2 - 0
101	1 - 44
102	1 - 31
103	1 - 19
104	1 - 9
105	1 - 0
106	0 - 52
107	0 - 46
108	0 - 40
109	0 - 34
110	0 - 30
111	0 - 26
112	0 - 23
113	0 - 20
114	0 - 17
115	0 - 15

> 4-(A) If a significant threshold shift is present, the employee shall be retested within one month. (B) If the shift persists: 1) Employees not having hearing protectors shall be provided with them in accordance with paragraph (f) of this section; 2) Employees already having hearing protectors shall be retrained and reinstructed in the use of hearing protectors; 3) The employee shall be notified of the shift in hearing level.

Signs clearly warning employees that areas are in excess of the proposal would be required if such areas exist. The signs would need to be posted at or around the periphery of the area. The signs would describe the hazards

Table IX. Noise Exposure Limits for 0.5 Noise Dose

Duration (hr/day)	Sound Level As dBA 0.5 Noise Dose
8	85
6	87
4	90
3	92
2	95
1.5	97
1	100
0.50	105
0.25	110

involved and the protective actions required. For each employee exposed to noise levels in excess of the standard, the employer would have to notify the employee, in writing, of the excessive exposure and the corrective action taken within five days of the exposure.

If employees are exposed to excessive noise levels, exceeding the proposal, engineering and administrative controls must be used to reduce employee exposure to within permissible limits. If engineering and administrative controls are not successful, they must still be used to reduce the noise level to the lowest level possible, and personal protective equipment must be used to meet the standard. The employer must continue to develop and implement engineering controls "as they become feasible." Furthermore, the employer would be required to establish and implement a written program to reduce sound levels to within permissible limits solely by engineering controls.

According to the proposal, an employee receiving a daily noise dose of between 0.5 and 1.0 and who has an audiogram showing significant threshold shift, must be provided hearing protection. Employees who receive noise exposures in excess of a daily dose of 1.0 can be fitted with hearing protection for the following circumstances: (1) during the period required for the implementation of feasible engineering and administrative control; (2) in instances in which engineering and administrative controls are feasible only to a limited extent; or (3) in instances in which engineering and administrative controls have been shown to be infeasible. The protective devices must reduce employee noise exposure to within the standard. If the devices are used, procedures must be established to assure proper maintenance, issuance and training in the use of hearing protection.

Under the authority given to EPA by the Noise Control Act, the proposal was challenged by EPA. EPA recommended to OSHA that the limit for eight hours be 85 dBA, with a doubling rate of 3 dB. Some feel the recommendation is without merit [12].

The final noise standard, according to recent reports, will be phased in over the period of a year with phase one concentrating on hearing conservation programs and phase two dealing with engineering and administrative controls [13,14].

HEARING CONSERVATION PROGRAM RULES

On January 16, 1981, OSHA promulgated the first phase of the revised noise standard (see p. 68). Phase one concentrates on hearing conservation programs. The revision incorporates much of the 1974 proposed hearing conservation amendment. Employers are required to administer a continuing hearing conservation program whenever:

- employee noise exposures equal or exceed an eight-hour time-weighted average (TWA) of 85 dBA; or
- a dose of 50%.

Exposures are to be computed based on Table X without regard to attenuation provided by personal protective equipment.

The standard requires that employers must determine whether any employee is exposed to noise equal to, or in excess of, an eight-hour TWA of 85 dBA. OSHA indicates that such a determination is to consider the following:

- Employee exposure records/measurements
- Employee noise complaints
- Difficulty understanding normal conversation in a given area at a distance of two feet

Employers are required to repeat the exposure determination, at least every two years and within 60 days, of a change in:

- Production
- Processes
- Equipment controls
- Personnel

which result in new exposures at or above 85 dBA.

If an employee's exposure is found to be equal to, or in excess of, a TWA of 85 dBA, then the employer must determine whether all other employees working in the affected area are similarly exposed. The employer must complete such a determination within 60 days of the first finding by performing individual exposure measurements or representative exposure measurements. If representative sampling is selected, then an employee who is believed to have the greatest exposure must be chosen.

Table X. A-Weighted Sound Level

A-Weighted Sound Level, L (decibel)	Reference Duration, T (hr)	A-Weighted Sound Level, L (decibel)	Reference Duration, T (hr)
80	32	105	1
81	27.9	106	0.87
82	24.3	107	0.76
83	21.1	108	0.66
84	18.4	109	0.57
85	16	110	0.5
86	13.9	111	0.44
87	12.1	112	0.38
88	10.6	113	0.33
89	9.2	114	0.29
90	8	115	0.25
91	7.0	116	0.22
92	6.2	117	0.19
93	5.3	118	0.16
94	4.6	119	0.14
95	4	120	0.125
96	3.5	121	0.11
97	3.0	122	0.095
98	2.6	123	0.082
99	2.3	124	0.072
100	2	125	0.063
101	1.7	126	0.054
102	1.5	127	0.047
103	1.4	128	0.041
104	1.3	129	0.036
		130	0.031

When noise exposures equal or exceed a TWA of 85 dBA, affected employees must be notified, in writing, within 21 days of the monitoring. The notification rule becomes operative whether individual or representative exposure sampling is performed.

The standard requires that instrumentation meeting certain nationally recognized standards:

- Dosimeters Class 2A-90/80-5 of ANSI SI.25-1978 with an operating range of 80–120 dB. Section 7.5 of ANSI 1.25–1978 for test signal at 90 dBA having a crest factor of 30 dBA
- Sound Level Meters Type II of ANSI S1.4-1971 (R1976)

OSHA requires that employee monitoring be conducted in the following manner:

- Dosimeters: Microphone be placed on the shoulder, head
- Sound Level Meters: Be set to A scale, slow response; continuous, intermittent and impulse noise from 80–130 dB must be integrated into the TWA; sampling strategy must be equivalent to Appendix B of the standard; microphone must be placed within 2 in.-2 ft of employee's ear.

The standard also provides a protocol for calibration of instrumentation.

Audiometric testing has now been included officially as a requirement of an "effective hearing conservation program." Audiometric testing must be: (1) made available to all employees whose exposure is equal to, or exceeds, a TWA of 85 dBA; (2) provided at no cost; (3) performed by a licensed or certified audiologist, otolaryngologist, or other qualified physician, or a person certified by the Council of Accreditation in Occupational Hearing Conservation, or other qualified technician reporting to a qualified physician; (4) performed within the guidelines of Appendix C of the standard.

A baseline audiogram must be established within four months of an employee's first exposure to a TWA of 85 dBA. The audiometric test can only be performed after a period of at least 14 hours without exposure to workplace noise (personal protective equipment may not be used to achieve the requirement). The employer must notify employees to avoid noisy activities during the 14-hour period. At least annually, after establishing a baseline audiogram, a new audiogram must be taken. The standard permits nonbaseline audiometric testing to be taken anytime during the workday without the 14-hour "rest" period; however, such a practice may produce results that are not comparable and weigh more heavily toward a conclusion of excessive exposure.

Annual audiograms are to be compared to baseline audiograms to determine whether a significant threshold shift has occurred. A significant threshold shift (STS) is defined by OSHA as:

1. a change in hearing threshold relative to the baseline audiogram of 20 dB or greater at any test frequency other than 500 Hz in either ear, if no previous audiograms have thresholds that exceed 25 dB with reference to audiometric zero as specified by American National Standard S3.6-1969; or
2. a change in hearing threshold relative to the baseline audiogram of 10 dB or greater at 1000 or 2000 Hz, 15 dB at 3000 or 4000 Hz, or 20 dB at 6000 Hz, in either ear, if any previous audiogram has one or more thresholds that exceed 25 dB with reference to audiometric zero; or
3. a change in hearing threshold relative to the baseline audiogram of 10 dB or greater at any test frequency other than 500 Hz in either ear, if any previous audiogram has thresholds exceeding an average of 25 dB with reference to audiometric zero at the frequencies 1000, 2000 and 3000 Hz; or
4. a change in hearing threshold relative to the baseline audiogram of 10 dB or greater at any test frequency other than 500 Hz in either ear, if the employee previously has suffered one or more permanent significant threshold shifts.

In determining whether a significant threshold shift has occurred, allowance may be made for the contribution of aging (presbycusis) to the change in hearing level by correcting the annual or retest audiogram according to the procedure described in Appendix F of the standard.

A determination of STS can be performed by an audiologist, otolaryngologist, or qualified physician based on the following information:

- Copy of OSHA rules
- Baseline and annual audiograms
- Background sound pressure levels in the audiometric test room per Appendix D of the standard
- Audiometer calibration records

If an STS is found, then a retest to obtain a new audiogram must be performed within 60 days to determine whether the STS is permanent. The 14-hour "rest" rule must be observed. If the retest reveals an STS, then it is to be considered permanent. Whenever an STS is found, the employer is required to take the following actions:

1. Employees must be fitted with hearing protectors and trained in their use.
2. Refitting and retraining of employees is required for employees already using protectors.
3. If STS is not permanent, then the use of hearing protectors may be discontinued, unless the standard is being exceeded.
4. If STS is found to be permanent, the employer must: (a) notify the employee(s) in writing within 21 days of such results; (b) refer the employee for clinical evaluation, additional testing, etc.; (c) inform the employer of the need for an otological examination; (d) record the STS on OSHA Form 200 when found to be work related; and (e) substitute the retest/annual audiogram for the baseline audiogram.

Hearing protection devices must be made available without cost to any employee exposed to a TWA of 85 or greater. The employer must ensure that all employees requiring hearing protectors wear such protective equipment. Employees requiring protective equipment would include those exposed to a TWA of 85 dBA or greater having a permanent STS, or those working in an area not in compliance with the standard.

Selection from a variety of protective equipment meeting the requirements of the workplace is afforded employees under the standard. Training on the use and care of protective equipment must be provided by the employer including a proper initial fitting and supervision covering correct use.

Under the new standard, employers are obligated to evaluate hearing protection attenuation. Appendix G of the standard is to be used to ensure that proper protector selection occurs. In all cases, the attenuation of protective equipment must attenuate noise to a level of TWA 90 dBA, or 85 dBA for employees experiencing an STS.

Training for proper use of hearing protectors must include:

- the contents of the noise standard and hearing conservation program,
- the effects of noise on hearing,
- the identification of specific machinery producing hazardous noise exposures,
- the role of engineering and administrative controls to reduce noise exposure,
- the contents of any noise control compliance plan,
- their advantages and disadvantages,
- their proper selection, fitting, use and care, and
- the purpose of audiometric testing and an explanation of test procedures.

For areas equal to, or exceeding, a TWA of 85 dBA, warning signs must be posted. The signs must indicate that the area is a high noise area and that hearing protectors may be required. OSHA provides the following example:

WARNING
HAZARDOUS NOISE AREA
HEARING PROTECTION MAY BE REQUIRED

As with other OSHA recordkeeping and access requirements, copies of the OSHA standard must be made available to employees. A copy of the standard also must be posted in the workplace. Affected employees must be provided any information or materials supplied by OSHA related to the noise standard. OSHA may request copies of any employer training and education program. Records that must be kept include the following:

1. *Employee exposure measurements* (individual/representative) covering date, location, number and result of measurements; description of noise measurement equipment and calibration record.
2. *Employee audiograms* covering name, job classification; date, examiner's name and qualifications; manufacturer and model no.; calibration record; most recent noise exposure assessment; determination of compliance with Appendix D of the standard.
3. *Audiometric test rooms* covering measurements of background sound pressure levels (for octave bands 500, 1000, 2000, 4000, 8000 Hz); date.
4. *Audiometers* with acoustical and exhaustive calibration; date and numerical results of calibration.

Record retention requirements are:

1. two years for noise exposure measurements,
2. five years plus employment period for audiometric tests, and
3. five years for background sound pressure levels and audiometer calibration in audiometric test rooms.

Employees are provided rights of access to noise exposure data under 29 CFR 1910.20.

The standard provides specific requirements for audiometric tests and audiometer calibration, which can be found in 1910.95(k) and (1), respectively. Appendixes to the standard are listed below:

Appendix	Title
A*	Noise Exposure Computation
B	Temporal Sampling Procedures
C*	Audiometric Measuring Instruments
D*	Audiometric Test Rooms
E*	Acoustic Calibration of Audiometers
F	Calculations and Applications of Age Corrections to Audiograms
G*	Methods For Estimating The Adequacy of Hearing
H	Availability of Referenced Documents
I	Definitions

*Indicates mandatory appendixes.

STATE WORKMAN'S COMPENSATION LAWS

Workman's compensation was one of the first avenues for the recognition of permanent partial hearing loss as an occupational disease. New York was the first state to award compensable status for permanent partial hearing loss. Gradually, all states adopted award maximums. However, as a state prerogative, each state has developed its own procedures and criteria for determining awards. Recent studies of the federal and state workman's compensation statute concluded the following [15]:

> Although States have adopted statutes covering hearing loss only nine States compensate more than a token number of hearing loss claims. Forty one States, where over 70% of the workers reside, pay little or no claims.

Table XI breaks down the nine states and the number of claims paid in 1977.

Table XI. Top Nine States Paying Claims in Hearing Loss, 1977

States	Number of Claims
New Jersey	3000
California	1925
New York	366
Washington	240
Wisconsin	149
Minnesota	50
Connecticut	50
Oregon	48
West Virginia	42

Of the states compensating few or no claims, nine have statutory requirements to prove wage loss or total impairment, which are difficult to prove. Maximum benefits for total loss in both ears vary between the states and federal programs: ranges are from $8000 in New Jersey to $135,000 in federal programs, the average award being $2000–$2500. Claims have been rising at a rate of 20–30% annually in the highest claim states. Discounting New Jersey, the federal program paid more claims than all other states put together in 1977; however, federal programs have paid more in total claims than the total of all state programs. A review of the significant features of state workman's compensation program is provided in Table XII. Table XIII is provided as a review of the hearing loss formulas used under the various state programs. Under state programs there are three methods under which claims are administered:

1. Employers are required to carry insurance. Carrier investigates, pays and disputes claims. Compensation agency monitors and judges disputes.
2. Employers may "self-insure" as an alternative to carrier and may handle claims themselves under the state workmen's compensation standards.
3. A government fund acts as carrier. Adjudication and monitoring functions are under separate agencies.

Most states permit both insurance and self-insurance. Although the specifics of claims procedure and processing under the different state statutes is beyond the scope of this review, Table XIV is provided as an overview of factors that may affect claims positively or negatively.

ABBREVIATIONS

BOM = Bureau of Mines
C = actual exposure time at a given noise level
cps = cycles per second
CPSC = Consumer Product Safety Commission
D = noise dose
DOC/NBS = U.S. Department of Commerce/National Bureau of Standards
DOD = U.S. Department of Defense
DOI = U.S. Department of Interior
EPA = U.S. Environmental Protection Agency
FAA = Federal Aviation Administration
HEW = U.S. Department of Health, Education & Welfare
HUD = U.S. Department of Housing & Urban Development
L = A-weighted sound level, slow response
NASA = National Aeronautics & Space Administration
NIEHS = National Institute of Environmental Health Sciences
NINDS = National Institute for Neurological Diseases and Stroke

NRR = noise reduction rating
NSF = National Science Foundation
OSHA = Occupational Safety & Health Administration
STS = significant threshold shift
T = permitted exposure time
USDA = U.S. Department of Agriculture

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Table XII. Numbers of Claims and Criteria for Hearing

Jurisdiction	Is Occupational Hearing Loss Compensable?	Number of Claims Paid–1977[a]	Maximum Benefits–Total Loss in Both Ears	Time Limit to File Claim	Apportionment (between employers)	Choice of Physician
Federal Employees Program	Yes	1,800	$135,600	D-3 yr	N	Employee
Longshore/Harbor	Yes	500	73,444	D-3 yr	N	Employee
Alabama	Yes	20	20,864	1 yr	Unk	Carrier
Alaska	Yes	4	28,000	D-2 yr	N	Employee
Arizona	Yes	10	32,999	1 yr	N	Employee
Arkansas	Yes	3	13,125	2 yr	Unk	Carrier
California	Yes	1,925	21,770	D-1 yr	Y	Employee
Colorado	Yes	6	11,676	3-5 yr	N	Carrier
Connecticut	Yes	50	22,932	D-1 yr	Y	Employee
Delaware	Yes	5	13,125	D-1 yr	N	Employee
Florida	No-PPD	0	18,900	D-2 yr	N	Carrier
Georgia	Yes	11	16,500	1 yr	N	Carrier
Hawaii	Yes	5	37,800	D-1-2 yr	Y	Employee
Idaho	Yes	3	18,576	1 yr	N	Carrier
Illinois	Yes	0	48,232	3 yr	N	Employee
Indiana	No-PPD	0	15,000	2-3 yr	Unk	Carrier
Iowa	Yes	10	42,700	2 yr	Y	Carrier
Kansas	Yes	6	14,197	1 yr	N	Carrier
Kentucky	Yes	2	17,472	1-3 yr	N	Employee
Louisiana	No-PPD	0	[i]	D-4 mo	Unk	Carrier
Maine	Yes	10	46,344	2 yr	Unk	Employee
Maryland	Yes	28	17,000	2 yr	Unk	Employee
Massachusetts	No-PTI	0	12,000	D-1 yr	N	Employee
Michigan	No-PPD	0	[j]	D-4 mo	N	Carrier
Minnesota	Yes	50	33,490	D-3 yr	N	Employee
Mississippi	Yes	2	13,650	D-2 yr	N	Carrier
Missouri	Yes	28	15,120	D-1 yr	N	Carrier
Montana	Yes	5	19,400	D-30 days	N	Employee
Nebraska	Yes	0	15,500	D-6 mo	N	Employee
Nevada	No-PTD	0	4,305	D-90 days	N	Employee
New Hampshire	Yes	0	38,520	2 yr	N	Carrier
New Jersey	Yes	3,000	8,000	D-1-2 yr	Y	Carrier
New Mexico	No-PTD	0	25,869	1 yr	Unk	Carrier
New York	Yes	366	15,750	D-90/2 yr	Y	Panel
North Carolina	Yes	17	25,200	D-2 yr	N	Carrier
North Dakota	Yes	5	8,000	1 yr	N	Employee
Ohio	No-PTD	0	13,500	6 mo	Y	Employee

Loss Compensation under Federal and State Programs [15]

HL Waiting Period	HL Formula	Deduction for Aging	Hearing Aid Provided[b]		Agency Providing Hearing Aid	Credit in Award for Hearing and Improvement	Aural Rehabilitation[c] Provided	Deduction for Preexisting Loss[d,e]
			I	R				
N	NIOSH	N	Y	Y	WC	N	P	N
N	Und	N	Y	Y	WC	N	Y	N
N	ME	N	Y	N	WC	N	P	Y
N	ME	N	Y	Y	WC	N	P	N
N	’59 AAOO	N	Y	Y	WC	N	Y	Y
N	ME	N	Y	Y	WC	N	Y	N
N	’79 AAOO[f]	N[g]	Y	Y	WC	P[h]	P	Y
N	ME	N	Y	N	WC	N	Y	Y
N	’59 AAOO	N	Y	P	WC	N	N	N
N	ME	N	Y	Y	WC	N	Y	Y
N	ME	N	Y	Y	WC	N	Y	Y
6 mo	’59 AAOO	N	Y	Y	WC	N	Y	Y
N	’59 AAOO	N	Y	P	WC	N	P	N
N	ME	N	Y	Y	WC	N	Y	Y
N	ME	NR	NR	NR	NR	NR	NR	Und
N	ME	N	Y	N	WC	N	Y	Y
N	ME	P	Y	Y	WC	N	Y	Y
N	’47 AMA	N	Y	Y	WC	N	Y	N
6 mo	’59 AAOO	Y	Y	N	WC	N	N	Y
N	ME	NR	NR	NR	NR	NR	NR	N
1 mo	’59 AAOO	N	P	P	WC	N	Y	Y
6 mo	’59 AAOO	Y	Y	Y	WC	N	Y	Y
N	ME	N	P	P	WC	NA	P	N
N	ME	N	Y	Y	WC	N	Y	Y
N	ME[k]	N	Y	Y	WC	N	Y	N
N	ME	N	Y	Y	WC	N	Y	Y
6 mo	’59 AAOO	Y	N	N	NA	N	N	Y
6 mo	’59 AAOO	Y	Y	Y	WC	N	Y	Y
N	’59 AAOO	N	Y	Y	WC	N	N	N
N	’79 AAOO	N	Y	Y	WC	N	P	Y
6 mo	’59 AAOO	P	Y	Y	WC	N	Y	N
N	’47 AMA	P	Y	P	VR	N	N	N
7 days	ME	NA	NA	NA	NA	NA	NA	Y
6 mo	’59 AAOO	N	Y	Y	WC	N	P	Y
6 mo	’59 AAOO	N	Y	N	WC	N	Y	Y
N	ME	N	Y	Y	WC	N	Y	N
N	ME	N	NA	NA	NA	N	Y	Y

Table XII,

Jurisdiction	Is Occupational Hearing Loss Compensable?	Number of Claims Paid–1977[a]	Maximum Benefits–Total Loss in Both Ears	Time Limit to File Claim	Apportionment (between employers)	Choice of Physician
Oklahoma	Yes	10	18,000	D-3-18 mo	Y	Carrier
Oregon	Yes	48	16,320	D-6 mo	N	Employee
Pennsylvania	No-PTI	0	55,380	120 days	Unk	Carrier
Rhode Island	Yes	10	9,000	D-2 yr	N	Employee
South Carolina	Yes	1	28,380	D-2 yr	N	Carrier
South Dakota	Yes	0	23,250	2 yr	Unk	Carrier
Tennessee	Yes	6	15,000	1-3 yr	N	Panel
Texas	Yes	2	13,650	6 mo	Y	Carrier
Utah	Yes	0	13,100	D-1 yr	N	Carrier
Vermont	Yes	3	38,915	1 yr	N	Employee
Virginia	Yes	8	18,700	D-2 yr	N	Panel
Washington	Yes	240	14,400	D-1 yr	Y	Employee
West Virginia	Yes	42	33,480	D-3 yr	N	Employee
Wisconsin	Yes	149	21,450	None[m]	Y	Employee
Wyoming	Yes	5	11,262	D-1/3 yr	N	Employee

[a] Some state figures are maximums, which may include a few traumatic hearing loss claims.

[b] States usually require medical proof or prescription for hearing aid.

[c] In most cases, provided by Vocational Rehabilitation agency.

[d] Where allowed, either preemployment audiogram or medical evidence required. Where deduction is made, it is determined by subtracting the previous rating from current rating.

[e] For states not deducting, preexisting loss is usually covered under second injury fund.

[f] California formula in effect since 1963; basis for 1979 AAOO formula.

[g] Compensation is generally decreased for ages below 39 and increased for ages above 39; also adjusted for type of employment.

[h] Award usually made on uncorrected audiogram since correction would also commit employer to lifetime purchase and maintenance of hearing aid.

[i] No fixed maximum; based on individual case.

[j] No maximum; all permanent disability benefits based on lifetime replacement of wage loss.

[k] No formula; courts have allowed speech discrimination scores, in addition to audiometric tests.

[l] Average of frequencies 500-4K with 25 dB low fence.

[m] In 1975 Wisconsin eliminated the Statute of Limitations for occupational diseases. Disease claims barred by the time limit for injuries are paid from a special state fund.

SOURCE NOTE

Data from telephone survey of federal and state compensation agencies and state statistical reports. In a few cases, other published sources were used (Barth, Fox, Na-

continued

HL Waiting Period	HL Formula	Deduction for Aging	Hearing Aid Provided[b]		Agency Providing Hearing Aid	Credit in Award for Hearing and Improvement	Aural Rehabilitation Provided[c]	Deduction for Preexisting Loss[d,e]
N	ME	N	Y	P	WC	N	Y	N
N	500-4K[1]	N	Y	P	WC	N	Y	Y
N	ME	N	N	N	NA	N	N	Y
6 mo	'59 AAOO	P	Y	Y	WC	N	Y	Y
N	ME	P	Y	N	WC	N	Y	Y
N	ME	N	Y	Y	WC	Y	Y	Y
N	ME	N	Y	N	WC	N	N	N
N	'59 AAOO	N	Y	Y	WC	N	Y	Y
6 mo	ME	Y	Y	N	WC	N	N	Y
N	ME	N	Y	Y	WC	N	Y	Y
N	'59 AAOO	N	N	N	NA	N	Y	Y
N	'59 AAOO	N	Y	Y	WC	N	NR	Y
N	'59 AAOO	N	Y	Y	WC	N	Y	N
2 mo	CHABA	Y	Y	Y	WC	N	Y	Y
N	ME	P	Y	Y	WC	N	Y	N

tional Commission on State Workmen's Compensation Laws, and U.S. Chamber of Commerce.) New Jersey, California, and Washington figures are close estimates from available raw data. Figures updated to October 1978 or later.

Abbreviations

D = Discovery rule (time limit begins when worker becomes aware of disability; otherwise, usually starts with date of injury)
I = Initial hearing aid
ME = Medical evaluation (impairment percent determined by physician; decision on degree of hearing impairment left to individual medical opinion, which usually means the AAOO formula)
N = No
NA = Not applicable
NR = No response
P = Possible
PPD = Permanent partial disability
PTI = Permanent total impairment
PTD = Permanent total disability
R = Replacement hearing aid
Und = Undecided
Unk = Unknown
VR = Vocational rehabilitation
WC = Worker's compensation
Y = Yes

Table XIII. Hearing Loss Formulas Used in U.S. State and Federal Workers Compensation Programs[a] [15]

Formula	Audiometric Frequencies Used (Hz)	Method of Calculation	Low Fence (ANSI-1969)	High Fence	Percent Per Decibel Loss	Better Ear Correction	States That Use Formula
AMA-1947	500, 1000, 2000 4000	Weighted average	20 dB	105 dB	Varies	7/1	KS, NJ
AAOO-1959	500, 1000, 2000	Average	25 dB	92 dB	1.5	5/1	AZ, CT, GA, HI, KY, MD, ME, MO, MT, NE, NH, NY, NC, RI, TX, VA, WA, WV
AAOO-1979[b]	Same as California	Average	25 dB	92 dB	1.5	5/1	CA

Table XIII. Hearing Loss Formulas Used in U.S. State and Federal Workers Compensation Programs[a] [15]

Formula	Audiometric Frequencies Used (Hz)	Method of Calculation	Low Fence (ANSI-1969)	High Fence	Percent Per Decibel Loss	Better Ear Correction	States That Use Formula
NIOSH Recommendation	1000, 2000, 3000	Average	25 dB	92 dB	1.5	5/1	FEC
CHABA Recommendation	1000, 2000, 3000	Average	35 dB	92 dB	1.75	4/1	WI
California Formula (Now 1979 AAOO)	500, 1000, 2000 3000	Average	25 dB	92 dB	1.5	5/1	CA
Oregon Formula	500, 1000, 2000 4000, 6000	Average	25 dB	92 dB	1.5	5/1	OR
Berney Formula	500, 1000, 2000 4000	Average	25 dB	92 dB	1.5	5/1	NJ

[a] Data are from Table I.

[b] States with no formula listed leave decision to examining physician (medical evaluation), who will probably now use the 1979 AAOO.

Table XIV. State and Federal Workers Compensation Rules Affecting Occupational Hearing Loss–Positive and Negative Impact on Claims [15]

	Jurisdiction	Number of Claims Paid–1977	Compensable □ yes ■ no	Maximum Benefits–[a] Total Loss in Both Ears □ Over $21,700 ■ Under $21,700	Time Limit to File Claim □ Discovery rule ■ No discovery rule	Apportionment (between employers) □ no ■ yes	Choice of Physician □ Worker choice ■ Insurer or employer choice or panel	HL Waiting Period □ no ■ yes	HL Formula □ Increased frequency above 2,000 Hz ■ No frequency above 2,000 Hz	Deduction for Aging □ no ■ yes	Deduction for Preexisting Loss □ no ■ yes
High Claim States	Federal Employees Program								□		
	Longshore and Harbor	□		□		□			b		
	California	□		□		■			□		
	Connecticut	□		□		■			■		
	Minnesota	□		□		□			□		
	New Jersey	□		■		■			□		
	New York	□		■		■			■		
	Oregon	□		■		□			□		
	Washington	□		■		■			■		
	West Virginia	□		c		□			■		
	Wisconsin	□		■		■			□		
Compensable–Few or No Claims	Alabama			■		■	■			□	■
	Alaska			□		□	□			□	□
	Arizona			□		□	□			□	■
	Arkansas			■		■	■			□	□
	Colorado			■		□	■			□	■
	Delaware			■		□	□			□	■
	Georgia			■		□	■			□	■
	Hawaii			□		■	□			□	□
	Idaho			■		□	■			□	■
	Illinois			□			□			b	b

	Jurisdiction	Number of Claims Paid—1977	Compensable □ yes ■ no	Maximum Benefits—[a] Total Loss in Both Ears □ Over $21,700 ■ Under $21,700	Time Limit to File Claim □ Discovery rule ■ No discovery rule	Apportionment (between employers) □ no ■ yes	Choice of Physician □ Worker choice ■ Insurer or employer choice or panel	HL Waiting Period □ no ■ yes	HL Formula □ Increased frequency above 2,000 Hz ■ No frequency above 2,000 Hz	Deduction for Aging □ no ■ yes	Deduction for Preexisting Loss □ no ■ yes
	Iowa	■	□	□	■	■	■	□	■	■	■
	Kansas	■	□	■	■	□	■	□	□	□	□
	Kentucky	■	□	■	■	□	□	■	■	■	■
	Maine	■	□	□	■	■	□	■	■	□	■
	Maryland	■	□	■	■	■	□	■	■	■	■
	Mississippi	■	□	■	□	□	■	□	■	□	■
	Missouri	■	□	■	□	□	■	■	■	■	■
	Montana	■	□	■	□	□	□	■	■	■	■
	Nebraska	■	□	■	□	□	□	□	■	□	□
	New Hampshire	■	□	□	■	□	■	■	■	■	□
	North Carolina	■	□	□	■	□	■	■	■	□	■
	North Dakota	■	□	■	■	□	□	□	■	□	□
	Oklahoma	■	□	■	□	■	■	□	■	□	□
	Rhode Island	■	□	■	□	□	□	■	■	■	■
	South Carolina	■	□	□	□	□	■	□	■	■	■
	South Dakota	■	□	□	■	■	■	□	■	□	■
	Tennessee	■	□	■	■	□	■	□	■	□	□
	Texas	■	□	■	■	■	■	□	■	□	■
	Utah	■	□	■	□	□	■	■	■	■	■
	Vermont	■	□	□	■	□	□	□	■	□	■
	Virginia	■	□	■	□	□	■	□	■	□	■
	Wyoming	■	□	■	□	□	□	□	■	■	□
Noncompensable	Florida	■	■	■	□	□	■	□	■	□	■
	Indiana	■	■	■	■	■	■	□	■	□	■
	Louisiana	■	■	c	□	●	●	□	■	b	□
	Massachusetts	■	■	■	□	□	□	□	■	□	□
	Michigan	■	■	c	□	□	■	□	■	□	■
	Nevada	■	■	■	□	□	□	□	□	□	■
	New Mexico	■	■	□	■	■	■	■	■	b	■
	Ohio	■	■	■	■	■	□	□	■	□	■
	Pennsylvania	■	■	□	■	■	■	□	■	□	■

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[a] Above and below average benefits, based on 50-state mean.
[b] Undecided or unknown.
[c] No fixed benefit levels; see Table I.
Legend: ■ *Limits claims.* □ *Encourages/does not discourage rightful claims.*

NOTE ADDED IN PROOF: OSHA REGULATORY CHANGES

As this book goes to press, additional regulatory changes are imminent. OSHA's noise control regulations, as presented in this chapter, were stayed by the Reagan Administration and partially lifted on August 21, 1981 (see *Federal Register* of that date, p. 42622).

Portions of the January 1981 regulations currently in effect are listed below:

1. A hearing conservation program is mandatory whenever employee exposures equal or exceed an 8-hr TWA of 85 dB.
2. The permissible exposure limit remains at 90 dB, 8-hr TWA.
3. Monitoring is required to determine employee exposure. (Must be completed by February 22, 1982, by area or personal monitoring).
4. Audiometric testing is required for all employees exposed to noise of 85 dB TWA or greater; to be completed by August 22, 1982. (Audiometric test booth and audiometer testing and specification regulations are covered in the standard.)
5. Audiogram evaluation procedures and training regulations are outlined.
6. Hearing protectors are mandatory for exposures of 90 dB TWA or more, or if STS has occurred (attenuation specifications are provided).
7. Information access, recordkeeping, record retention and access is regulated.

Future changes are a certainty, including the remaining portions of the hearing conservation standard and engineering standards.

Review the *Federal Register* of August 21, 1981, and establish a working relationship with a qualified acoustical engineering consultant as a way to keep abreast of regulatory changes. (Institute of Noise Control Engineering, Poughkeepsie, NY, and National Council of Acoustical Consultants, Silver Spring, MA, can help in finding one).

4.

NOISE ANALYSIS

Anthony J. Schneider
San Clemente, California

Noise measurements usually fall into one of two categories. The first includes measurements of dBA level for Occupational Safety and Health Administration (OSHA) surveys, community noise enforcement and product noise rating. Common measuring instruments are sound level meters, L_{eq} meters and noise dosimeters. The second category consists of measurements in support of programs to reduce environmental noise and to design quiet products. In addition to dBA level, these measurements usually require frequency analysis and amplitude distribution analysis.

Distinction must be made between measurement of noise emission and measurement of environmental noise. These distinctions affect the selection, placement and orientation of microphones, as well as the manner in which tests are conducted and data reported.

MICROPHONE DESIGNS

The microphone is the key to good acoustical data. The sound level meter's electronic package is very straightforward in this day of integrated and hybrid circuits, but the microphone requires a craftman's design. Microphones control the sections of sound level meter specifications and industry measurement standards that deal with frequency range, directivity and stability. In fact, the microphone is the primary distinguishing factor among the three ANSI sound level meter classifications.

Ideally, the microphone should produce an electrical signal that is an exact replica of the acoustical disturbance. It should operate over wide amplitude and frequency ranges. Further, it should be stable during severe changes in environmental conditions. Of the many principles of acoustical transducer construction, only piezoelectric and condenser microphones are used for instrumentation purposes.

Piezoelectric microphones are used primarily for field measurements on general purpose sound level meters and dosimeters. Condenser microphones are used in laboratories and in the field on precision sound level meters. Condenser microphones are either the air-condenser or the electret-condenser type.

Air-Condenser Microphones

The construction of a stretched-metal-diaphragm microphone, commonly called an air-condenser microphone, is shown in Figure 1. The transducer consists of a thin, tightly stretched metallic diaphragm in close proximity to a rigid backplate. The diaphragm and backplate are insulated electrically and form the plates of a capacitor. A dc polarizing voltage is applied across the plates. Variations in pressure due to sound waves set the diaphragm in motion, thereby varying the width of the air gap and causing generation of an alternating charge on the capacitor. By careful design it is possible to keep the electrical output proportional to sound pressure over a wide range of amplitudes and frequencies.

Microphones are critically damped, so there are no resonance frequencies to consider as there usually are with other dynamic transducers such as accelerometers. So that changes in atmospheric pressure will not change the static position of the diaphragm and cause a change in sensitivity, the air gap is vented to atmosphere. A uniform temperature coefficient is selected for the metals in the diaphragm and in the housing to provide excellent temperature stability.

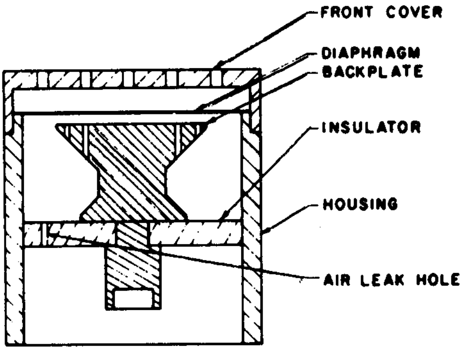


Figure 1. Schematic construction of an air-condenser microphone.

Air-condenser microphones have a long history of laboratory and field use. Size for size, they generally have a higher sensitivity and higher frequency response than the other types of instrumentation microphones, but are the most fragile and expensive designs. They are also susceptible to arcing across the air gap when used for long periods in humid environments.

Electret-Condenser Microphones

The electret-condenser design [1], shown in Figure 2, uses a principle similar to the air-condenser design. A fundamental difference, however, is that the capacitor's charge is embedded permanently in a layer of "electret" insulating material that is bonded to the backplate and forms, with the air, the dielectric of the capacitor. Because an electrostatic charge is embedded permanently in the electret material, electret-condenser microphones do not require an external polarizing voltage. This simplifies signal conditioning and reduces hazards in explosive environments.

Electret-condenser microphones do not suffer from humidity problems because of the bound nature of the electret charge. They have also proven to withstand rigorous handling by inexperienced users. They are used widely for laboratory and field measurements.

Piezoelectric Microphones

Piezoelectric microphones (Figure 3) use a ceramic element that generates an electrical charge when subjected to dynamic forces. The diaphragm responds mechanically to acoustical pressures and transmits corresponding

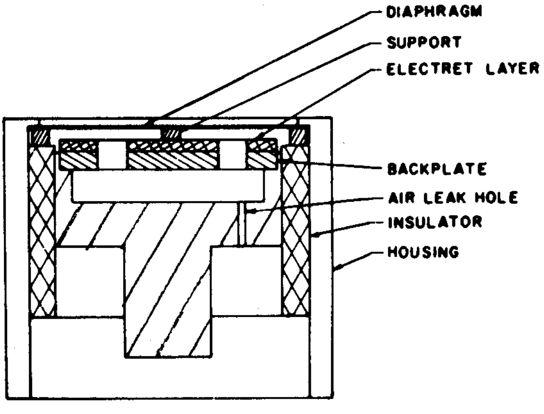


Figure 2. Schematic construction of an electret-condenser microphone.

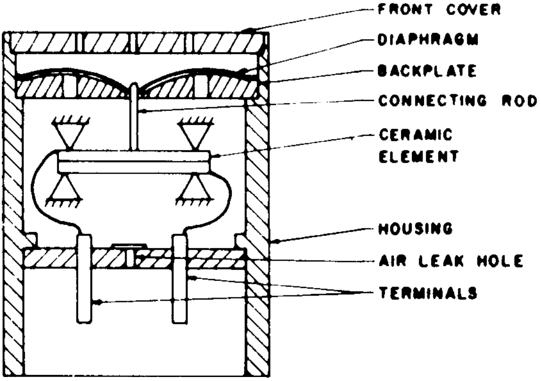


Figure 3. Schematic construction of a piezoelectric microphone.

forces through a connecting rod to the piezoelectric element. Like the electret-condenser microphone, piezoelectric microphones do not require an excitation voltage. They have a lower sensitivity and a narrower frequency bandwidth than condenser microphones, but are less expensive and quite adequate for general purpose measurements.

Special high-intensity designs of piezoelectric microphones are used for aerospace applications such as boundary layer noise measurements.

SOUND FIELDS

Before proceeding with the discussion of microphones, it is necessary to describe the concept of sound fields [2] as they relate to measuring noise emission. Figure 4 shows a graph of sound level versus distance from a complex noise source. The boundary between the near and far fields is determined by the distance of the microphone from the sound source. The free and reverberant field boundary is determined by the environment in which the measurement is performed.

Near and Far Field

In the near field, sound pressure is heavily dependent on the proximity and the radiating characteristics of individual noise-generating mechanisms. Small changes in microphone location can show large differences in noise level and frequency spectrum. This is illustrated by the shaded area in the near field

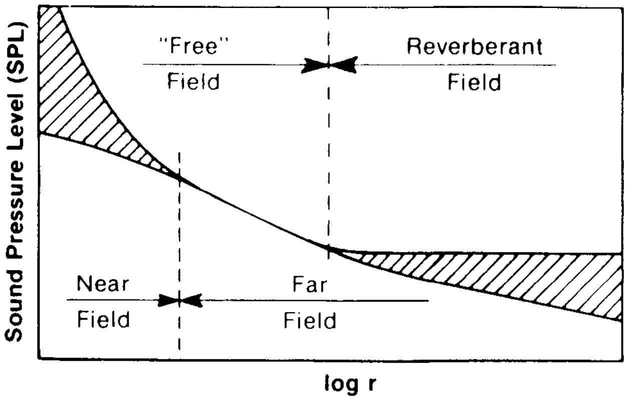


Figure 4. Variation of sound level as a function of distance from a source. Shaded areas indicate regions in which level varies with position.

in Figure 4. In this region, product noise emission cannot be measured, but microphones can be used as noise probes to aid in identifying the source of undesirable frequency components in a product noise signature. In the far field a sound wave is propagated, and sound pressure is inversely proportional to distance from the source. In practice, the boundary between the near and far fields is considered to be at a distance of about three times the largest dimension of the largest radiating surface of the sound source.

Free and Reverberant Fields

The boundary between the free and reverberant fields is determined by the environment in which the acoustical measurement is performed. A free field is one in which there are no reflections. This condition is often simulated in anechoic rooms to measure noise radiation and directional characteristics of sound sources. In a free field environment in the far field of a noise source, noise level decreases 6 dB for each doubling of distance. Under these conditions, noise emission can be measured accurately, and the data can be used to predict the level at greater distances. Measurement distance must always be reported with sound level, e.g., 85 dBA at 10 meters.

Real-life environments, such as outdoor and factory areas, are not free fields. The ground or floor and walls reflect some of the sound. The result is that more than one sound wave may impinge on the microphone. The total sound pressure may be higher or lower than the directly radiated sound, depending on the amplitude and phase differences between the direct wave and the reflected waves. The greater the separation between source and microphone, the more reverberant the environment and the less accurate the measurement of noise emission.

Such environments generally are not recommended for measuring product noise emission, but there are important and practical exceptions. Automotive vehicles and construction machinery are tested in open fields. Procedures are standardized by SAE and ANSI for a variety of vehicles. They specify ground condition (soft grass for most vehicles, but snow for snowmobiles); require an open test area; dictate position of observers; and specify microphone distance and height above the ground. Similarly, there are NMTBA (National Machine Tool Builders Association) procedures for testing large machine tools on the assembly floor.

Totally reverberant environments (diffuse fields) have sound waves impinging from all directions. Sound level theoretically is the same at all locations. These conditions are approached in reverberation chambers. This is a typical environment for measuring sound power of air conditioning equipment and electric motors, as well as for measuring the statistical absorption of acoustical materials.

MICROPHONES AND THE ACOUSTICAL ENVIRONMENT

An ideal microphone would operate in a sound field without affecting progress of a sound wave. Unfortunately, microphones do affect progress of the wave and thereby disturb the acoustical field. This causes microphones to be directional at higher frequencies. A variety of microphone sizes and designs are available so users can select one that is nearly ideal for a particular requirement [3].

Microphones are omnidirectional at low frequencies. At high frequencies, where the wave length of sound approaches the diameter of the microphone, the microphone disturbs the progress of the wave and causes perturbations. This results in the microphone's frequency response varying as a function of the angle of incidence of the sound wave. For practical selection, a 24-mm (1-in.) microphone is directional above about 3 kHz, a 12-mm ($^1/_2$-in.) microphone above about 6 kHz, and a 6-mm ($^1/_4$-in.) above 12 kHz. Directional variations are greatest at about 8 kHz for 24-mm-diameter microphones and about 16 kHz for those 12 mm in diameter.

Two microphone designs are available: (1) perpendicular incidence, and (2) grazing incidence. Careful consideration always should be given to the type of microphone in use.

Perpendicular-incidence microphones (Figure 5) have a flat broad-band response when pointed at a sound source so the direction of sound propagation is perpendicular to the plane of the microphone's sensing surface. This

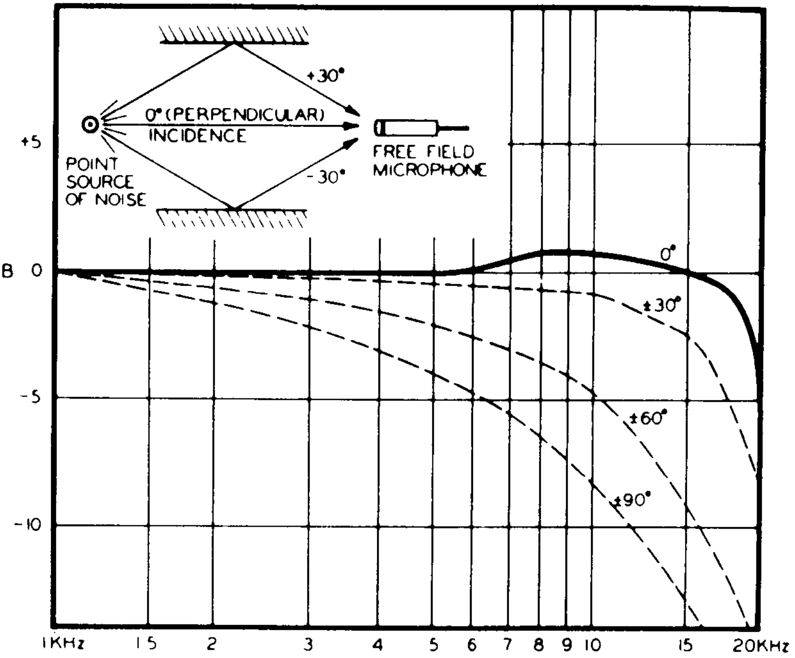


Figure 5. Frequency response of a typical perpendicular-incidence, air-condenser microphone as a function of angle of incidence.

is also called 0-degree incidence to the axis of the microphone. Grazing-incidence microphones (Figure 6) have a flat response when oriented so the sound wave grazes across the sensing surface, also called 90-degree incidence to the axis.

All noise measurement procedures include the fundamental instruction: "orient the microphone with respect to the sound source in the manner prescribed by the manufacturer." This assures a flat frequency response when monitoring a single sound source. If reflections or other sound sources are present, the frequency response may be different for each source. A microphone size should be selected to assure flat response over the frequency bands of the noise sources.

An important distinguishing characteristic of the perpendicular-incidence microphone is that its published axis of flat response is also its most sensitive axis. Sound waves incident from other angles may have their high-frequency components attenuated, but never amplified. The perpendicular-incidence microphone is therefore a "safe" microphone. It will never overestimate a

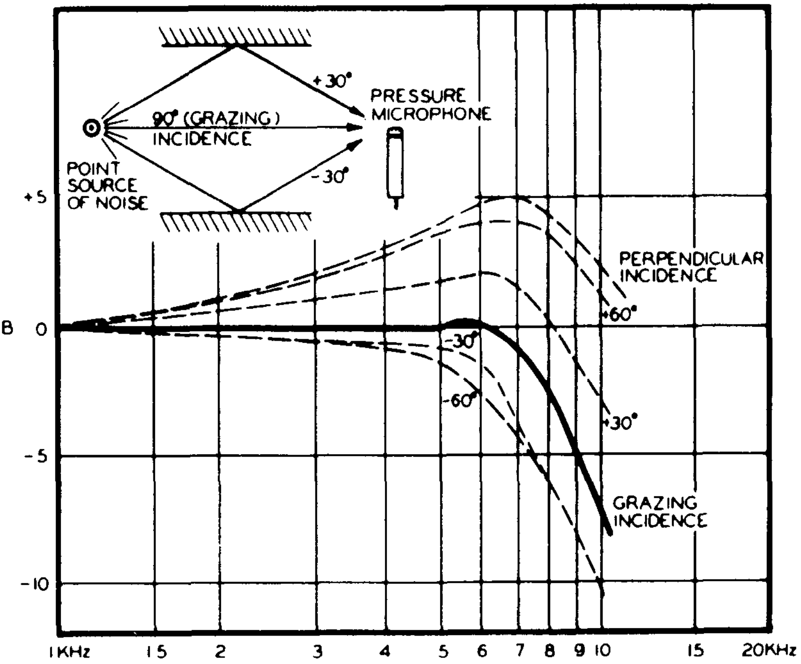


Figure 6. Frequency response of a typical grazing-incidence, air-condenser microphone as a function of angle of incidence.

noise level, even if oriented incorrectly. By this reasoning, it is an excellent choice for OSHA measurements.

Grazing-incidence microphones have a flat response when sound waves graze across the diaphragm. This is an ideal characteristic for measuring vehicle driveby noise and aircraft flyover noise. As the sound source passes by, sound waves continue to arrive at grazing incidence to ensure a uniform frequency response; however, it is very important that the user does not point this type of microphone at a sound source. This microphone is often called a random-incidence microphone because essentially it has a flat response under random-incidence conditions. It also has a flat response as a probe microphone in near field conditions and is frequently called a pressure microphone. In its smaller sizes it is also acceptable for measuring environmental noise. Therefore, grazing-incidence microphones are more versatile than perpendicular-incidence designs.

Electret- and air-condenser microphones are available in both perpendicular- and grazing-incidence designs. Piezoelectric microphones generally are avail-

Table I. Upper Frequency Limit and Ripple for Various Microphones

	Typical 1-in. Diameter		Typical 0.5-in. Diameter	
	Upper Frequency Limit, 2 dB Down (kHz)	Ripple (±)	Upper Frequency Limit, 2 dB Down (kHz)	Ripple (±)
Electret-Condenser, Random-Incidence Response	10	1	20	1
Electret-Condenser, Perpendicular-Incidence Response	15	1	25	1
Air-Condenser, Perpendicular-Incidence Response	18	1	40	1
Air-Condenser, Pressure Response	8	1	20	1
Ceramic, Random-Incidence Response	12	2		

able only in the grazing-incidence design. Table I shows typical upper frequency limits for different sizes and designs.

MICROPHONE ACCESSORIES

Various accessories are available to improve the reliability of field measurements. Wind screens are used when measuring community noise and vehicle noise. They are open-pored polyurethane spheres that fit over the microphone and suppress the disturbing effects of wind, which otherwise may raise the system noise to an unacceptable level. Wind screens also protect microphones against flying metal chips and oil spray while performing OSHA noise surveys.

Remote microphones are desirable on noise emission measurements because they eliminate the need of an observer, who is a reflective body in the vicinity of the microphone. Remote-condenser microphones are mounted on a preamplifier powered by the sound level meter or a separate power supply.

Weatherproof systems are used for ongoing community and airport noise monitoring where measurements must be made under unpredictable weather conditions. The system in Figure 7 consists of a microphone and preamplifier, which are protected completely by a rain screen, a wind screen and a bird-deterrent spike. A desiccant is provided inside the assembly to protect against humidity. Outdoor systems are supplied with a mounting mast for attaching

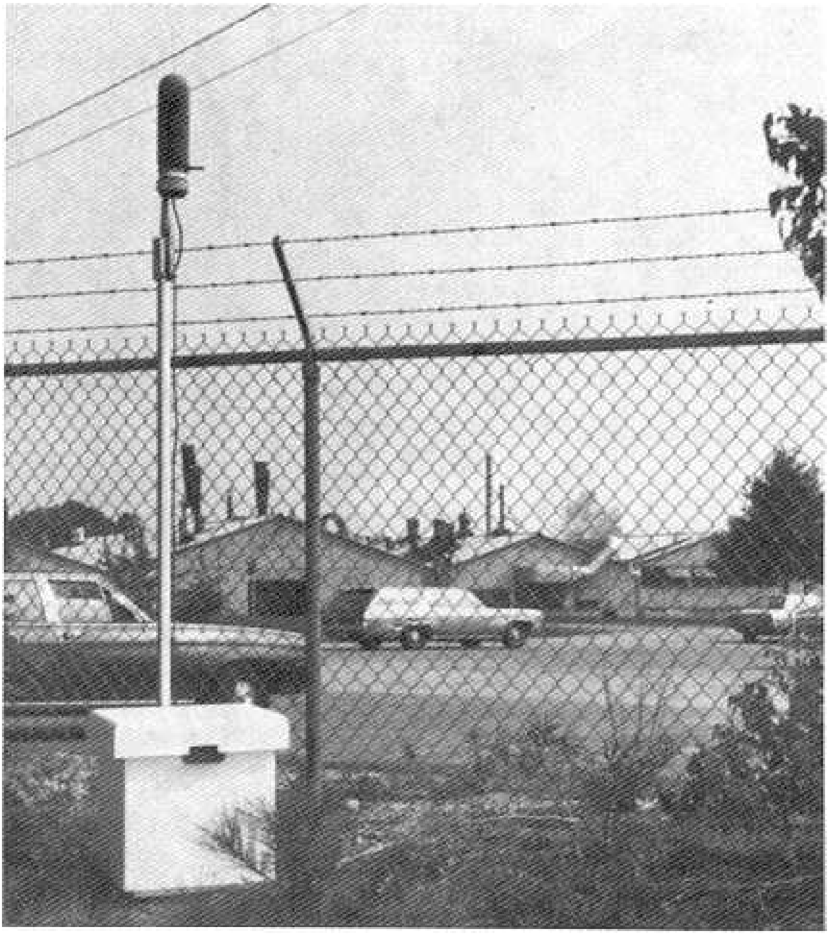


Figure 7. A typical weatherproof microphone for long-term outdoor monitoring.

to utility poles. The preamplifiers have a low impedance output for driving long lines to a portable noise analyzer or data acquisition station.

FREQUENCY WEIGHTING

Microphones are dynamic pressure sensors that measure disturbances in atmospheric pressure. They should have a flat frequency response from about 20 Hz to 20 kHz, unless otherwise dictated by the frequency spectrum of the sound source. When measuring with a linear amplifier over this range, the readings are referred to as dB SPL (decibels, sound pressure level).

Sound pressure level should not be used to measure sound subjectively because the human ear does not exhibit a flat frequency response. Most acoustical measurements are in dBA, which means that an A-weighting filter similar to that shown in Figure 8 was inserted in the electrical circuit of the sound level meter. Weighted measurements such as dBA are properly referred to as sound level, by contrast to sound pressure level for linear data.

The A-weighting curve represents the average hearing loudness response of a group of young persons with unimpaired hearing when they listened to pure tones of sound at moderate sound pressure levels. These tests were conducted more than 40 years ago. At higher levels, the ear's response to pure tones is more linear (B and C weighting). But many other factors are present. Frequencies between 1 kHz and 5 kHz are more annoying than lower frequencies. Subjective response to complex sounds is different from that to pure tones, etc. Numerous criteria have been proposed over the years for evaluating loudness level, but dBA proves to be the best single measure of sound level for wide-ranging sounds and amplitudes. Moreover, the dBA also is used as the descriptor for evaluating hearing damage risk. In other words, it is generally assumed that the higher the dBA level, the greater will be its perceived loudness level and the hearing damage risk for repeated or continuous exposure. For this reason, an A-weighting filter is a required feature on sound level meters and noise dosimeters.

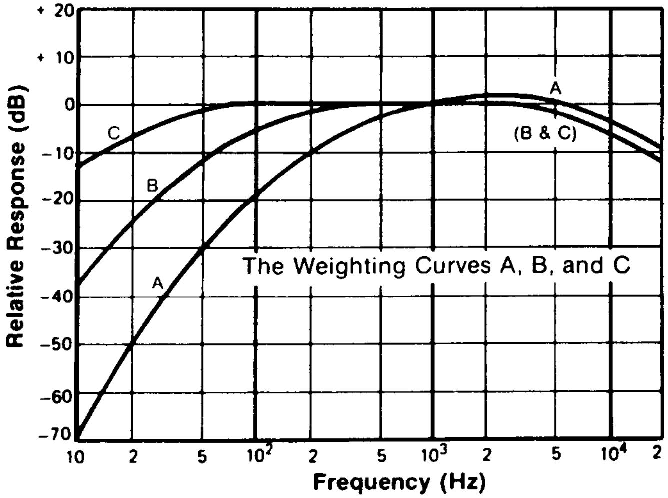


Figure 8. Frequency-weighting networks for sound level meters.

SOUND LEVEL METERS

A sound level meter [4] is an acoustical measuring instrument consisting of a microphone, amplifier, frequency-weighting filter and readout meter. Figure 9 shows a block diagram of a typical sound level meter. It will meet one or more governing standards. ANSI S1.4-1971 dominates in the United States, but IEC-179 is often specified for more exacting work. In due time, the two standards are expected to be combined into a single standard. S1.4-1971 specifies three types of sound level meters:

1. Type 1–precision sound level meter
2. Type 2–general purpose sound level meter
3. Type 3–survey sound level meter

The standards outline straightforward electrical specifications, such as meter damping, response of frequency-weighting networks and certain environmental characteristics. However, the distinguishing factor among the three types of meters is the tolerance allowed on frequency response and directional response, which are controlled by the microphone. Therefore, the microphone determines which standard a sound level meter meets.

The different types of sound level meter will be compared here by their A-weighted response. System A-weighting tolerances of current standards are summarized in Figure 10 for the important range above 1 kHz. Heavy roll-off at lower frequencies makes low-frequency tolerances less critical. Note that it is permissible for precision sound level meters to have no output above 15 kHz, and general purpose and survey sound meters are guaranteed to operate only up to 10 kHz. Most users demand more than the absolute minimum, so the prospective user must check the specifications of individual instrument models.

Of much greater importance to the user are the directional tolerances shown in Figure 11. These curves are normalized so that conformance to the A-filter by main-axis measurements under free field conditions is represented by a flat response. ANSI standards permit use of grazing-incidence microphones, which overestimate high-frequency sound waves with perpendicular incidence to the sensing surface. The type 3 meter is permitted to have positive errors ranging up to 14 dB at 8 kHz. To protect users, OSHA has disapproved the use of type 3 survey meters for operator exposure surveys. Tolerances for type 2 meters are much tighter. Most OSHA surveys are performed with type 2 general purpose sound level meters. A typical meter is shown in Figure 12.

Tolerances for type 1 meters are similar to type 2 but are extended to 15 kHz. Many organizations are not satisfied with type 1 directional tolerances, so the IEC-179 standard is often specified. IEC-179 essentially requires that the most sensitive axis coincide with the main axis response.

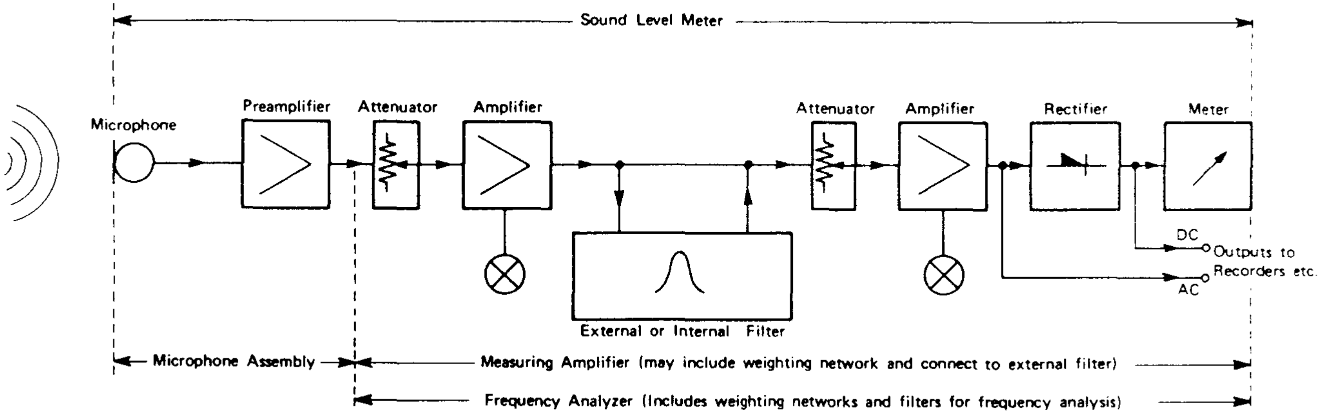


Figure 9. Block diagram of the important elements of a sound level meter.

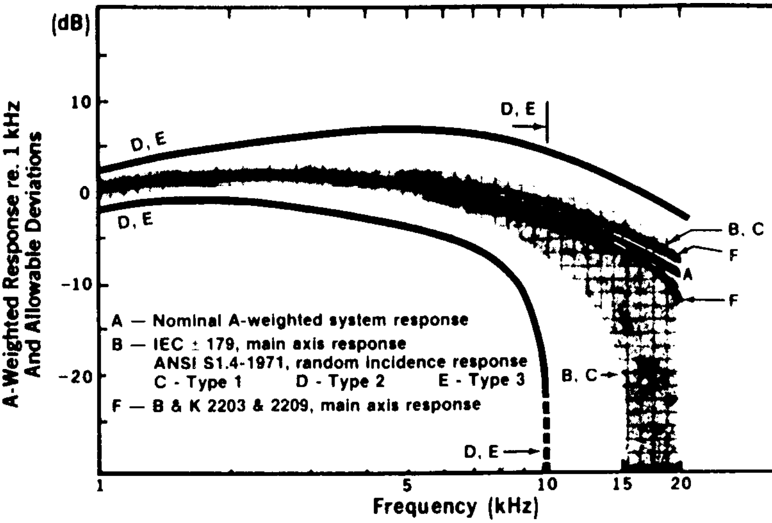


Figure 10. Frequency-weighting networks used in sound level meters.

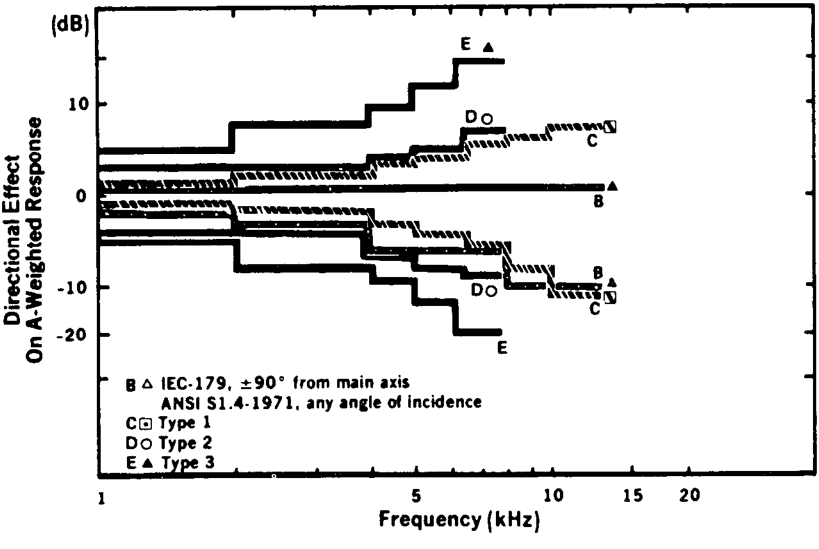


Figure 11. Directional tolerances permitted by various sound meter standards.

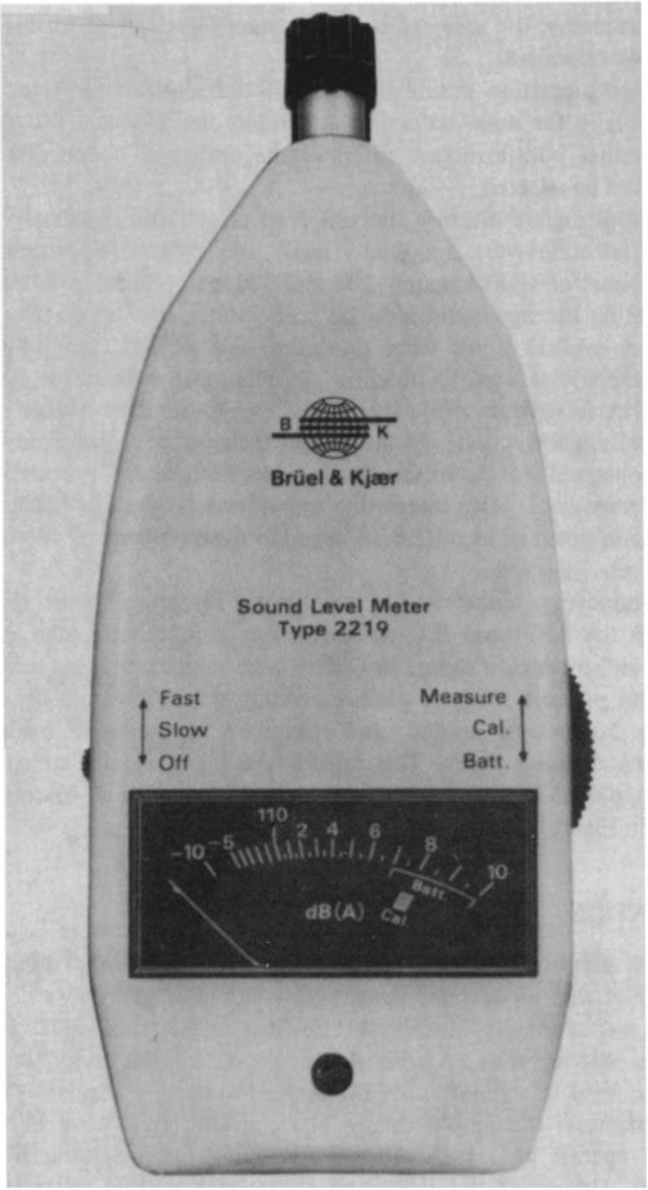


Figure 12. A typical general purpose sound meter used for OSHA and community noise surveys.

The intent is to specify a perpendicular-incidence microphone that can never overestimate sound level in semireverberant fields. By attaching the appropriate microphone, the user can adapt the sound level meter to the ANSI or IEC precision standards.

One other suggestion should be made. If the sound level meter is to be used eventually for noise reduction or product improvement programs, one that has either built-in octave filters or the option of connecting external filters should be selected.

Sound level meters measure the rms level of acoustic signals. Two meter-damping selections are required—"fast" and "slow"—corresponding to averaging times of approximately 200 and 800 msec. "Fast" response is used for estimating the maximum level of noise events, such as driveby and flyover noise, cyclical noise from machines, and general community noise. "Slow" response is used to obtain a single-number estimate of fluctuating noise. OSHA surveys are made with "slow" response. Even in this mode the meter usually will fluctuate. In these cases the operator must note the range of levels observed on the meter. Some observers take an "eyeball" estimate of the average level. With integrating sound level meters discussed in a later section, it is possible to obtain an accurate measurement of the long-term average level.

OSHA imposes a measurement requirement for impact noise that is not covered in the ANSI and IEC standards. For impact noise such as forging, stamping and press operations, an OSHA noise limit is imposed based on the peak sound pressure level. A peak-responding detector with a rise time not exceeding 50 μsec is needed, and measurements must be made in the C-weighting or linear mode. This capability is provided in some sound level meters. A precision sound meter with peak mode and built-in octave filters is shown in Figure 13.

CALIBRATION

Common practice and most industry standards require that sound meters be calibrated with an acoustic signal before and after each day's use or each series of measurements. Most calibrators use an electrical signal to drive a diaphragm that serves as a loudspeaker in the calibration cavity. Because the calibration level is a function of the applied voltage, a regulating circuit is used to maintain the supply voltage at a constant level. Most calibrators of this type operate at 1 kHz. At this frequency the weighting filters have unity gain. This offers the distinct advantage that a 1-kHz calibrator can be used with the sound meter in its A-weighting operating mode without any correction factor. Figure 14 shows a typical acoustic calibrator in general use for laboratory and field measurements. Other models are available for calibrating at several frequencies and amplitudes.

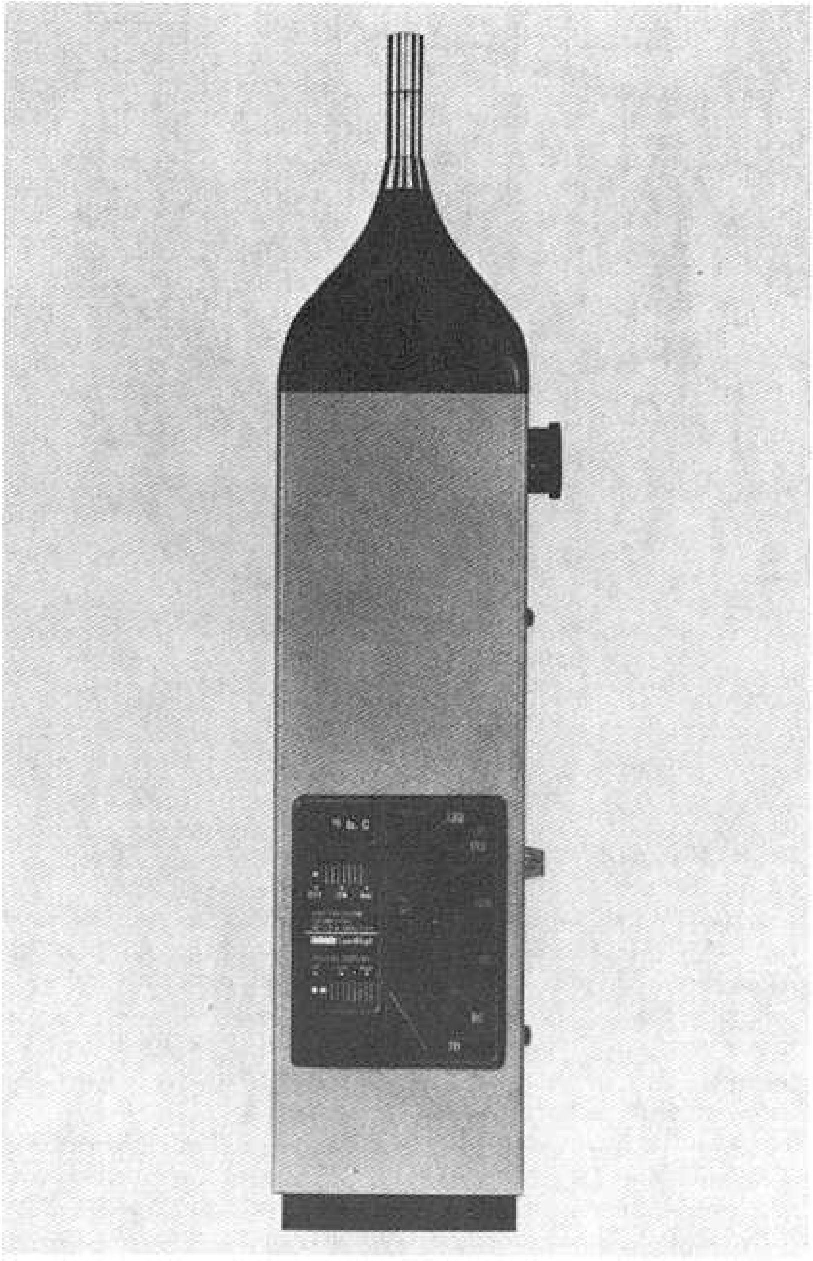


Figure 13. A precision sound level meter with built-in octave filters and OSHA peak-hold circuit.

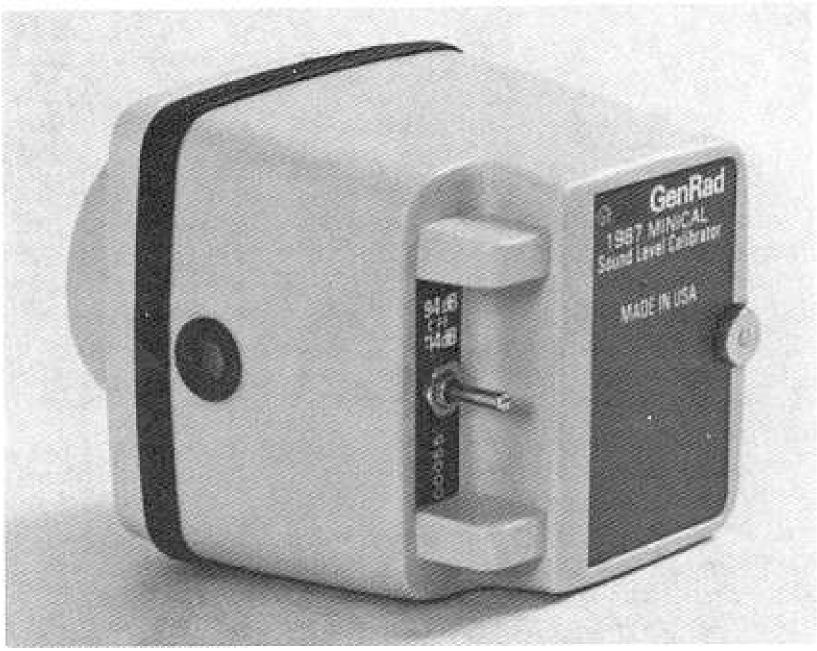


Figure 14. A typical acoustic calibrator for field use.

INTEGRATING SOUND LEVEL METERS

Most sound meters are designed for measuring steady or transient noise; however, they cannot average noise over periods of time. Long-term averages could be obtained by tedious analysis of strip chart records or by an expensive digital processing of data on a laboratory computer, but today's microprocessor technology permits data to be computed in small hand-held instruments. They are called integrating sound level meters [5] and they measure equivalent continuous sound level (L_{eq}).

The concept of L_{eq} is quite simple. It is the level in dBA of a hypothetical constant noise which, if substituted for the actual noise over the same period of time, would produce the same amount of acoustical energy at the microphone position. In community noise, environments are often rated by their 24-hour L_{eq}, and time histories described by successive hourly L_{eq} values. For most work, a series of L_{eq} values is much easier to describe and interpret than a continuous record of sound level vs time. An L_{eq} measured over a several second interval is an excellent method of measuring the average level of nonstationary machine noise.

Integrating sound meters sample the dBA digitally and use a dedicated microcomputer to compute L_{eq} by the following equation:

$$L_{eq} = 10 \log \frac{1}{n} \sum 10^{L_i/10} = 10 \log \frac{1}{n} \sum \text{antilog} \frac{L_i}{10}$$

where n = the number of samples taken
L_i = the A-weighted level of each sample

The antilog of each sample is computed as the sample is taken and summed in a storage register, which contains the sum of all previous antilogs. The total number of samples is stored in a second register. The microcomputer calculates and updates L_{eq} from the data in the registers.

A typical hand-held L_{eq} meter is shown in Figure 15. Although the primary readout is L_{eq}, instruments of this type take advantage of other available data from the information processing system and present additional information. The unit displays each dBA value as it is sampled. A third register stores L_{max}, the highest dBA level that was sampled. And a measurement duration display permits the operator to time his sample.

L_{eq} meters are very convenient to use. When measuring cyclical machines or traffic noise the operator usually waits until L_{eq} converges to a steady value and then takes a reading. There is no need to time the measurement unless required to do so, e.g., measure more than five machine cycles or measure hourly L_{eq}.

NOISE DOSIMETERS

Noise dosimeters [6] are special purpose L_{eq} meters that read out in percentage of maximum allowable noise exposure over an eight-hour period. Most dosimeters are used in industrial hygiene programs to determine hearing damage risk due to many years of noisy work conditions. Some are used to rate vehicles and machines for noise exposure at the operator work station.

The OSHA law requires characterization of varying noise environments by a single-number descriptor. The environment may be that experienced by a mobile employee whose work takes him into many different factory areas, or it may be a fixed work area where intermittent machine operations produce unpredictable variations in noise level. OSHA specifies a maximum daily noise (D) of unity:

$$D = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{C_n}{T_n}$$

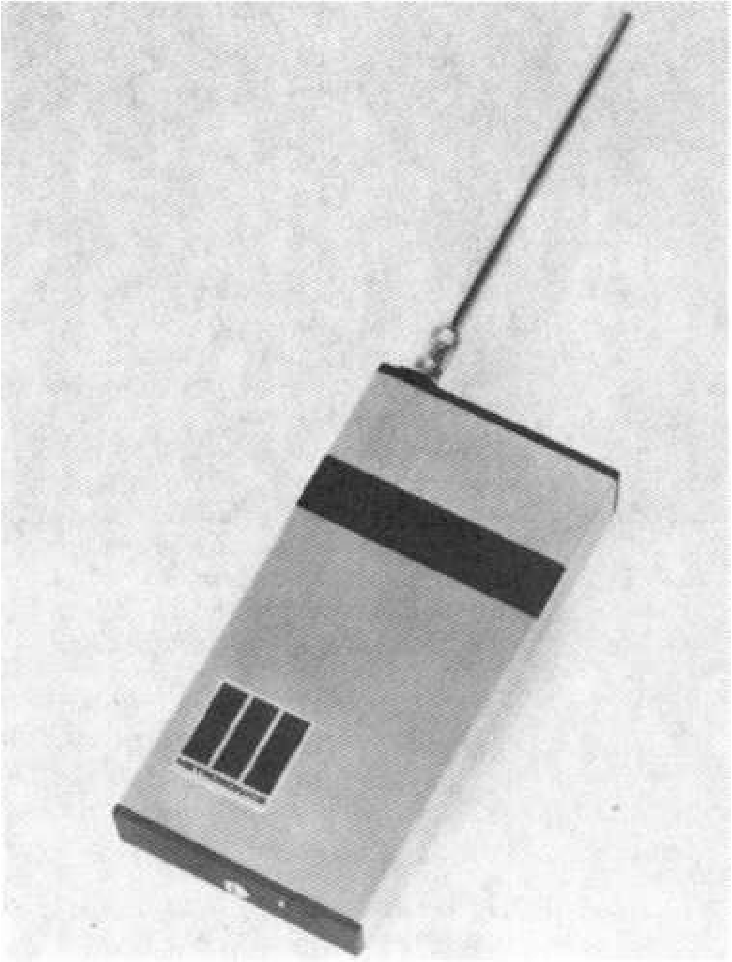


Figure 15. A hand-held L_{eq} meter for measuring L_{eq}, L_{max} and dBA level.

where C = the total exposure at a given steady dBA level
T = the maximum allowable exposure time at that level during an eight-hour workday

The relationship between dBA level and allowable duration of exposure is shown in Figure 16.

The graph shows that the maximum steady exposure level is 90 dBA for 8 hours, 95 dBA for 4 hours, 100 dBA for 2 hours, etc. The rest of the workday must be spent in a quiet area below the OSHA threshold of

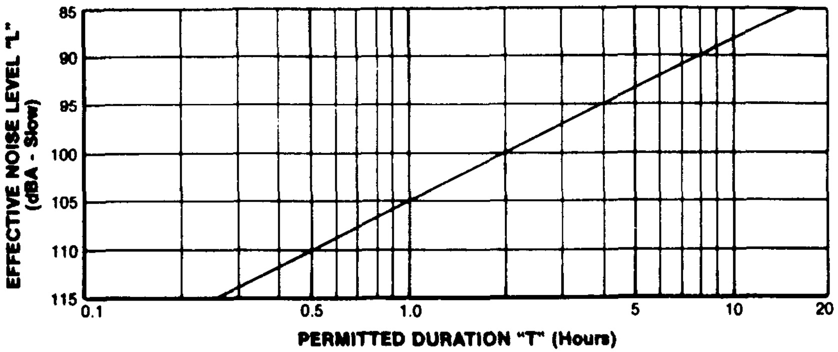


Figure 16. OSHA table of dBA level versus allowable exposure time.

90 dBA. This halving of exposure time for each 5 dB increase in noise level is called a 5 dB trading ratio or exchange ratio. The ISO trading ratio is 3 dB, i.e., 90 dBA limit for 8 hours, 93 dBA for 4 hours, 96 dBA for 2 hours, etc.

Noise dose can be predicted for mobile workers by studying their movements and estimating the total time they are exposed to each different level. In a similar manner, the exposure of stationary workers can be predicted based on the duration of various machine operations. Alternatively, dosimeters can be worn by the employee to obtain a direct measure of noise dose.

Most dosimeters convert dBA level to frequency in accordance with the appropriate trading ratio and accumulate frequency count on a counter that reads out in percentage noise exposure. The readings can be converted to L_{eq} if the trading ratio is 3 dB, or L_{OSHA} if 5 dB, but percent exposure is often a better descriptor for communicating with company management.

Dosimeters and L_{eq} meters yield the same information. Dosimeters preceded L_{eq} meters and use less sophisticated circuitry. Dosimeters are restricted to 8-hour measurements. For shorter periods, the measurement time must be timed accurately and the data corrected for the shorter observation period. L_{eq} meters use microcomputer circuits and are direct-reading, regardless of the measurement period. This is especially advantageous when evaluating cyclical machine noise.

FREQUENCY ANALYZERS

Sound level meters are used to rate the noise emission of products and to evaluate hearing damage risk and annoyance potential of environments. As such, they are go, no-go monitors. They give little insight to the person responsible for reducing noise levels. He must know the frequency content of the sound to design a barrier or enclosure, or to quiet a noise source.

Portable Analyzers

Precision sound meters with octave or one-third octave hand filters are used to analyze environmental noise. The operator manually steps the filter and plots the data one band at a time. The filters separate the frequency spectrum into a series of bandwidths to determine the dominant frequencies in the noise source. Filter characteristics are controlled by ANSI S1.11-1966. Table II lists the center frequencies and the passbands of octave and one-third octave filters. Octave filters are quite broad, particularly at middle and upper frequencies, yet they yield sufficient data for selecting acoustic materials because sound-absorbing and -isolating materials used in enclosures and barriers have rather smooth acoustical response curves. The sound meter shown in Figure 13 has integral octave filters.

For more detailed frequency analysis, one-third octave filters are used. Although they produce only a threefold increase in the number of analysis bands, they are able to reveal pure tones, which dominate a noise source. In some states it is unlawful to generate noise with outstanding pure tone components at plant boundaries. Noise codes in these states specify use of one-third octave filters to determine presence of outstanding pure tones. Figures 14–16 show, respectively, a typical acoustic calibrator for field use, a hand-held L_{eq} meter for measuring L_{eq}, L_{max} and dBA level; and an OSHA table of dBA level versus allowable exposure time.

Historically, sound level meters have been designed so that frequency analysis can be performed only when the meter is in its flat frequency response mode. This prevented analysis of A-weighted signals. But today it is standard practice to series-connect the A-weighting and octave filters to directly and reliably identify the dominant frequency bands in A-weighted spectra. A typical A-weighted analysis is shown in Figure 17.

Laboratory Analyzers

Most laboratory analyzers on the market today are real time devices of either the one-third octave or narrow band type. Some narrow band analyzers have optional computational capabilities for one-third octave analysis. The two types of analyzers often are considered to be competitive in the marketplace. This is unfortunate because they actually complement each other. Most laboratories use both types, although for new facilities it is frequently necessary to consider seriously which should be acquired first.

Table II. Third-Octave and Octave Passbands

Band Number	Nominal Center Frequency (Hz)	Third-Octave Passband (Hz)	Octave Passband (Hz)
1	1.25	1.12-1.41	
2	1.6	1.41-1.78	
3	2	1.78-2.24	1.41-2.82
4	2.5	2.24-2.82	
5	3.15	2.82-3.55	
6	4	3.55-4.47	2.82-5.62
7	5	4.47-5.62	
8	6.3	5.62-7.08	
9	8	7.08-8.91	5.62-11.2
10	10	8.91-11.2	
11	12.5	11.2-14.1	
12	16	14.1-17.8	11.2-22.4
13	20	17.8-22.4	
14	25	22.4-28.2	
15	31.5	28.2-35.5	22.4-44.7
16	40	35.5-44.7	
17	50	44.7-56.2	
18	63	56.2-70.8	44.7-89.1
19	80	70.8-89.1	
20	100	89.1-112	
21	125	112-141	89.1-178
22	160	141-178	
23	200	178-224	
24	250	224-282	178-355
25	315	282-355	
26	400	355-447	
27	500	447-562	355-708
28	630	562-708	
29	800	708-891	
30	1,000	891-1,120	708-1,410
31	1,250	1,120-1,410	
32	1,600	1,410-1,780	
33	2,000	1,780-2,240	1,410-2,820
34	2,500	2,240-2,820	
35	3,150	2,820-3,550	
36	4,000	3,550-4,470	2,820-5,620
37	5,000	4,470-5,620	
38	6,300	5,620-7,080	
39	8,000	7,080-8,910	5,620-11,200
40	10,000	8,910-11,200	
41	12,500	11,200-14,100	
42	16,000	14,100-17,800	11,200-22,400
43	20,000	17,800-22,400	

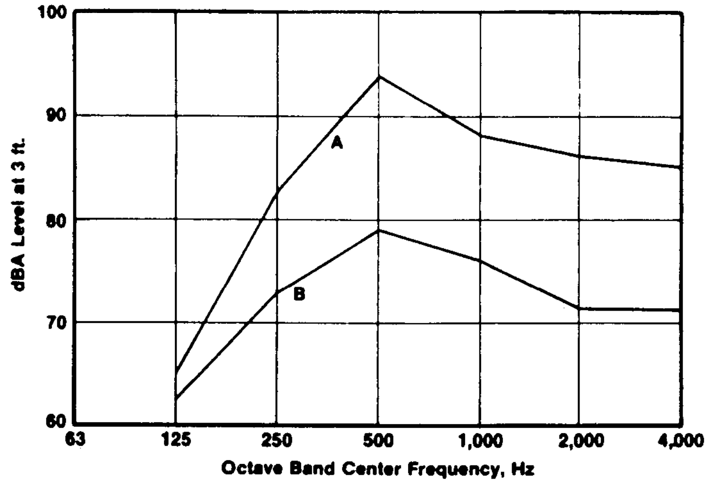


Figure 17. Octave analysis of noise level 3 ft from an enclosed electric motor. Design A is a standard enclosure; design B is lined with sound-absorbing material.

One-third octave analyzers are more versatile for general laboratory use. They are widely used for data editing. Because they divide the audio spectrum into a practical number of frequency bands (30 per decade), which can be observed in real time, it is easy to identify the dominant band (or bands) that must be reduced. Changes with time also can be studied. A typical one-third octave analyzer and its spectrum display are shown in Figure 18. To the project engineer who knows from prior mechanical analysis or experience the probable noise sources in a product, identification of the dominant band is often sufficient to reveal the noise-generating mechanism. One-third octave filters are also used in computing sound power and effective perceived noise level (EPNdB).

One-third octave filters offer the distinct convenience that the spectral analysis can easily be documented in tabular form. Because the band levels can be readily summed by proper decibel addition to obtain the overall level, it is a simple matter to develop a design spectrum that will meet a specific noise limit before performing any rework on a product.

Narrow band analyzers, such as the one shown in Figure 19, are used to supplement one-third octave analyzers when several potentially troublesome frequencies exist in a given one-third octave band or where it is necessary to distinguish between two closely spaced frequencies. These FFT (Fast Fourier Transform) analyzers [7] typically divide a selected frequency range into

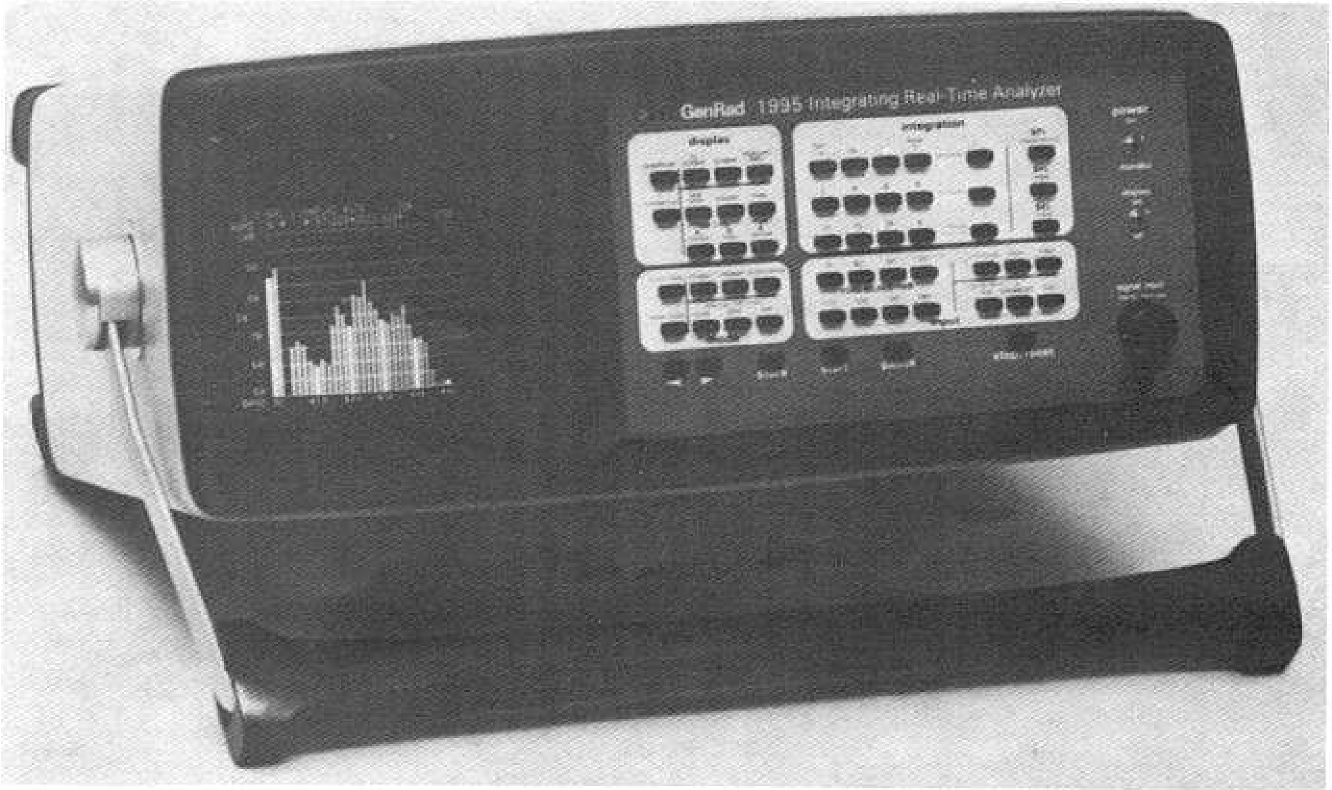


Figure 18. Real-time, one-third octave analyzer showing a typical spectrum.

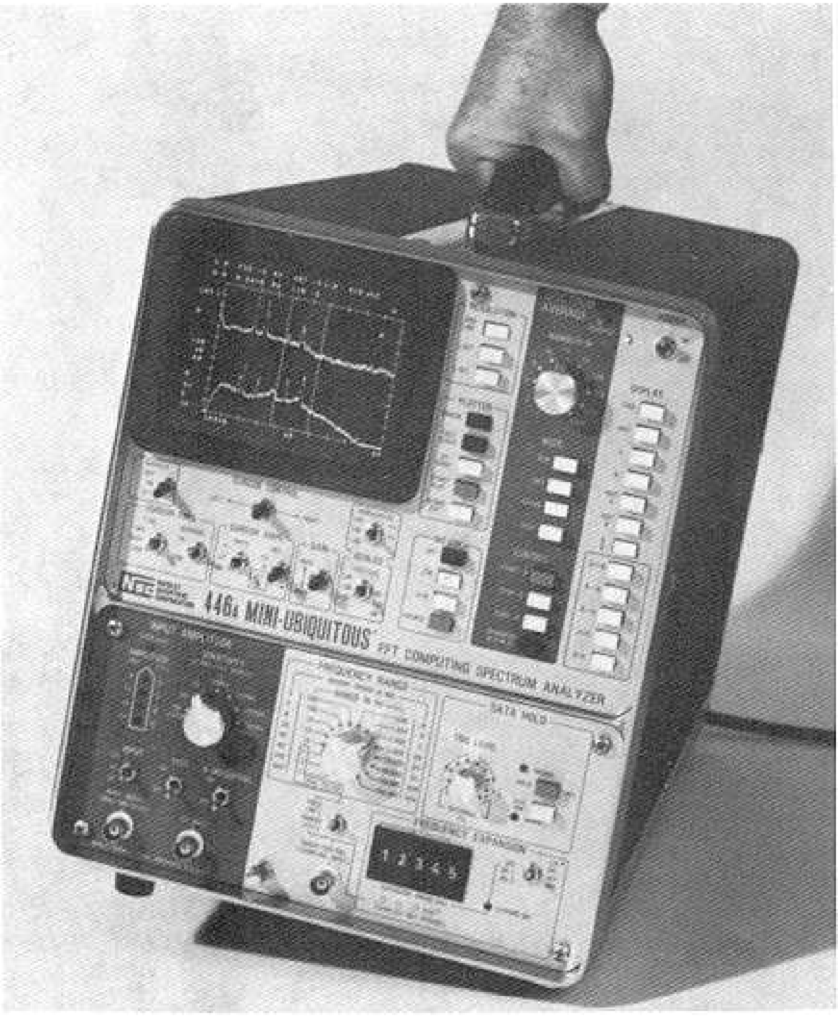


Figure 19. Narrow band real-time analyzer.

400 frequency bands of equal bandwidth, e.g. 0–10 Hz in 0.025-Hz bandwidths up to 0–20 000 Hz in 50-Hz bandwidths. They also offer a convenient zoom feature that permits investigators to obtain extremely fine frequency detail by centering the analysis within a narrow range about a selected frequency.

Other features include the abilities to switch between a logarithmic amplitude display for acoustic signals and a linear display for vibration signals; to store two or more spectra for comparison to real time signals; and to isolate individual signal sources by subtracting out random background data.

Most narrow band analyzers have optional capabilities for one-third octave and octave analysis. They will not function in real time at high frequencies, typically above 10 kHz. This means that they will not process all of the incoming data at high frequencies, but this is not a problem with typical stationary signals.

AMPLITUDE DISTRIBUTION ANALYZERS

Amplitude distribution analyzers [5] statistically describe noise level variations over intervals of time, ranging typically from 1 to 24 hours. They supplement dosimeters in the manner that frequency analyzers supplement sound level meters. In addition, the statistical designators themselves often are used as enforcement and design criteria in the field of community noise control.

Amplitude distribution analyzers produce either an amplitude histogram or a cumulative probability distribution. In either case, the objective is to describe amplitude variations in a form more easily interpreted than that of a detailed chart record of amplitude history. Amplitude distribution analyzers are portable instruments that can be used in both industrial and field environments.

An amplitude histogram is shown in Figure 20. It shows the number of samples found in a series of amplitude intervals. The data also may be interpreted as the probability of the noise level occurring in each interval, or as the accumulated percentage of time that the signal level exists within each interval. Amplitude histograms can be very useful to the industrial noise control engineer. First, it should be pointed out that the data can be used with the OSHA criteria in Figure 16 to predict noise dose. Confronted with a noise control problem, the amplitude histogram can help identify the most economical solution. If noise occurs a high percentage of the time just above the dosimeter threshold, simple maintenance or changes in material handling procedures may reduce these levels to below threshold and solve the exposure problem very economically. If exceedance is overwhelmingly caused by a noisy machine that operates intermittently, the histogram information can be used to determine the number of dB noise reduction required.

A cumulative probability distribution also is shown in Figure 20. It shows the probability of exceeding any dBA level. From it is derived L_N levels, the

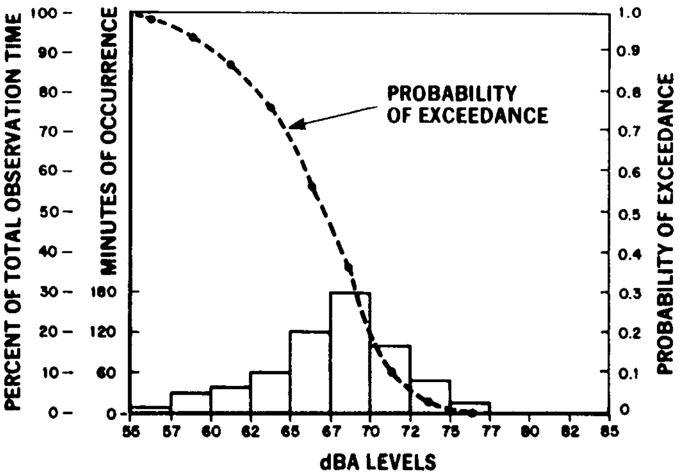


Figure 20. Histogram of community noise showing alternative graph of probability of exceedance.

dBA level exceeded N% of the time. For example, L_{10} is the dBA level exceeded 10% of the time, and L_{90} is the level exceeded 90% of the time. In community noise enforcement and environmental impact projections, L_{10} and L_{90} are used to indicate peak and residual noise levels.

It is common practice to report L_{eq}, L_{10} and L_{90} each hour to describe average noise level, as well as its short-term variability. High-level transient noise intrusions, such as aircraft flyovers, can be a greater annoyance than steady level noise. This is shown in the computation of noise pollution level, L_{NP}, where

$$L_{NP} = L_{eq} + (L_{10} - L_{90})$$

This designator, valid for gaussian dBA distribution, is used in Europe to rate community environments.

A designator used widely in the United States is L_{dn}, which is similar to a 24-hour L_{eq}, except that 10 dB is added to all levels measured between 10 PM and 7 AM, when people are least tolerant of noise. Therefore, L_{dn} includes some measure of annoyance.

Amplitude distribution analyzers are digital sampling instruments that use a series of storage registers to count dBA samples that occur in each of a series of amplitude intervals. The intervals are typically 1 dB wide and span a range of at least 80 dB and, preferably, 100 dB for 24-hour measurements. The analyzers use a microprocessor to retrieve and process data from the storage registers. The registers can be interrogated to read amplitude probability distribution, cumulative distribution, L_N, L_{eq} and L_{dn} at selected time intervals. Figure 21 shows a typical portable, battery-operated, amplitude distribution analyzer for community noise measurements.

Amplitude distribution analysis also may be applied to OSHA noise exposure surveys. Figure 22 shows a personal monitor that can be worn by industrial workers. It is programmed by a plug-in chip to digitally store either amplitude probability or amplitude history in typically one-minute L_{eq}. It is later interrogated by a reader instrument, which further processes the data and prints out the analysis on paper tape. It is used as a profiling dosimeter to study the nature of industrial noise exposure and as a digital, time-history recorder.

Airport noise monitors are another type of special-purpose amplitude distribution analyzer. They are designed to print the time history of aircraft flyover noise when the noise level exceeds a predetermined noise threshold. They also print hourly L_{eq}, L_{dn}, maximum level of noise events as well as special aircraft noise criteria such as CNEL (community noise exposure level) and SENEL (single-event noise exposure level).

RELATED VIBRATION MEASUREMENTS

Vibration is the source of many noise problems. A resonating mechanical component, improper gear mesh, unbalanced or misaligned rotating shafts, and dynamic mechanical forces transmitted to adjoining structures are typical examples of noise-generating mechanisms. To control such noise sources, the related vibration must be eliminated, suppressed or translated to a less bothersome frequency. Therefore, vibration measurements are closely associated with acoustical measurements in solving most noise problems.

Transducer Designs

Vibratory motion may be described by its displacement, its velocity or its acceleration. Displacement is measured when low frequencies dominate the vibration spectrum. Displacement is also measured when balancing rotating components. Velocity is used in condition monitoring to detect changes or trends in vibration level that indicate a need for machine maintenance. Acceleration is used to measure shock, as well as vibrations that span a wide frequency spectrum. Most vibrations encountered in noise control programs require acceleration measurements.

Transducers [8] are available for directly measuring displacement, velocity or acceleration. However, since all three parameters are related mathematically, the choice of transducer can be made independently from the

Figure 21. Long-term community noise analyzer.

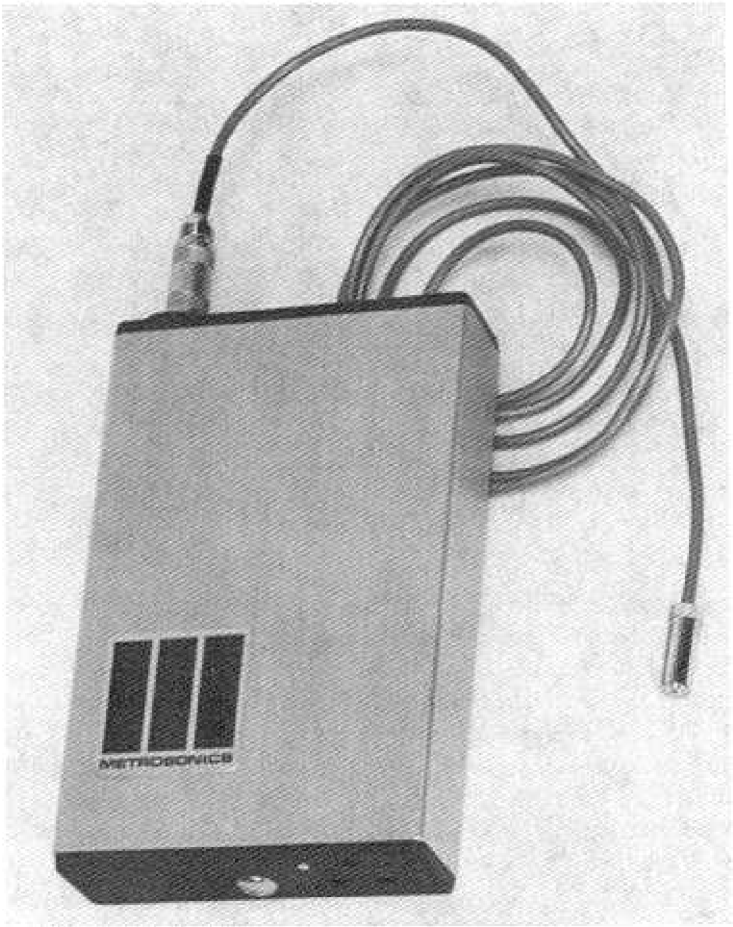


Figure 22. Personal noise monitor for storing amplitude distribution or time-history data.

parameter selected to be measured. For example, an accelerometer can be used with an appropriate amplifier to measure acceleration, velocity or displacement. Accelerometers are used for most measurements because of their light weight, wide frequency response, long life and ease of installation. And most accelerometers are of the self-generating piezoelectric design. A typical accelerometer is shown in Figure 23.

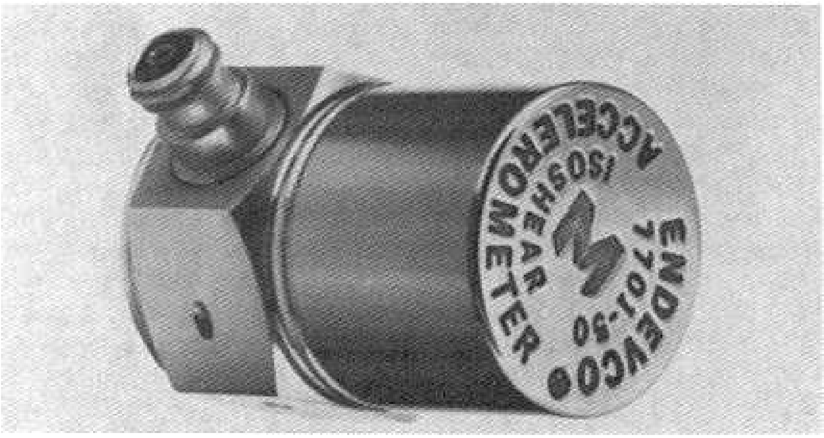
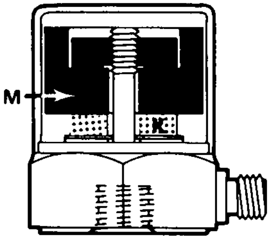


Figure 23. Typical piezoelectric accelerometer.

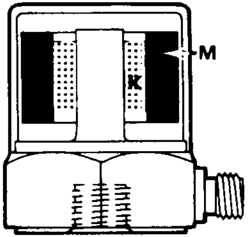
Piezoelectric accelerometers use a spring-mass system to generate a force proportional to the amplitude and frequency of vibration. The force is applied to a piezoelectric element, which produces a charge on its terminals that is proportional to the mechanical motion. The single-ended compression design, shown in Figure 24a, is used for general purpose work. It has a center post on which the mass, M, is torqued down to prestress the sensing element, K, which also serves as the spring. The annular shear design, Figure 24b, has its mass attached to the periphery of the sensing element to cause a shear force. Shear designs are used where the application requires miniature size, minimum weight or very high-frequency response. The low-profile shear design in Figure 24c has a center hole that enables it to be conveniently bolted to a structure or machine component. The ISOSHEAR design in Figure 24d uses a stack of flat plate sensing elements in the shear configuration, which are attached to the center post by a mounting bolt. This high sensitivity design has excellent insulation from nonvibration environments. Measurements can be made readily down to 0.1 Hz in environments of severe thermal transients, acoustic noise, or base bending conditions.

Performance Characteristics of Accelerometers

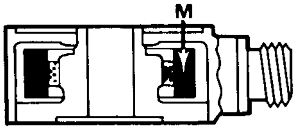
To obtain high-fidelity test data [9], the user must select carefully an accelerometer that will acquire the necessary data without affecting the vibration of the vibrating body and without being affected by the test environment. Many accelerometer designs are available, each intended to



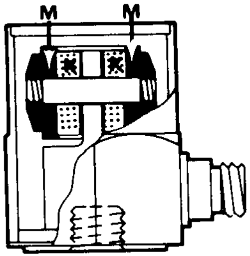
SEC design has a center post on which mass M is torqued down to pre-stress sensing element K which also acts as a spring.



Annular shear design has its mass attached to the periphery of the sensing element to cause a shear force.



Some annular shear designs feature convenient center-hole mounting.



ISOSHEAR design uses a stack of flat plate sensing elements attached to the center post by a mounting bolt.

Figure 24. Current accelerometer designs.

provide improved fidelity in particular applications. The most critical tradeoffs usually relate to sensitivity, weight and frequency response.

Sensitivity

The higher the sensitivity, the greater the system signal-to-noise ratio and the lower the susceptibility to electrostatic and electromagnetic noise pickup. But the higher the sensitivity for a specific design, the greater the weight and the lower the resonance frequency. Therefore, sensitivity selection may be limited by weight and frequency response constraints.

Mass Loading

Vibratory motion will be attenuated appreciably if the dynamic mass of the accelerometer approaches the dynamic mass of the specimen on which it is mounted. Too heavy an accelerometer will cause a reduction in vibration level. Therefore, lightweight accelerometers must be used on small printed circuit boards and thin panels to obtain accurate vibration data. If the test object exhibits a single-degree-of-freedom response, a heavy accelerometer will lower the resonance frequency and possibly cause a significant increase in vibration level. Therefore, miniature accelerometers are used in all resonance response testing.

Low-Frequency Response

Low-frequency response is determined by the amplifiers used with piezoelectric accelerometers. Low-frequency cutoff is usually 2–5 Hz. This protects against spurious output that may be caused by temperature transients or by sudden changes in operating temperature. Highly isolated designs can be used down to 0.1 Hz in severe environments. Piezoresistive accelerometers (not discussed here) are capable of dc response.

High-Frequency Response

Piezoelectric accelerometers are undamped systems. They exhibit a single-degree-of-freedom frequency response. A typical mounted response is shown in Figure 25. Miniature shock accelerometers have resonances as high as 250 kHz. To produce a uniform frequency response, the accelerometer must be attached securely to the test object by a steel stud, an adhesive or a mounting bolt in center-hole transducer designs.

Frequency response is flat ±5% up to about one-fifth of the mounted resonance frequency. The mounted resonance should always be used when specifying or evaluating accelerometers for system response characteristics.

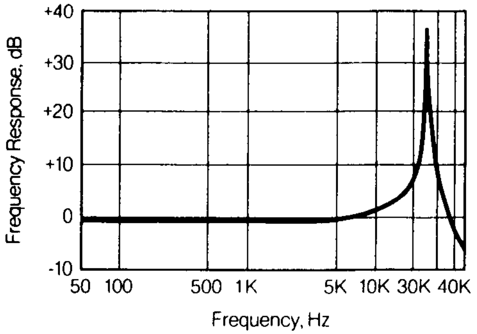


Figure 25. Mounted resonance response of a typical undamped accelerometer.

Do not be misled by the accelerometer's natural resonance. This is its resonance when freely suspended in air and is about 50% greater than the mounted resonance.

Signal Conditioners

Piezoelectric accelerometers are self-generating transducers. They do not require an external power supply and may be treated as either voltage or charge generators.

Accelerometer signals can be converted readily to velocity or displacement signals by the use of low-pass filters (commonly called integrating networks) built into the signal conditioner. These filters give the necessary $1/f$ or $1/f^2$ weighting to convert an acceleration signal to a velocity or displacement signal. They give the system flexibility to read out in displacement, velocity or acceleration.

Voltage Amplifiers

Treated as a voltage generator, the piezoelectric accelerometer's output signal can be connected directly to a very high-impedance preamplifier, or to a voltmeter, oscilloscope or sound level meter. Low-frequency cutoff is determined by the following formula:

$$f_{-3\mathrm{dB}} = \frac{1}{2\pi R_i(C_s + C_c)}$$

where R_i = the input impedance of the amplifier, ohms

C_s = the accelerometer capacitance, farads

C_c = the cable capacitance, farads (typically 190 pF/m)

With a 100-megohm input impedance, 100-pF accelerometer and short cable, frequency response will be uniform down to about 2 Hz. Higher-capacitance accelerometers are available for lower-impedance instruments.

Voltage amplifiers have wide dynamic range and rapid overload recovery. Their disadvantage is that system sensitivity is a function of cable length. This causes calibration uncertainty with long cable lengths unless the system is calibrated end to end. It also reduces the signal:noise ratio and thereby restricts low-level measurements.

Charge Amplifiers

Piezoelectric accelerometers are usually treated as charge generators, using charge amplifiers for signal conditioning. The advantage is that sensitivity is independent of cable length. Use of the dial-in sensitivity feature of most charge amplifiers produces a reliably calibrated system.

A charge amplifier, as shown schematically in Figure 26, is essentially an operational amplifier with integrating feedback. Output voltage is proportional to the charge generated by the transducer. Low-frequency response is determined by feedback capacitor, C_f, and dc stabilizing resistor, R_f. Caution should be taken on critical measurements to avoid overload because recovery will be at the low-frequency time constant of the amplifier.

Cabling and Grounding

Piezoelectric accelerometers are always connected to their signal conditioner by low-noise, coaxial cable. High-quality cables protect against tribo-

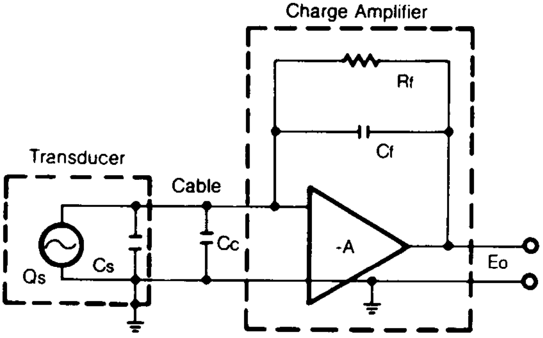


Figure 26. Equivalent circuit of a piezoelectric accelerometer, cable and charge amplifier.

electric noise induced when the cable flexes at very low frequencies. To further protect against triboelectric noise, cables are usually secured to the test specimen near their exit point from the accelerometer.

To avoid electromagnetic noise pickup, cables should never be run in the vicinity of power transformers or large motors. Further, they should not be run in bundles with current-carrying cables. If such environments are unavoidable, the charge amplifier should be located near the accelerometer or a remote charge converter used.

Ground loops occur when a current other than the vibration signal is introduced into the system. This happens easily when a system is grounded at more than one point. Most efficient grounding [10] usually is achieved when case-grounded accelerometers are insulated from the test object and grounded at the amplifier.

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5.

VIBRATION ANALYSIS AND INSTRUMENTATION

Paul O. L. Carlson
Electronic Dynamic Balancing Co.
Hillside, Illinois

Vibration analysis has been simplified greatly with the aid of new instrumentation. It is also much easier to use "vibration severity" velocity tolerances, which incorporate both displacement amplitude and frequency into one value. Comparison can be made quickly between similar or dissimilar equipment operating at different rpm. Interpretation of the vibration readings based on rotational speed and multiple harmonics also is more straightforward.

Modern rotating machinery tends to be operating at higher speeds, and maintenance costs and lost production have increased significantly during the past decade. As all costs spiral upward, there is a greater requirement for more careful surveillance of all machinery vibration characteristics. Interest in a simplified approach to vibration analysis is expressed in all industries and areas of design, manufacturing, production and maintenance.

INSTRUMENTATION

In general, the days have passed when the water-filled glass or the readily available buffalo head nickel were used to evaluate vibration amplitude. Instrumentation is now available to provide values that can be read, recorded and understood with meaning. New instrumentation is now easy to use, extremely reliable and does not require subjective interpretation. The instruments used should provide broad band (unfiltered) readings of velocity in inches per second, peak and/or readings that are filtered at discrete frequencies.

VIBRATION METERS

The simplest meters are low in cost, and any operator can be instructed to set the switch to read velocity. Figure 1 shows a typical vibration meter. A convenient carry strap and velocity probe with a strong magnet eliminate the need for the probe to be hand held. All new instruments use rechargable ni-cad batteries. For comparative readings, the pickup must be placed in the same location. Any change in lateral or angular position will produce different readings, which will lead to inaccurate results.

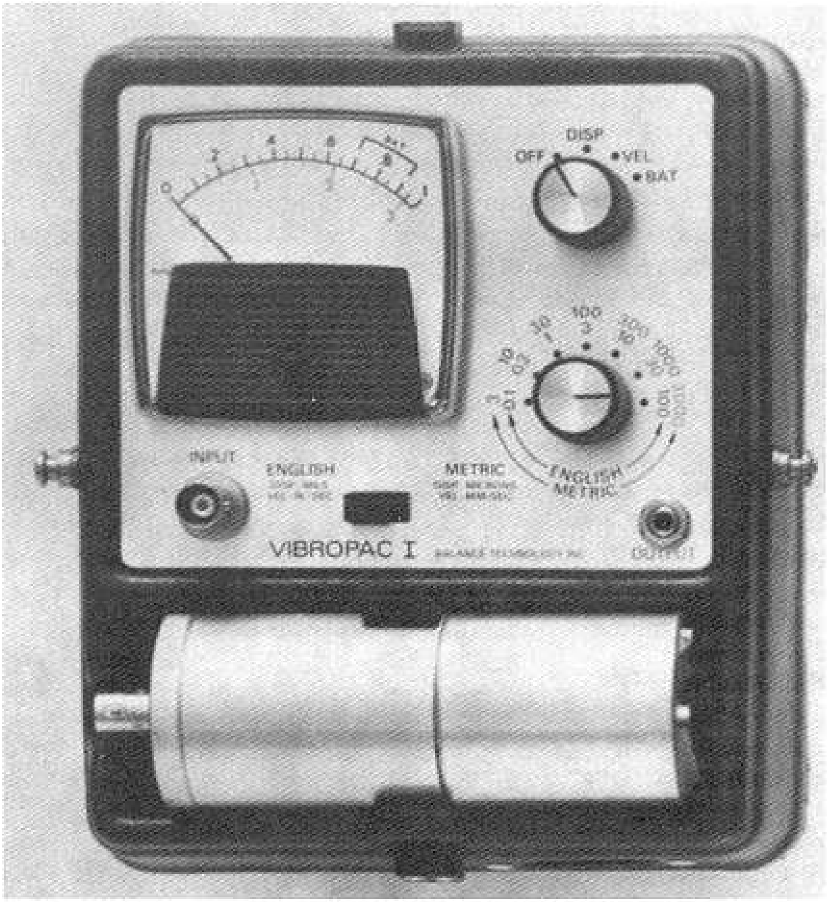

Figure 1. A simple, inexpensive vibration meter that reads broad band (unfiltered) velocity and/or displacement.

The 1.0 in./sec full-scale switch position will be appropriate for more than 90% of the readings taken on the majority of rotating machinery. At time of startup of new or rebuilt equipment, the readings can be taken for the purpose of comparison to the standards set up for that equipment.

Figure 2 shows a bar chart of comparative velocity readings using a simple broad band vibration meter. However, a simple vibration meter is limited to the readings that are broad band and, therefore, is not of great value to "analyze" vibration. Any dominant frequency can be determined by using the following relationship:

$$\text{cpm} = \frac{19{,}120 \times V}{D}$$

where cpm = frequency, cpm
V = velocity, peak, in./sec
D = displacement, mils

EXAMPLE: V = 0.25 in./sec, peak
D = 2.73 mils, peak to peak

$$\text{cpm} = \frac{19{,}120 \times 0.25}{2.73}$$

$$\text{cpm} = 1750 \text{ cpm}$$

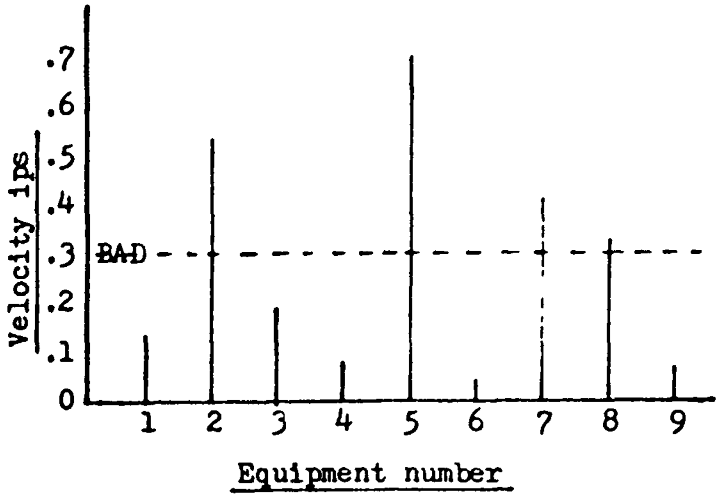

Figure 2. Comparison of velocity readings using a simple vibration meter.

The above frequency is important to know to evaluate the vibration source from imbalance, misalignment, etc. This may or may not be determined accurately with a simple vibration meter. Therefore, for greater ease and accuracy in determining the vibration frequencies, it is necessary to use a vibration analyzer.

VIBRATION ANALYZERS

A tunable filter is required to analyze vibration. The basic analysis involves reading the broad band amplitude and then determining the various discrete frequencies present in the machine. For instance, an electric motor could have vibration from imbalance, bad bearings, looseness and an electrical problem. A fan could have vibration from imbalance, bad bearings, looseness, misalignment and bad belts, as well as aerodynamically induced vibration. To determine the source of vibration, the frequency must be determined with a vibration analyzer. Figure 3 shows a typical analyzer that has a tunable filter and reads both velocity and displacement. Manual tuning of the filter is the means of obtaining the data for analysis. Table I shows a typical analysis of a 1500-rpm fan driven by a 1750-rpm motor. The broad band (unfiltered) reading in the above example was 0.416 in./sec. Mathematically, this is expressed as follows:

$$V_{bb} = \sqrt{(V_1)^2 + (V_2)^2 + (V_3)^2 + \ldots (V_n)^2}$$

where V_{bb} = broad band (unfiltered)
V_1 = first-filtered amplitude
V_2 = second-filtered amplitude
V_3 = third-filtered amplitude

EXAMPLE: $V_1 = 0.4$ in./sec
$V_2 = 0.1$ in./sec
$V_3 = 0.06$ in./sec

$$V_{bb} = \sqrt{(0.4)^2 + (0.1)^2 + (0.06)^2}$$

$$V_{bb} = 0.416 \text{ in./sec, peak}$$

The data in Table I are quite easy to obtain but do require time, patience, skill and an amount of training. It is also possible to overlook some frequencies that may be important to the proper analysis of any faults present in the equipment. Therefore, vibration signature analysis is becoming increasingly important as a means of gathering and providing a hard copy of the data obtained.

Figure 3. Typical vibration analyzer with manually tunable filter, commonly used in vibration analysis.

Table I. Typical Vibration Analysis Data for Motor- and Belt-Driven Fan

Vibration Frequency (cpm)	Amplitude (in./sec)	Probable Cause
1,500	0.4	Fan unbalance (bad)
1,750	0.1	Motor and sheave unbalance (good)
22,000	0.06	Antrifriction bearings (good)

VIBRATION SIGNATURE ANALYSIS

New developments in electronics in recent years have made possible a compact battery-powered instrument using integrated circuitry. Figure 4 shows a swept-frequency analyzer and x-y recorder built into one convenient, compact, lightweight, portable unit. The simplicity of operation is welcomed by field engineers, servicemen, technicians and consultants. By depressing one simple "Start" button, a complete process of analysis begins that requires only 60 seconds. This automatic analysis provides for a recording of frequency on the x-axis and amplitude on the y-axis. There are two scales for frequency and two scales for amplitude. Prior to the recording of the spectrum, the scales that have been selected, either manually or automatically, are marked automatically by the pen. In this way no mistakes are made. Colored pens are used to color code horizontal (red)

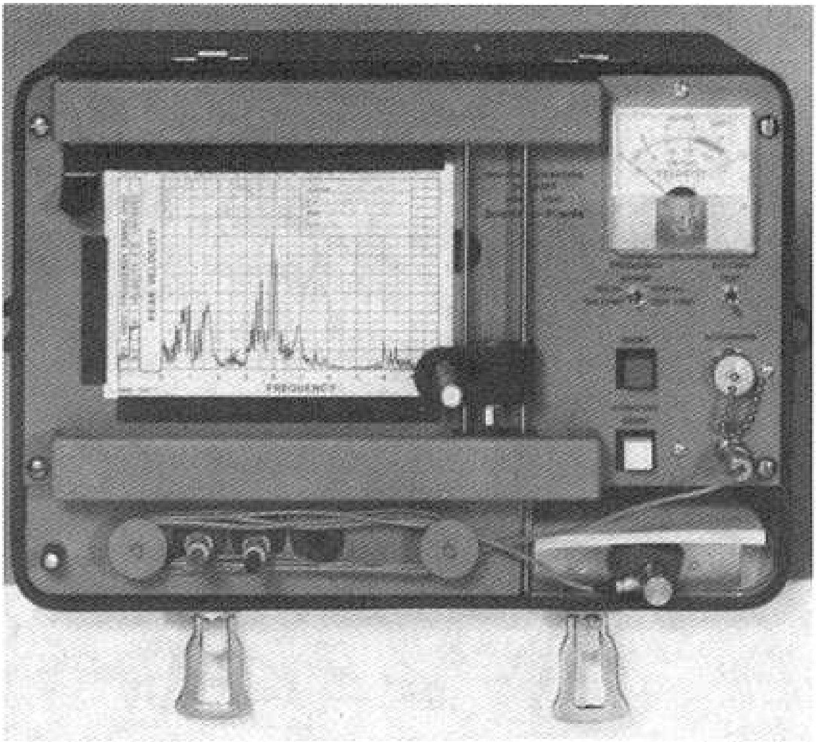

Figure 4. Automatically operated swept frequency analyzer with built in x-y recorder, which operates conveniently on nickel-cadmium (ni-cad) rechargable batteries.

and vertical (blue) readings and readings before (red) and after (green) corrective action. This type of instrument requires a minimum of training of plant personnel to obtain accurate, consistent data. Typical signatures for imbalance, misalignment and bad bearings are shown in Figures 5, 6 and 7.

DATA AT STARTUP

As mentioned earlier, data obtained at startup of either new or rebuilt equipment provide baseline information of vibration frequency and amplitude. Equipment that is within the warranty period and out of acceptable tolerances will incur minimum damage if shut down after a brief running time. Necessary corrections can be made in the most efficient manner and generally at minimum expense.

At a large Midwestern university, a 250-hp, 3600-rpm motor indicated a "bad" vibration of 0.3 ips; therefore, the motor was removed to a service shop for the necessary repairs. On reinstallation after repairs had been made, the vibration remained at 0.3 in./sec at 3600 cpm, indicating that the fault

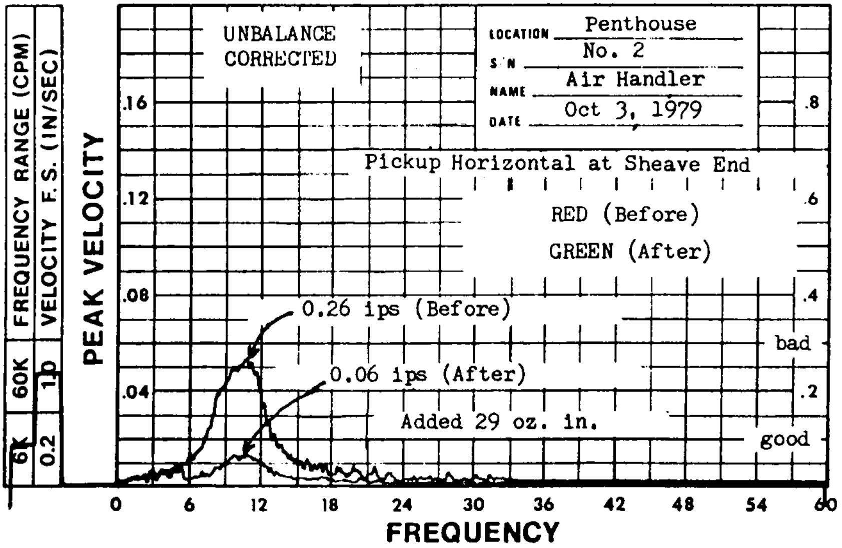

Figure 5. Signature showing vibration of 1100-rpm air handler before and after in-place balance correction.

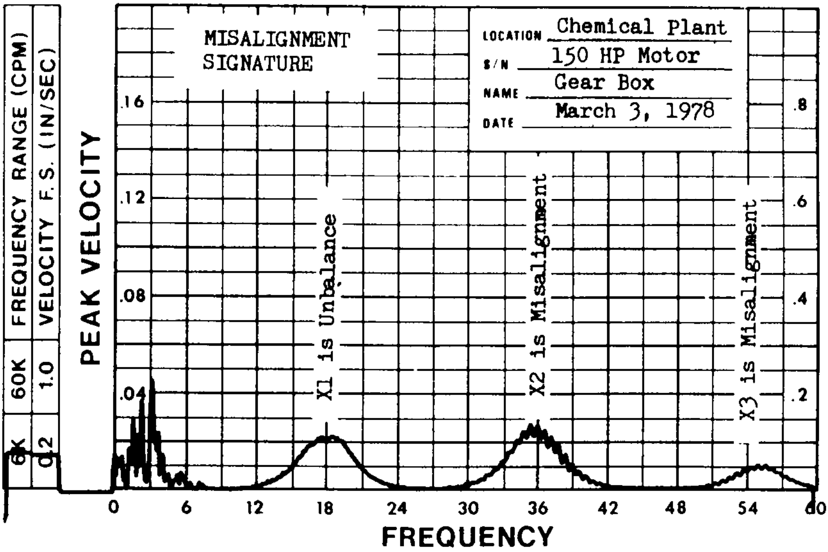

Figure 6. Signature analysis showing unbalance and misalignment in large motor direct coupled to gear box.

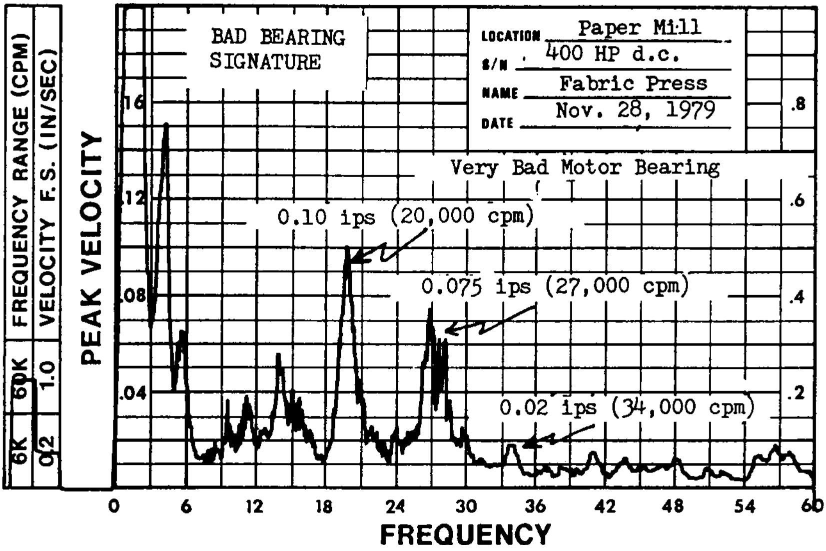

Figure 7. Bearing signature with high amplitudes at high frequencies indicating a bad bearing.

had not been corrected. The motor was returned to the shop and more careful analysis revealed the source of the problem. After a precision shop balance, the vibration was less than 0.05 in./sec, which was considered to be "very good." The vibration signature had indicated a X 1 rpm reading, which was interpreted as unbalance, and the final correction confirmed the basic analysis.

VIBRATION SEVERITY MEASURED IN VELOCITY

In the past, most vibration standards used displacement, in mils (peak to peak), based on the early investigation and writing by T. C. Rathbone of the Massachusetts Institute of Technology. However, displacement data also must include frequency for tolerances and comparative data to be meaningful. Blake [1] began to introduce new velocity vibration standards as early as 1964. Currently, International Organization for Standards (ISO) and American National Standards Institute (ANSI) standards are presented in terms of velocity, in./sec, peak or rms. This is much simpler since the velocity is the rate of change of displacement with respect to time and incorporates the frequency into data obtained.

Machinery is classified according to type (e.g., agricultural to aircraft) and application (e.g., motors used for precision grinders and those used for fans and pumps). Balancing tolerances are based on the type of equipment and the application. Buildings such as hospitals require equipment with lower vibration and noise levels. A general vibration severity guide for a large segment of equipment based on the published ISO and ANSI standards coupled with field data gathered over a long period of time would be as follows:

Simplified Vibration Velocity Severity Guidelines

0.1 in./sec	Good
0.2 in./sec	Fair
0.3 in./sec	Bad
0.5 in./sec	Very bad

NOTE: Bearing velocity tolerances are about 10–20% of the above and generally at frequencies above 8000 cpm, but also relate to severity of failure and the rpm of part.

STROBE LIGHT ANALYSIS

The strobe light used with a conventional portable balancer/analyzer (Figure 8) has the distinction of being able to literally "pinpoint" the source of vibration. With the vibration pickup in contact with the bearing

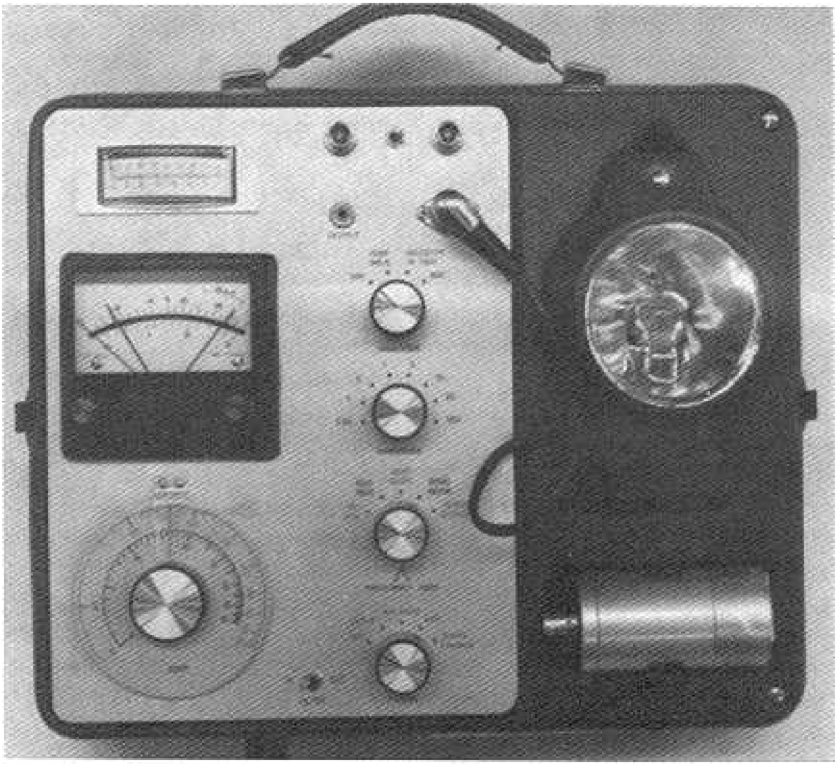

Figure 8. Complete portable balancer/analyzer with tunable filter, frequency and amplitude meters and strobe light, used to balance in-place without any disassembly.

housing, the tunable filter is tuned to the frequency that gives a maximum reading on the vibration meter. (This procedure is similar to tuning a vu meter on a stereo amplifier.)

When the above settings are made, the strobe is switched to the "balance" mode and the unbalance signal from the pickup causes the strobe light to flash at a steady rate corresponding to the frequency of the offending part. This will stop motion and "pinpoint" the unbalanced part. Necessary corrective balancing adjustments then can be made.

Case History

A large 36-in.-diameter, 2200-rpm fan was belt driven by a 150-hp, 1750-rpm motor. The vibration at the fan bearing was 0.8 in./sec and the analyzer frequency meter indicated 1750 cpm. With the strobe switched to "balance" and the strobe illuminating the motor shaft and sheave, the keyway in the motor shaft appeared "frozen." The strobe light revealed that a section of the outer groove of the six-groove sheave had been broken out previously when motor bearings had been replaced. This large imbalance had caused motor bearing and shaft failures to occur several times and at considerable expense.

THE "BIG FOUR" SOURCES OF VIBRATION

Imbalance is the source of vibration in 50–70% of the cases involving a vibration problem. This also causes noise, and the excessive centrifugal force leads to premature bearing failure. The simple centrifugal force formula is as follows:

$$F = 1.776 \times 10^{-6} \times \text{oz. in.} \times (\text{rpm})^2$$

where F = force, lb
oz. in. = imbalance amount
rpm = operating rpm of part

EXAMPLE: oz. in. = 2.0 oz. in.
rpm = 3600 rpm
$F = 1.776 \times 10^{-6} \times 2 \times (3600)^2$
F = 46 pounds of force

Misalignment in direct-drive systems occurs when alignment tolerances are not adhered to, coupling is eccentric, or the shaft is bent between the bearing and the coupling.

Looseness of various elements is a common occurrence. It is important to check all bolts and set screws for adequate torque and investigate to see whether there are cracks in either the rotating or stationary items of the equipment being analyzed. The shaft also must be of proper size at the bearing locating diameter or the signature may indicate looseness, which often is not easily detected.

Bad ball or roller bearings are another source of vibration. In the initial stages of failure, defective bearings have very low amplitudes in comparison to imbalance, misalignment and looseness, and the frequencies are very high. As a bearing deteriorates, the frequencies generally decrease to as low as X 1 rpm for a totally destroyed bearing or X 2 rpm indicating "looseness." A shaft worn undersized at the bearing locating diameter will indicate vibration frequencies similar to those from looseness. A chart to be used as a guide for bearing and shaft condition analysis is shown in Table II.

In this simplified approach, the ability to identify and correct the "big four" sources of vibration will yield a significant payback in machine

Table II. Chart for Analysis of Bearing and Shaft Condition[a,b]

Condition and Recommendations	Diagnosis
Races and balls are pitted, brinelled or spalled. Recommendation: replace bearing.	Use velocity only and observe high frequencies and low amplitude.
Shaft worn undersize at bearing diameter. Recommendation: new shaft, metalize or move bearing to new location.	Use dial indicator and raise the shaft with a pry bar: Slight wear–0.003 in., extreme wear–0.030 in. Signature analyzer indicates: ×1 as imbalance and ×2 as looseness or misalignment.
Locking collar is loose and inner bearing race is slipping on shaft. Recommendation: tighten collar and note any serious shaft wear.	Use strobe tuned to shaft rpm and observe shaft and bearing race.
Outer race loose in housing. Recommendation: rework motor end bell or bearing housing.	Use dial indicator and bar. Observe only 0.002–0.003 in. Vibration meter may oscillate.
Misaligned bearing outer races in pillow block bearing resulting in out-of-square condition. Recommendation: realign bearings.	Use square and gauge to check for squareness. Vibration may occur at ×2 rpm.
False brinelling caused by vibration when bearing is stationary. Recommendation: balance nearby equipment to precision tolerances.	Use vibration signature analyzer to determine amplitude and frequency at bearing of unit that is not operating.
Worn bearing, e.g., excessive looseness at bearing. Recommendation: replace bearing.	Use dial indicator and pry bar. Signature analysis may indicate ×1 and ×2 frequencies.

[a] Carefully follow standard procedures when installing new bearings.
[b] Detailed, informative booklets are available from most manufacturers of bearings.

and equipment "up-time." One also must be aware of other vibration sources including belts, gears, oil whip, electrical, hydraulic, aerodynamic, etc. A chart of common vibration sources with appropriate explanations is presented in Table III.

CONCLUSION

Analysis should not require a complicated procedure. Look for a simple problem on new or rebuilt equipment. There should be only one or two faults. On older equipment, analysis may point up several faults that need to be corrected. When information is gathered properly with new, simpler instruments, the data can be interpreted more easily, thus leading to correct solutions. The task of vibration analysis therefore will become much easier and simpler. Great benefits will be realized in longer equipment life and lowered operational cost.

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Maten, S. "Velocity Criteria for Machine Vibration," *Hydrocarbon Proc. Mag.* (January 1967).

Table III. Common Sources of Vibration Based on Equipment rpm and Harmonics

× 0.4–0.5	× 1	× 2	× 3	× 4	× N	3600 or 7200	Many ×
Oil Whip[a] or Oil Whirl	Imbalance[b]	Imbalance harmonic	Imbalance harmonic	Imbalance harmonic	Aerodynamic[c] rpm × No. of fan blades	Electrical[d] 1 or 2× synchronous or rpm × 1	Bad antifriction bearings[e]
Worn or Oversize Sleeve Bearing	Alignment	Alignment[f]	Alignment	Alignment			
	Eccentric adjustable motor sheave	Hydraulic[g] rpm × No. of vanes	Hydraulic rpm × No. of vanes	Hydraulic rpm × No. of vanes	Hydraulic multivane impeller		
	Failed bearing[b]	Looseness[h]	Looseness harmonic	Looseness harmonic	Gear teeth[i]		
	Bent shaft[b]	Bent shaft[j]			Belts[k]		
	Electrical[d]	Nearly failed bearing[h]					
		Reciprocating forces					

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[a] At 40–50% of rotational speed and occurring only in sleeve bearings.

[b] Vibration responds to weight change when cause is mass unbalance, eccentric part or eccentric bearing rate, bent shaft where part is mounted, improper key, wear, uneven buildup of dirt, etc. Generally 0.1 ips is good and 0.5 ips is very bad. Refer to specific ISO and ANSI standards.

[c] Aerodynamic frequencies of vibration are number of blades × rpm.

[d] Electrical vibration is caused by eccentric rotor, unbalanced winding, uneven air gap, loose rotor bar. Vibration drops instantly when power is turned off.

[e] Frequencies are generally over 8000 cpm, and amplitude is low compared to other faults. Must use velocity and not displacement. As a guide, 0.01 is good and 0.1 ips is very bad. Look for sideband frequencies.

[f] Misalignment frequencies relate to type of coupling and mounting, mostly × 2 rpm and/or × 3 rpm.

[g] Hydraulic frequencies of vibration are number of vanes × rpm.

[h] Looseness includes base, worn bearings, loose part on shaft, worn shaft at bearing, loose bolts, cracks, etc.

[i] Gear mesh frequency is number of teeth × rpm and amplitude may be low. Must use velocity.

[j] Bent shaft at coupling has frequency of × 2 rpm, similar to that indicated for misalignment. Use dial indicator to confirm condition.

[k] Use analyzer with strobe and tube to belt frequency. Belt cpm equals $\frac{\text{Motor rpm} \times \text{Pulley Diameter} \times 3.14.}{\text{Belt length}}$

6.

MEASUREMENT TECHNIQUES FOR SOUND LEVEL METERS

Charles E. Wilson

New Jersey Institute of Technology
Newark, New Jersey

Excess noise is one of our most pervasive problems. As noted by the U.S. Environmental Protection Agency (EPA) [1]:

> Sound, so vital a part of our existence, is growing to such disagreeable proportions within our environment that today it is a very real threat to our health. . . . Unless controlled, noise polution will exact an increasingly heavy toll on society. Already an estimated 16 million people in the United States suffer from some degree of hearing loss directly caused by noise.

NOISE LEVEL AND FREQUENCY

Sound may be characterized by its pressure level and frequency. The frequency range of the undamaged human ear extends from about 20 Hz to 20,000 Hz (20 kHz). The threshold of hearing corresponds to a sound pressure of about 20 μPa (20×10^{-6} N/m^2), or an intensity of 10^{-12} W/m^2. The threshold of pain corresponds to a sound pressure of about 200 Pa, or an intensity of 10^2 W/m^2.

To avoid use of this wide range of values, the intensity of a sound is given by its sound pressure level in decibels:

$$L = 10 \log_{10} \frac{p_{rms}^2}{p_{ref}^2} = 20 \log_{10} \frac{p_{rms}}{p_{ref}} \qquad (1)$$

where p_{rms} is the root mean square sound pressure and p_{ref} = 20 μPa. The sound intensity level in dB is given by

$$L_I = 10 \log_{10} \frac{I}{I_{ref}} \qquad (2)$$

For airborne sound at typical pressures and temperatures, sound pressure level and sound intensity level are approximately equal and may be used interchangeably. The relationship of sound pressure level in decibels, sound pressure and sound intensity is as follows:

Sound Pressure Level (dB)	Sound Pressure (Pa)	Sound Intensity (W/m²)
140	200	100
130	63.2	10
120	20	1
110	6.32	10^{-1}
100	2	10^{-2}
90	0.632	10^{-3}
80	0.2	10^{-4}
70	6.32×10^{-2}	10^{-5}
60	2×10^{-2}	10^{-6}
50	6.32×10^{-3}	10^{-7}
40	2×10^{-3}	10^{-8}
30	6.32×10^{-4}	10^{-9}
20	2×10^{-4}	10^{-10}
10	6.32×10^{-5}	10^{-11}
0	2×10^{-5}	10^{-12}

THE SOUND LEVEL METER

A basic sound level meter consists of a microphone, a calibrated attenuator, amplifiers, weighting networks and an indicating meter. An octave band filter set and other features also may be included.

Accuracy of the sound level meter depends largely on the microphone. A condenser microphone is generally preferred. It consists of a thin metal diaphragm and a back plate, charged by a dc polarization voltage. Variations in pressure (sound waves) impinging on the diaphragm are transformed into voltage variations, and the corresponding sound level in decibels is indicated on the meter. The diaphragm section is generally vented so that changes in atmospheric pressure do not affect the readings. The condenser microphone has reasonably high sensitivity, a flat frequency response within the range of interest and good long-term stability. However, it is sensitive to high humidity, and a special desiccator sometimes is used when the relative humidity exceeds 90%. Thus, humidity should be determined and recorded at the time of sound measurements. A sling psychrometer or other measuring device may be used.

Frequency Response

Variation in microphone response occurs when the wavelength of the sound is of the same order of magnitude as the microphone diameter. For a 25-mm (1-in.) microphone, some error in response may occur at frequencies above 1.5 or 2 kHz. A smaller microphone will have improved response at higher frequencies, but reduced sensitivity. For most noise surveys where broad band noise is present, the overall effect of microphone size will not be critical.

Meter Response

Most sound level meters incorporate fast and slow response settings. Although it is desirable for the sound level meter to follow variations in noise level closely, the needle may tend to fluctuate too rapidly for the observer when set for fast response. For this reason, slow response is commonly specified. Some meters incorporate a "hold" function and measure impulse as well.

Microphone Orientation

The manufacturer will generally specify preferred microphone orientation. For a perpendicular-incidence microphone, the microphone axis is pointed at the noise source to obtain best response. If the sound level meter is supplied with a random-incidence microphone, the microphone axis should not be pointed at the noise source but at an angle of 70° to 90° from the noise source (grazing incidence). For typical noise surveys, the overall effect of microphone orientation will not be critical. The observer may avoid interference in the sound field by holding the sound level meter away from his body.

The Effect of Wind

Wind produces a turbulent air stream about the microphone and is incorrectly sensed as sound. For outdoor measurements a wind screen should be used. At wind speeds greater than 24 kmh (15 mph), the effect may be great enough to make measurements invalid, even with a wind screen. Thus, unless the measurement involves a very loud noise source, it is best to reschedule measurements when wind speeds exceed 24 kmh.

WEIGHTING

Microphones are designed to respond equally (as far as possible) to all frequencies in the range of interest. While the human ear may respond to tones in the frequency range of 20 Hz to 20 kHz, the response is not the same at all frequencies. To be heard, the intensity of a low-frequency sound (near 20 Hz) must be greater than the intensity of a sound at 1 kHz. Conversely, a 1 kHz tone will sound louder than a 20-Hz tone if both have the same intensity in W/m^2. Weighting networks in the sound level meter simulate human hearing by reducing the meter response to low-frequency tones (near 20 Hz) and high-frequency tones (near 20 kHz).

A-, B- and C- weighting are three of the standardized adjustments that simulate human hearing response (approximately) at different sound levels. A-, B- and C- weighting networks are commonly available in sound level meters. At this time, however, A- weighting has found more acceptance than other weightings and B- weighting is hardly used at all. If A- weighting is to be used exclusively, it may be desirable to hold the weighting switch on the meter in position with tape to prevent errors. The weighting should be shown on the data sheet.

PRECISION

Specifications for sound level meters are given by the American National Standards Institute (ANSI) [2]. Type 1 (precision sound level meters) and type 2 (survey sound level meters) will be satisfactory for most uses. Measurement accuracy depends on noise frequency content and other variables, but type 1 meters will be accurate to roughly one dB and type 2 meters to roughly 2 dB under typical conditions. Given the wide variation in noise level with time and location encountered in field work, an error of one to two dB is generally acceptable.

CALIBRATION

Instrument calibration is crucial in noise measurement. Sound level meters are often supplied with an internal check of battery level and an internal electronic calibration check. An acoustical calibration is recommended as a test of the entire system. If an electronic acoustic calibrator is used producing a 1 kHz signal, the meter should read the specified sound level with the A-, B- or C-weighting. When checking A-weighting at other frequencies, the specified level must be corrected. The pistonphone (a mechanical acoustic calibrator) produces a 250-Hz signal. The A-weighted reading will then be 8.6 dB less than the specified pistonphone output.

HUMAN RESPONSE

Human response may be expressed in terms of annoyance and other subjective criteria. Response depends on the frequency content and the time patterns of the noise and differs widely among individuals. Table I gives average expected human response to a wide range of noise levels in A-weighted decibels.

DEFINING THE MEASUREMENT PROBLEM

Consider the case of a stationary receiver (e.g., a worker at a fixed job location) subject to noise of constant level due to a stationary noise source. Sound level in dBA may be measured in the vicinity of the worker's ear. If the level does not exceed 90 dBA, current Occupational Safety and Health Administration (OSHA) standards [3] will not be violated. However, it must be noted that the worker may be subject to hearing loss after long-term exposure, and standards are subject to review and change from time to time.

Most actual measurement problems will be more complicated than the example cited above. We may encounter moving noise sources and receivers, time-varying noise and poorly defined standards. Determining a measurement program then may be a most difficult task. We must first determine the goals and intent of the study, which may include worker hearing conservation, community noise reduction, elimination of speech interference or other criteria.

If the noise level varies with time, a statistical percent exceeded level may be used. In particular L_{10} (exceeded 10% of the time) or L_{50} (the median level, exceeded 50% of the time) are in use as well as L_{90} (exceeded 90% of the time, sometimes defined as background noise level). The equivalent noise level, L_{eq}, is an energy average. Equivalent noise level in dBA has been selected by EPA [4] as a criterion for hearing protection.

It is important that the time interval be specified. For example, the statistical percent exceeded level, L_{10}, may be determined for "worst hour" traffic as a criterion for highway location. OSHA [3] criteria are essentially based on an 8-hour workday. Equivalent sound level, L_{eq}, the criterion used by EPA to protect hearing, is based on an annual average. Day-night equivalent sound level, L_{dn}, requires measurements representative of one or more 24-hour periods, with nighttime noise (10 PM to 7 AM) weighted by adding 10 dBA to actual measured levels.

The preferred measurement location depends on the goal of the study. For worker hearing protection studies, the microphone generally will be placed near the ear of the worker. Community noise codes may specify that readings be taken at the property line of the receiving residential use.

Table I. Sound Levels and Human Response [1]

	Noise Level	Response	Hearing Effects	Conversational Relationships
Carrier Deck Jet Operation	140		Contribution to Hearing Impairment Begins	
		Painfully Loud		
	130	Limit Amplified Speech		
Jet Takeoff at 60 meters (200 ft)	120			
Discotheque Auto Horn at 1 meter (3 ft)	110	Maximum Vocal Effort		
Riveting Machine Jet Takeoff at 600 meters (2000 ft)	100			Shouting in Ear
Garbage Truck NY Subway Station Heavy Truck at 15 meters (50 ft)	90	Very Annoying Hearing Damage (8 hours)		Shouting at 0.6 meter (2 ft)
Pneumatic Drill at 15 meters (50 ft) Alarm Clock	80	Annoying		Very Loud Conversation at 0.6 meter
Freight Train at 15 meters (50 ft) Freeway Traffic at 15 meters (50 ft)	70	Telephone Use Difficult		Loud Conversation at 0.6 meter
		Intrusive		Loud Conversation at 1.2 meter (4 ft)
Air Conditioning Unit at 6 meters (20 ft)	60			
Light Auto Traffic at 30 meters (100 ft)	50	Quiet		Normal Conversation at 3.2 meters (12 ft)
Living Room Bedroom	40			
Library Soft Whisper at 5 m (15 ft)	30	Very Quiet		
Broadcasting Studio	20			
	10	Just Audible		
	0	Threshold of Hearing		

DETERMINATION OF PERCENT-EXCEEDED NOISE LEVELS

Statistical percent-exceeded noise levels may be obtained by using a statistical analyzer. Percent-exceeded levels also may be obtained by sampling noise using a simple sound level meter.

Suppose we wish to determine L_{10}, the level of noise that is exceeded 10% of the time during a one-hour period. Let the noise be generated by highway rush-hour traffic, which varies second-by-second but is stationary in a statistical sense over longer periods. That is, noise levels measured during any 5- or 10-minute period would be typical of the entire rush-hour period.

Sampling Procedure

The following sampling procedure may be used.

1. Select an appropriate location, calibrate the meter, and check humidity and wind velocity if applicable.
2. Measure noise level in dBA every 10 seconds for a total of 50 readings. Instantaneous values should be noted at time equal zero, 10 seconds, 20 seconds, etc., without regard to peak values that may occur between readings.
3. Record readings with checkmarks in the appropriate row of a data sheet similar to the sample in Table II.

Interpretation

If there are 50 readings, 5 will be greater than the 10% exceeded level, L_{10}. Thus, L_{10} falls between the 5th and 6th highest readings. Using Table II, with readings recorded to the nearest whole number, the 5th and 6th highest readings are both 73 dBA (circled on the sample data sheet). Thus, $L_{10} = 73$ dBA. Similarly, the median, L_{50}, falls between the 25th and 26th highest readings. For this set of data, $L_{50} = 70$ dBA. The 90% exceeded level falls between the 45th and 46th highest readings (68 and 67). Thus, we may estimate $L_{90} = 67.5$ dBA.

Confidence Limits

In some cases, noise levels may vary over a wide range, making it necessary to secure a large number of samples to obtain percent exceeded levels with reasonable precision. For 50 samples, the error limits to L_{10} are represented by the 1st and 10th highest readings. Using Table II, they are 74 ± 0.5 and 72 ± 0.5, respectively. Thus, L_{10} could fall between 71.5 and 74.5, and we may report, with 95% confidence, that $L_{10} = 73 \pm 1.5$ dBA. If 100 samples are taken, L_{10} falls between the 10th and 11th highest readings and the error limits are the 5th and 17th highest readings.

Table II. Data Sheet for Noise Sampling

Location ____________
Day _____ Date ________
Time: Begin ____ End ______
Calibration ____________

Wind ________ Precipitation ________
Temperature DB _____ WB ___ R.H. ____ %
Attached Location Map ____________
Comments ____________

Engineer/Technician ____________

Noise Level ±0.5 dBA	Occurrences (number of readings at each level)		Cumulative Occurrences
80			
79			
78			
77			
76			
75			
74	X X	2	2
73	X X X X X X X	7	9
72	X X X X X X X X X	9	18
71	X X X X	4	22
70	X X X X X X X X X X	10	32
69	X X X X X X X X	8	40
68	X X X X X	5	45
67	X X X X	4	49
66	X	1	50
65			
64			
63			
62			
61			
60			

DETERMINATION OF EQUIVALENT SOUND LEVEL

The equivalent sound level, L_{eq}, is the level which, if constant, would represent the same acoustical energy as the time-varying sound in question. That is, L_{eq} is the energy average sound level and is generally based on A-weighted measurements.

Since sound level is defined by

$$L = 10 \log_{10}(I/I_{ref}) \tag{3}$$

sound intensity (W/m^2) is given by

$$I = I_{ref}\, 10^{L/10} \tag{4}$$

Averaging the intensity over a time period, T, we obtain the equivalent sound level

$$L_{eq} = 10 \log_{10}\left[\frac{1}{T}\int_0^T 10^{L/10}\, dt\right] \tag{5}$$

L_{eq} may be measured with an integrating sound level meter or an integrating real time analyzer. Using an ordinary sound level meter, it is necessary to use a sampling procedure. The sampling procedure suggested above for determination of percent exceeded noise levels may be used for L_{eq} as well. For N readings we then have

$$L_{eq} = 10 \log_{10}\left[\frac{1}{N}\sum_{i=1}^{N} 10^{L_i/10}\right] \tag{6}$$

For example, with only 5 readings, say L = 70, 72, 75, 78 and 80 dBA, we obtain

$$L_{eq} = 10 \log_{10}\left[\frac{1}{5}\left(10^{7} + 10^{7.2} + 10^{7.5} + 10^{7.8} + 10^{8}\right)\right]$$

$$L_{eq} = 76.45 \text{ dBA}$$

This result can be obtained quickly using a calculator with antilog (10^x), memory and memory + functions. Note that the arithmetic average of the levels, 75 dBA, is not equal to L_{eq}.

As a second example, let us determine equivalent sound level, L_{eq}, for the data given in Table II.

Again, using Equation 6 we have

$$L_{eq} = 10 \log_{10}\left[\frac{1}{50}\left(2 \times 10^{7.4} + 7 \times 10^{7.3} + 9 \times 10^{7.2} + 4 \times 10^{7.1} + 10 \times 10^{7.0} + 8 \times 10^{6.9} + 5 \times 10^{6.8} + 4 \times 10^{6.7} + 1 \times 10^{6.6}\right)\right] = 70.8 \text{ dBA}$$

Of course, this is the equivalent sound level for the period over which the readings were taken (a period of about eight minutes using the procedure suggested). If the noise measurements represent highway traffic, which is steady for the rush-hour period, the value of L_{eq} obtained above would be valid for the entire rush-hour period.

LONG-TERM AVERAGE

Noise-induced hearing damage may occur when an individual is exposed to extremely high noise levels for a short period, e.g., artillery fire or an explosion. Hearing loss due to industrial noise, however, is likely to occur after years of exposure. Thus, to assess the risk of significant permanent hearing loss, or permanent threshold shifts (PTS), we may evaluate an individual worker's annual average noise exposure. Of course, it is not practical to make actual noise measurements for the entire period. Noise measurements taken during representative periods of greatest noise exposure may be combined with data obtained by interviewing the worker. The procedure is explained in the example that follows:

A group of workers in a certain metal products industry were known to have been exposed to high noise levels. Measurements of noise exposure were made using a sound level meter held at approximate ear level of the exposed workers. For a representative period of time, noise exposure was as follows:

Level dBA	% of Time
90	50
100	24
104	24
108	2

Using Equation 6, the equivalent sound level for the measurement period is given by

$$L_{eq} = 10 \log_{10}(0.5 \times 10^{9} + 0.24 \times 10^{10} + 0.24 \times 10^{10.4} + 0.02 \times 10^{10.8})$$

$$L_{eq} = 99.86 \text{ dBA}$$

Considering vacations and other absence from work, as well as the average overtime, it was determined that this pattern was typical for 2000 hours annually. For an average year of 8766 hours, if we assume low exposure levels during nonworking hours, the energy average equivalent sound level is again given by Equation 6:

$$L_{eq(24)} = 10 \log_{10} [(2000/8766)10^{9.986}]$$

$$L_{eq(24)} = 93.4 \text{ dBA}$$

The subscript 24 implies an average 24-hour day, but $L_{eq(24)}$ is actually based on a projected energy average over a full year made up of workdays and low exposure nonworkdays.

OSHA CRITERIA

Currently, OSHA [3] sets daily noise exposure limits of 90 dBA for 8 hours, 95 dBA for 4 hours, 100 dBA for 2 hours, etc., up to 115 dBA. These values are based on a different model and cannot be compared with L_{eq} values. Cumulative exposure is considered acceptable if

$$\sum_{\text{8-hr day}} C/T \leqslant 1 \tag{7}$$

where C is the exposure time at a given noise level and T is the allowable time at that level. Fitting the OSHA levels to an equation, we have

$$T = 8 \times 0.5^{(90-L)/5} \tag{8}$$

Using data from the example cited above and computing T from Equation 8, we have:

Level (dBA)	Percentage of 8-hr Day	C (hr/day)	T (hr/day)
90	50	4	8
100	24	1.92	2
104	24	1.92	1.149
108	2	0.16	0.5598

Comparing Equation 7, we find

$$\sum_{\text{(8 hr day)}} C/T = 4/8 + 1.92/2 + 1.92/1.149 + 0.16/0.5598 = 3.42$$

Thus, the exposure pattern cited is unacceptable.

It must be noted that the levels cited in this example are likely to cause substantial loss in hearing ability. The need for individual hearing protection and noise reduction measures is clearly indicated for this situation.

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7.

AUDIOMETRY

Elizabeth Wilson
Bergen Community College
Paramus, New Jersey

CHARACTERISTICS OF SOUND

In common usage, the word "sound" usually refers to audible, airborne sound within the range of human hearing. Sound is an important factor in communication and other aspects of human life, while excessive sound causes auditory damage. The ear can detect pressure variation in air, with frequencies ranging from very low tones at approximately 20 Hz to very high tones at approximately 20,000 Hz.

The Threshold of Hearing

The threshold of hearing, the weakest detectable sound, has a pressure variation of 20 μPa. A pressure variation of 20 μPa corresponds to a sound level of 0 dB. Even within the range of audible sounds, the threshold of hearing is frequency dependent, the middle range tones being easier to hear than the highest and lowest tones.

Sound Level

It is common practice to characterize sound by its frequency and its level where sound level, L, is given in dB according to the equation

$$L = 10 \log \frac{p_{rms}^2}{p_{ref}^2} \qquad (1)$$

where p_{rms} is the root mean square pressure, p_{ref} is the reference pressure of 20 μPa, and log refers to base 10 logarithm.

Sound intensity (in W/m^2) is proportional to sound pressure squared. Thus, from Equation 1 intensity is proportional to $10^{\Delta L/10}$, where ΔL is the change in sound level in dB. Consequently, a sound level increase of about 3 dB corresponds to a doubling of intensity, and an increase of 10 dB corresponds to an intensity 10 times as great. The human ear, however, does not respond in proportion to intensity. A change of 1 dB in sound level is barely detectable, while an increase of 10 dB in sound level seems, to the average person, like a doubling of loudness.

THE HUMAN EAR: PHYSIOLOGY

The ear processes sound waves by converting mechanical energy into electrical energy, a form that the brain can accept and interpret. The ear is divided into three major parts: the external ear, middle ear and inner ear. The important structures of the ear are shown schematically in Figure 1.

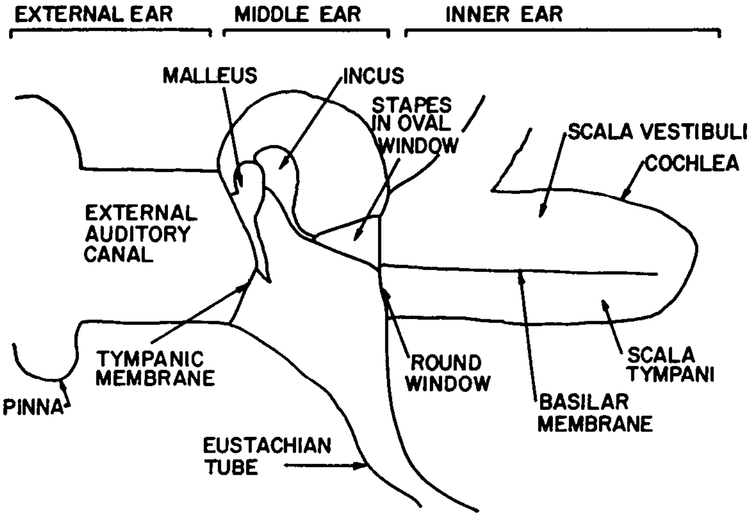

Figure 1. Simplified diagram of major parts of ear involved in hearing. Cochlea is actually a coiled tube, but is shown straight.

The Mechanical Phase of Hearing

The external ear consists of the pinna, or auricle, and the external auditory canal. The pinna is the outside structure usually referred to as "the ear." It has minimal function and is not essential to adequate hearing, although it may help in the location of sound source and acts to collect sound waves and direct them inward. The sound waves then are carried along the external auditory canal to strike the tympanic membrane, or eardrum, which separates the external and middle ear.

The middle ear is an irregular cavity in the temporal bone. Anteriorly, it communicates with the eustachian tube that provides a channel between the middle ear and the nasopharynx (postnasal space). This portion of the ear also contains three small bones and two openings to the inner ear, the oval and the round windows, both covered with membrane.

The alternate compression and decompression of the air adjacent to the tympanic membrane causes vibration, which is transmitted directly to the structures of the middle ear. The three articulating bones–malleus, incus and stapes–referred to as the ossicles, transmit the motion of the tympanic membrane. The malleus moves the incus. This, in turn, pushes the stapes against the oval window, which bulges into the inner ear causing movement of the fluid there.

The cochlea or hearing portion of the inner ear resembles a shell and is imbedded deep within the temporal bone. It is a membranous device formed of coiled tubes. These contiguous tubes are filled with fluid and separated by membranes. The fluid composition varies and is necessary for the correct function of the sound receptor cells, the hair cells. The basilar membrane, a strong fibrous structure, separates the scala media from another tube, the scala tympani. Located on the surface of the basilar membrane are the hair cells.

The stapes of the middle ear acts as a piston pushing the oval window inward and causing pressure waves in the fluid (endolymph) of the scala media and the fluid (perilymph) of the scala vestibuli (another of the coiled tubes of the cochlea). The pressure changes send waves along the basilar membrane and cause it to vibrate. Fluid in the scala tympani is then moved and pushes outward against the round window. This reciprocal inward and outward movement continues as sound waves stimulate the motion of the ossicles. High frequencies cause more vibration of the basilar membrane close to the oval window at the base of the cochlea, while low frequencies cause increased vibration at the apex. The cochlea analytically transforms mixed frequency sounds by vibrating at various points along the basilar membrane. Figure 2 is a diagrammatic representation of sound waves traveling along the basilar membrane.

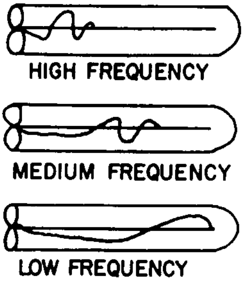

Figure 2. Diagrammatic representation of sound waves traveling along the basilar membrane [1].

Electrical Phase

Motion of the basilar membrane causes bending of the hair cells. Movement of the hairs excites the cells and generates impulses in the cochlear nerve endings, which encircle the hair cells. Electrical impulses are then transmitted through a series of lower auditory structures to the brain.

HEARING DISORDERS

Conductive Hearing Loss

Any interference of the mechanical phase of hearing is termed a conductive hearing loss. To prevent this, the middle ear transformer mechanism must be intact. This mechanism, involving the ossicles and tympanic membrane, overcomes the air-to-water impedence factor. The transfer of sound pressure from air (gaseous medium) to fluid (liquid medium) results in much energy loss. To overcome this physiological phenomenon, the tympanic membrane and ossicles collect the sound energy and transmit it directly to the fluid of the inner ear, preventing most of the energy loss.

Some Causes of Conductive Hearing Loss

External Ear Disorder. Any blockage of the external auditory canal due to foreign bodies, inflammation or accumulation of cerumen (waxy secretions) may lead to partial hearing loss. These conditions are treatable and reversible.

Middle Ear Fluid. Serous otitis media is an important cause of progressive and insidious hearing loss. It may be due to allergy or respiratory infection causing the presence of fluid in the middle ear. There are many other causes of middle ear inflammation that lead to fluid accumulation in the normally air-filled middle ear space. The fluid causes changes in the tympanic membrane diminishing its ability to function effectively. Treatment for these conditions may be medical or surgical, depending on the cause of the fluid accumulation.

Ossicle Disease. Congenital malformation, trauma or otosclerosis may cause immobility or diminished function of the bones of the middle ear. Otosclerosis-caused hearing loss may be corrected partially by hearing aids or improved considerably by microsurgery techniques. If allowed to progress, otosclerosis may lead to sensorineural loss also.

Eustachian Tube Blockage. There will be sensations of fullness and pressure in the ear along with diminished auditory acuity when the eustachian tube is blocked. Treatment is directed toward removing the underlying cause of the problem and is usually successful.

Sensorineural Hearing Loss

Since the electrical phase of hearing requires intact hair cells and nerve fibers, any damage to either that interferes with the production or transmission of the electrical response will impair hearing.

Some Causes of Sensorineural Hearing Loss

Noise Exposure. Exposure to excessive noise levels will damage the delicate hair cells. Impulsive noises, such as gunfire, appear to be particularly damaging. Early recognition and elimination of noise sources or the wearing of protective devices, such as those used in industrial settings, may prevent hearing loss. After subjection to loud noise, hearing loss may occur immediately and seem to resolve some time after exposure. This is deceiving, however, since some permanent loss is inevitable. Hearing aids may prove of some use to correct irreversible deficit; however, the noise trauma also causes a distortion phenomenon, which is not corrected by hearing aids.

Presbycusis. Hearing impairment experienced in old age is called presbycusis. Although degenerative changes contribute, much of the damage is thought to be due to repeated noise exposure and other ototoxic insults throughout life.

Congenital Factors. Complete absence of the inner ear is very rare, but may occur. Conditions during pregnancy, such as infections the mother may have, could result in damage to the inner ear of the developing fetus. In addition to damage caused by viruses and syphilis, the pregnant mother's use of ototoxic drugs also may be harmful.

Early detection of hearing loss in infants is extremely important so that early attempts at rehabilitation can be undertaken. Many hospitals are screening newborns with audiometers especially designed for infants.

Infections. Viral diseases such as mumps, measles and flu may lead to hair cell damage and hearing loss. Fortunately, this loss often involves only one ear.

Trauma. Injury such as severe blows to the head may also damage hair cells. Foreign bodies introduced into the external auditory canal, which are then manipulated inexpertly, may push the stapes into the inner ear and also damage the hearing structures.

Systemic Disease. Certain systemic diseases also may be responsible for hearing loss. Diabetes may damage blood vessels of the inner ear, interfering with circulation to the hearing apparatus. Paget's disease may compress the nerve fibers due to changes in bone structure. Either condition may produce sensorineural loss.

Ototoxic Drugs. Certain drugs have been found to be damaging to the ear by affecting the hair cells. Included in this group are streptomycin, kanamycin, neomycin, quinine and forosemide. At the first sign of tinnitus (ringing or other ear noises) the drug should be discontinued, since at this point damage may be reversible. Aspirin and other salicylates are also ototoxic to some degree. When aspirin is required for the treatment of arthritis, the permissible dose is determined by confining it to the amount that does not cause ringing in the ears.

ASSESSMENT OF HEARING IMPAIRMENT

Even though audiometers can be constructed with precision, the nature of hearing acuity measurement is such that results from successive tests on the same individual may vary by several decibels at a given frequency. Recent exposure to high noise levels is one cause of temporary threshold shifts (TTS). After a rest period away from the noise source, hearing ability may be recovered. Thus, it is desirable to schedule hearing tests at times other than after periods of high noise exposure, if only permanent threshold shifts (PTS) are to be measured.

Hearing Handicap

Hearing impairment traditionally has been looked on as inability to understand speech communication. One approximation that has been used to assess the ability to hear major speech components is the average of hearing levels at frequencies of 500, 1000 and 2000 Hz. Hearing handicap has been defined in terms of this average loss such that a 25 dB loss represents zero handicap, and each decibel of average loss above 25 dB represents 1.5% handicap.

Other hearing impairment criteria recognize the importance of higher frequencies. The average of hearing loss at 500-, 1000- and 3000-Hz frequencies is also used with the same (25 dB) lower limiting value. The U.S. Environmental Protection Agency (EPA) [2] notes that when damaged by noise, the human ear is typically affected by the 4000-Hz frequency first. Consequently, EPA's identification of maximum exposure levels is based on protection of up to the 96th percentile of the population against noise-induced permanent threshold shifts (NIPTS) exceeding 5 dB at 4000 Hz.

The American Council on Otolaryngology [3] has recently developed new criteria calling for referral of workers to a specialist for a possible hearing problem when audiograms show significant changes. The criteria involve changes of more than 15 dB at 500 or 1000 or 2000 Hz; more than 20 dB at 3000 Hz and more than 30 dB at 4000 or 6000 Hz. The elapsed time between audiograms used for comparison should not exceed two years, according to the criteria.

Other criteria suggesting referral include: (1) average hearing level greater than 55 dB at 3000 Hz, or greater than 30 dB at 500, 1000 or 2000 Hz; (2) a difference in average hearing level between the better and the poorer ear exceeding 15 dB at 500, 1000 and 2000 Hz, or more than 30 dB at 3000, 4000 and 6000 Hz; and (3) unusual or inconsistent audiometric responses.

AUTOMATIC RECORDING AUDIOMETERS

When it is necessary to screen a large number of personnel or to monitor a hearing conservation program, a recording audiometer is particularly useful. The recording audiometer permits rapid testing of air conduction hearing threshold levels at selected audiometric frequencies.

The automatic recording audiometer includes an audio oscillator with frequency and level control systems so that pure tone signals at several frequencies can be presented to the left ear, and then to the right ear via earphones. In automatic operation mode, the signals are controlled by the person being tested.

Typical Application

In a typical application (Figure 3), the subject sits in a sound-attenuating audiometric testing booth. A pure tone signal is presented at a sound level that increases at a rate of 5 or 10 dB/sec until the subject hears the signal and presses the handswitch button. The audiometer may be designed to reduce the rate of change in signal level once the hearing threshold is neared. The signal level then decreases until he releases the button. This sequence is repeated a few times at the same frequency to improve the validity of the results. The audiometer then switches to another pure tone frequency at which the sequence is repeated several times. The test continues until both ears have been tested at each set of frequencies. Each ear is tested at pure tone frequencies of 500, 1000, 2000, 4000, 6000 and 8000 Hz. The test duration is about 30 seconds for each frequency.

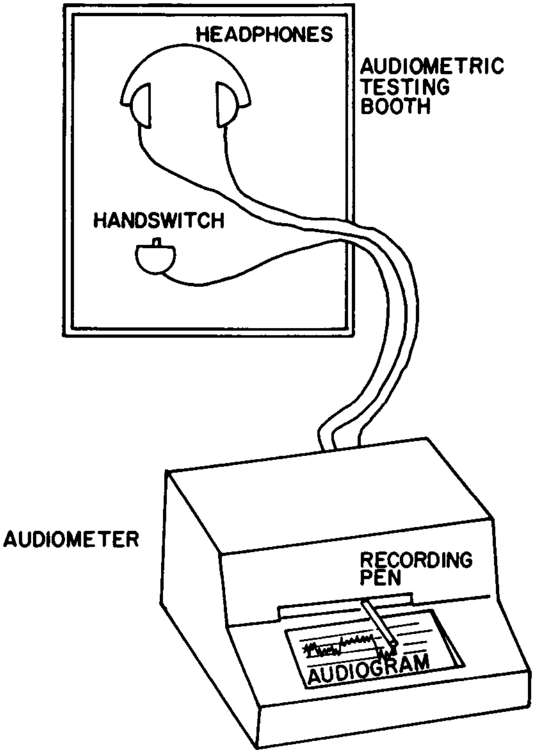

Figure 3. Typical audiometric test configuration.

A recording pen drive system is synchronized with the frequency and level control drive system so that the results are recorded automatically. The record of hearing threshold vs frequency is called an audiogram.

Routine Testing

Routine test results generally are not influenced by operator technique since the operator will not intervene once the test has begun. A 1000-Hz test signal may be presented to one ear at the beginning of the test sequence to familiarize the subject with the procedure. Since this tone is repeated, it serves as a partial indication of test validity. A subject who intentionally simulates hearing loss would be unlikely to give the same response when the 1000 Hz signal is repeated.

Instructing the Subject

If the subject is not already familiar with the type of audiometric test he is about to be given, he should be put at ease and instructed as follows:

> First your right ear and then your left ear will be tested with a series of musical tones. You will control the loudness with a handswitch. Press the handswitch if you hear or think you hear the tone. Release the switch when the tone fades away and you no longer hear the tone. Don't let the tone get too loud. Press the handswitch as soon as you hear it. Don't let the tone remain silent. Release the switch as soon as the tone is silent.

Typical Operator Options

The audiometer system may have the capability of producing both a steady tone and a pulsed tone (on 200 msec, off 200 msec) at the operator's discretion. In addition, the operator may choose to hold the test tone at a given frequency or change the frequency of test tones manually. These options could be used if the test were interrupted by extraneous noise or if there were doubt due to a wide spread of values at a given frequency. Furthermore, some subjects lack the ability to respond promptly to test tones by pressing and releasing the handswitch button. The operator may then change tones manually and mark the subject's response, which may be indicated by hand signals or some other type of signal.

A microphone may be incorporated into the system whereby the operator can communicate with the subject, with voice communication presented to the ear, which currently is not under test.

THE AUDIOGRAM

As noted above, each pure tone audiometric signal is presented several times in succession at varying levels. The level decreases when the button is depressed and increases when the button is released. The recording pen indicates the level of the signal at each test frequency by a zig-zag trace. Figure 4 shows a typical audiogram conforming with American National Standards Institute (ANSI) standard S 3.6-1969 [4] and International Organization for Standards (ISO) 389-1975 [5]. This audiogram was obtained using an automatic recording audiometer. It can be seen that the subject has near normal hearing at the lower frequencies, but some hearing loss at the middle and upper frequencies. The audiogram indicates about 40 dB of hearing loss at 8000 Hz in the right ear. Note that the 1000-Hz tone was presented as a pretest and again following the 500-Hz tone. The subject's response was similar in both cases, as it should be.

Figure 5 shows an audiogram recorded by the operator of a manual audiometer. The test is similar to that using automatic equipment except that the subject uses hand signals or presses a button to light a light when he hears the test tone. The operator has recorded the subject's response using an X for the left ear and a large dot for the right ear.

The Normal Threshold of Hearing

The audiometric zero or normal threshold of hearing is based on tests of a large number of young adults who showed no evidence of a defect in their hearing. In general, the sound pressure level at the normal threshold of hearing is different for each frequency. However, the audiometer is adjusted to compensate for this so that a subject whose hearing acuity corresponds to the standard will record a zero hearing level (threshold) at each frequency.

Determination of Hearing Threshold

A hearing level of 20 dB at a given frequency represents a threshold of hearing 20 dB higher than the standard. Assuming the subject had normal hearing at one time, he would now be said to have a 20 dB hearing loss at the given frequency. Negative readings imply a hearing acuity better than that of the population of young adults used to establish the "normal threshold of hearing."

The mean value of the audiogram excursions at each frequency is generally taken as the hearing threshold. However, some subjects may respond slowly and cause abnormally long excursions. This may be due to inexperience of the subject, in which case he is reinstructed and the test repeated. This problem also may be caused by extraneous noise interfering

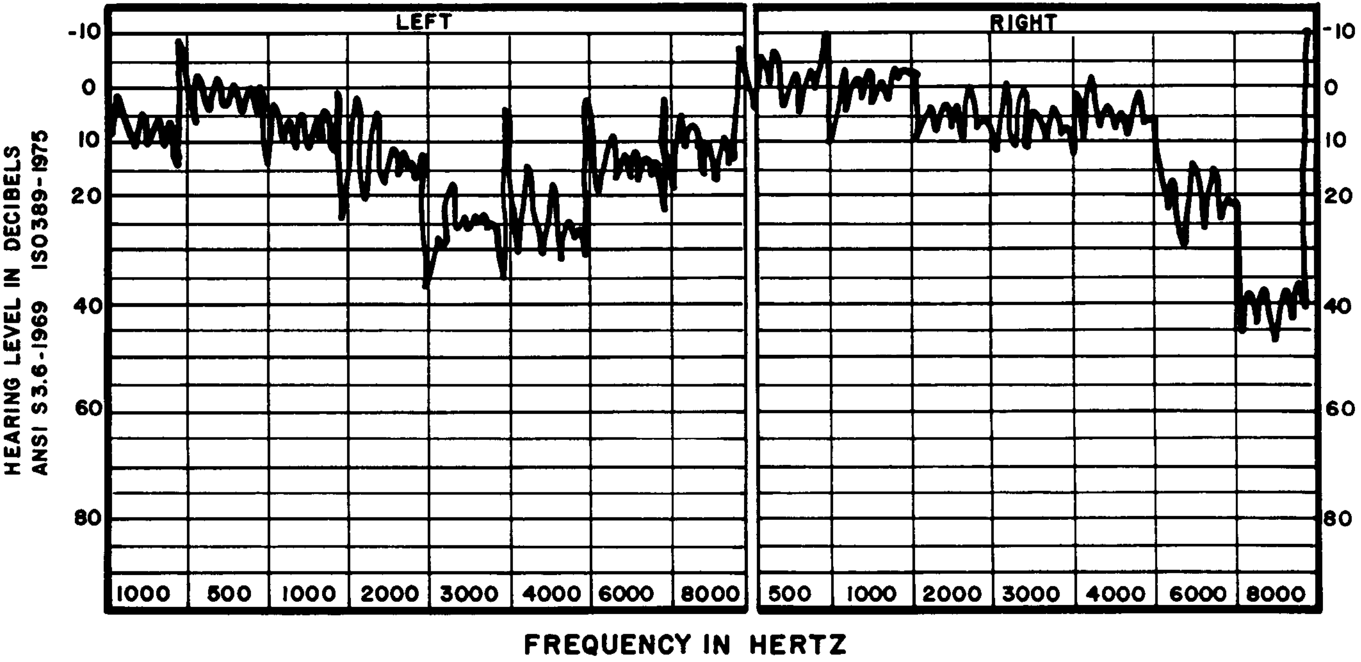

Figure 4. Typical audiogram recorded automatically.

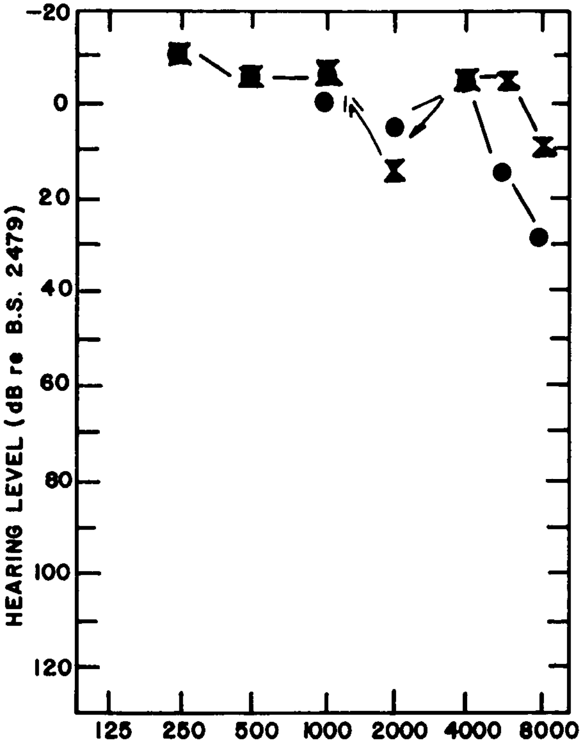

Figure 5. Audiogram recorded manually.

with the test. Since no audiometric booth can exclude all noise, it is desirable to maintain reasonable quiet near the facility. Exterior noise and poor fitting of earphones can cause an erroneous indication of hearing loss in both ears at low frequency (500 Hz).

AUDIOMETRIC BOOTHS

Audiometric testing could be performed by introducing a sound field of known intensity into a room and noting the subject's response. Instead, the usual practice, as described above, utilizes earphones with the subject in an audiometric booth. The typical booth is a sound shelter large enough for a seated subject. It includes a door, which may be opened from the inside or outside, a window between operator and subject, lighting, forced ventilation with intake and exhaust silencers and a jack panel for the earphones. The subject generally sits as not to face the operator.

Maximum allowable sound levels and desirable sound levels given by ANSI [6] are as follows for the interior of audiometric booths:

Test Frequency (Hz)	500	1000	2000	3000	4000	6000
Maximum Sound Level (dB) (octave band)	40	40	47	52	57	62
Desirable Sound Level (dB) (octave band)	30	29.5	34.5	39	42	41

Noise Reduction

To achieve desirable testing conditions, the booth must provide substantial noise reduction. Also, the location must be selected to minimize exterior noise. The audiometric booth may be evaluated by putting it in a sound field in a reverberant room. Noise reduction is the difference between sound levels measured inside and outside the booth. Typical values by two manufacturers for prefabricated booths are as follows:

Octave Band Center Frequency (Hz)	Noise Reduction, dB	
	Audiometric Booth 1	Audiometric Booth 2
125	18	Not reported
250	32	35
500	38	40
1000	44	44
2000	51	52
4000	52	53
8000	50	53

AUDIOMETER CALIBRATION

Both physiological and instrumented calibration checks of audiometers should be made periodically. Recent evidence of calibration assures test validity and may be necessary where claims of hearing loss are involved.

Physiological Calibration Check

An audiogram should be made of one or more individuals who are expected to be available in the future. These audiograms should be filed for future comparison. If a new audiogram for the same individual varies from the first by more than about 5 dB at any frequency it may indicate a need for audiometer recalibration. By listening to each test tone, an experienced individual (the operator, for example) may determine whether the instrument has maintained its frequency calibration.

Instrumented Calibration

Precise frequency calibration can be performed at each test tone by using a frequency counter. Level calibration generally requires a coupler or artificial ear to couple the earphone to a sound level meter. Reference equivalent threshold sound pressure levels are given by ISO [5] for each test frequency and depend on the pattern of the earphone and the type of artificial ear or coupler.

ABBREVIATIONS

ANSI = American National Standards Institute
dB = decibel (noise level)
Hz = hertz (cycles per second; frequency)
ISO = International Organization for Standards
log = base 10 logarithm
m = meter
NIPTS = noise-induced permanent threshold shifts
Pa, μPa = pascal, micropascal (pressure)
p_{ref} = reference pressure (20 μPa)
p_{rms} = root mean square sound pressure
PTS = permanent threshold shifts
TTS = temporary threshold shifts
W = watt

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8.

ANALYSIS OF VALVE AND PIPING NOISE

Lewis Aldridge
Leslie Co.
Parsippany, New Jersey

Piping system noise can be produced in many ways, some of which are cavitation, water hammer, mechanical vibration of valve trim and the noise of the fluid itself.

CAVITATION

Valve cavitation occurs when the pressure of a liquid momentarily is reduced below the vapor pressure. As the liquid passes through the valve orifice, it passes through a low-pressure region (Vena Contracta). If the Vena Contracta pressure is lower than the vapor pressure of the liquid, small vapor bubbles are formed. As the liquid leaves the Vena Contracta, some of the velocity head is converted to pressure. If this higher pressure is greater than the vapor pressure, the bubbles will collapse. The collapse of these bubbles causes extremely high local pressures, noise and possible mechanical damage. The noise created usually is described as being similar to "gravel going down a metal chute." Cavitation noise is limited to liquid systems under specific pressure/temperature conditions. It can be eliminated by changing the pressure/temperature conditions, or reduced by acoustic pipe insulation.

CAVITATION IN LIQUID SYSTEMS

The following equation, verified by Leslie Co. and other investigators, provides a means of predicting cavitation in a control valve:

$$K_c = \frac{p_1 - p_2}{p_1 - p_v} = \frac{\Delta p}{p_1 - p_v}$$

where Δp = pressure differential, psia
p_1 = inlet pressure, psia
p_2 = outlet pressure, psia
p_v = vapor pressure of the liquid, psia
K_c = index of incipient cavitation

The K_c of any given valve design can be determined experimentally. For a single-stage, flow-to-open contoured plug, 0.6–0.7 is the typical value. When K_c calculated from the flow conditions exceeds the inherent K_c of the valve, cavitation will occur. The maximum pressure drop that may be taken across a given valve without cavitation may be calculated from

$$\Delta p(\text{Max.}) = K_c(p_1 - p_v)$$

From this equation it is apparent that the maximum pressure drop that should be taken across a given throttling stage is directly proportional to the inlet pressure to that stage. In a multiple-stage valve, therefore, the pressure drop at each successive stage should be less than the pressure drop in the immediately preceding stage. The optimum design will provide a pressure drop across each stage equal to a constant percent of the difference between the inlet pressure and vapor pressure.

The optimum ratio of the pressure drop at a given stage to the pressure drop of the preceding stage is given by

$$p_r = (1 - K_c)$$

where p_r = pressure drop of a given stage divided by the pressure drop of the preceding stage

If it is suspected that flashing or cavitation will be a problem due to the high pressure drop or downstream pressure being near or below the vapor pressure of the liquid, the process coefficient of incipient cavitation, K_c, should be calculated:

If the value of $\Delta/(p_1 - p_v)$ is greater than the K_c of the valve type under consideration, but is less than 1.0, then cavitation will occur. If the value of $\Delta p/(p_1 - p_v)$ is greater than 1.0, then flashing will occur.

The valve selected should have a K_c value higher than that calculated. A selection made on this basis will result in noise levels of less than 85 dbA with an optimum designed system. Adherence to proper piping and reasonable pipe velocities is also important in reducing cavitation and noise.

WATER HAMMER

Water hammer occurs in liquid systems when the fluid stream is decelerated rapidly, causing shock waves, high instantaneous pressures and noise. Water hammer can be eliminated by decreasing the rate of flow change or by the installation of air chambers.

MECHANICAL VIBRATION

Mechanical vibration of valve parts can take many forms. One of the most common is the vibration of "floating" or "self-aligning" valve discs. These loose discs tend to vibrate in the fluid stream, producing mechanical noise. Fluid noise also can be created by the pulsating flow produced by disc vibration.

Mechanical vibration can occur also in one-piece inner valves. This can be due to vibration of the entire inner valve or of a portion of the valve, such as the skirt of a ported valve. Vibration of the complete inner valve usually is caused by inlet pressure pulsating or by inherent instability of the valve. Portions of the inner valve can vibrate due to excitation by the fluid stream. A resonant condition can be created producing what is known as valve "scream" or "whistle." This usually can be eliminated by modifying the trim.

FLUID NOISE

The most common source of noise in valves and piping systems is the sound produced by the fluid itself. All operating piping systems produce some noise. When the noise level created in the piping system exceeds the background noise level in any audible frequency band it may become objectionable. When the levels created exceed 90 dBA permanent hearing damage can occur, and the requirement of state and federal laws usually apply.

The flowrates in most *liquid* piping systems are limited to reduce pressure drop and prevent erosion of the system components. As a result, the number of noise problems in liquid systems is comparatively low.

The flow velocities in compressible fluid (steam, air, gas) systems are generally 10–30 times higher than those in liquid systems. These high velocities are the basic source of fluid noise.

The sources of noise are many and will vary from one installation to the other. Noise will depend on the particular piping layout, steam flowrates, velocities through pipes, fittings and valves, and equipment such as heat exchangers or pumps, which are connected to the line. We can follow practices that will reduce the possibility of objectionable noise.

CONTROL VALVE NOISE PREDICTION: COMPRESSIBLE FLUIDS

A useful and accurate control valve noise prediction method is now available. It is based on theoretical considerations and actual tests. The method provides estimated values of sound pressure levels in a semianechoic room, as measured at a point three feet from the pipe centerline and three feet downstream of the valve outlet. (A semianechoic room is one that is substantially free of echoes and reverberations.) The sound pressure levels provided by this method can be used to estimate noise levels at other locations provided that piping is not a major contributor to the total noise level. Also, when applying this noise level prediction method to actual installations, the effects of the environment must be considered.

In developing this prediction method, a wide range of complex and variable factors—both functional and acoustical—were considered. Accounting for so many factors is never simple; therefore, this method is applicable only under the following conditions:

- For use with single-seated globe and cage-type valves with contoured, ported or quick-opening main valves,
- For use with body outlet velocities less than sonic. Under high pressure drop conditions, the velocity at the outlet of a valve can reach sonic velocity. In general this should be avoided by using a larger valve body with reduced trim where required.
- For use with downstream piping sized for a maximum velocity of 300 ft/sec.
- For use with absolute pressure ratios $(p_1 - p_2)/p_1$ from 0.1–0.96 only.
- For use with steam flowrates from 100–250,000 lb/hr.

Two Techniques—Numerical and Graphical

The method may be used by direct application of the appropriate equation: For x less than, or equal to, 0.18,

$$\text{SPL(dBA)} = 20 \log(w) + 7.12 \log(x) - 1 + C$$

For x greater than 0.18,

$$\text{SPL(dBA)} = 20 \log(w) + 31.3 \log(x) + 17.3 + C$$

where x = the pressure drop ratio $(p_1 - p_2)/p_1$
p_1 = the inlet pressure, psia
p_2 = the outlet pressure, psia
w = the flowrate, lb/hr
C = the pipe wall thickness factor from Table I

Table I. Factor C–Pipe Wall Thickness Factor

	Schedule	
Pipe Size	**40**	**80**
2	0	–6
4	0	–7
6	0	–8
8	0	–8
10	0	–9
12	0	–10

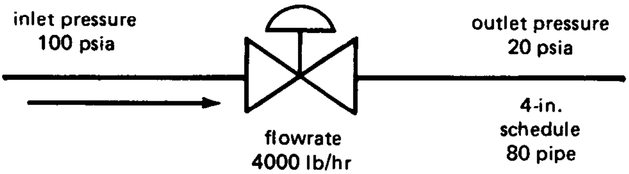
The method also may be used graphically:

$$\mathrm{SPL(dBA)} = A + B + C$$

where A = the flowrate factor from Figure 1
B = the pressure ratio factor from Figure 2
C = the pipe wall thickness factor from Table I

EXAMPLE:

The following example illustrates both the numerical and graphical techniques for using this control valve noise prediction method:



Numerically

1. From Table I, C = –7
2. Calculated pressure ratio, x:;

$$(p_1 - p_2)p_1 = (100\text{-}20)/100 = 0.8$$

3. x is greater than 0.18; therefore,

$$\begin{aligned}\mathrm{SPL(dBA)} &= 20\log(4000) + 31.3\log(0.9) + 17.3 - 7\\ &= 20(3.6) + 31.3(-0.097) + 17.3 - 7\\ &= 79.3\end{aligned}$$

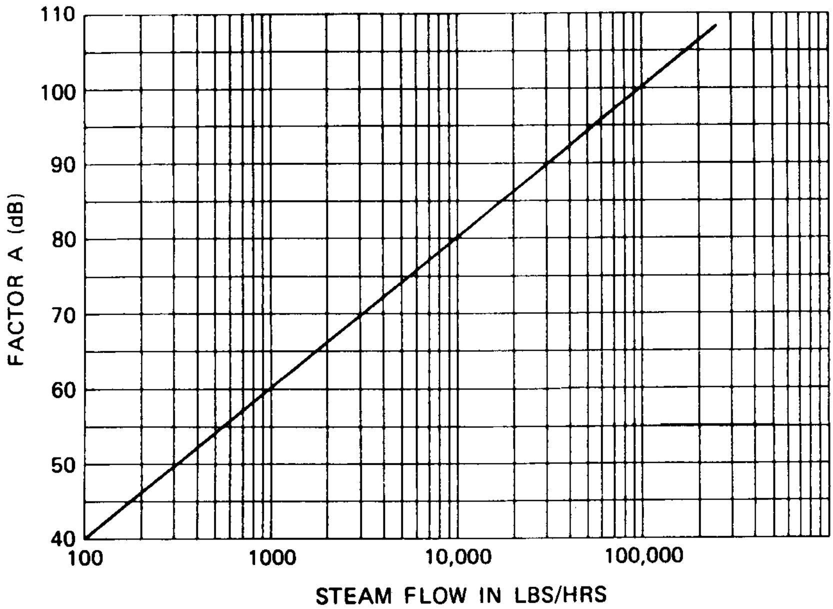


Figure 1. Factor A–flowrate–for single-seated, globe- and cage-type valves with contoured, ported or quick-opening main valves only.

Graphically

1. From Figure 1: for flowrate equal to 4000 lb/hr, Factor A is 72.1.
2. From Figure 2: for calculated pressure drop ratio of 0.8, Factor B is 14.2.
3. From Table I: for 4-in. schedule 80 pipe, Factor C is −7.0.
4. SPL(dBA) = 72.1 + 14.2 − 7 = 79.3.

NOISE ATTENUATION

Silencers for Compressible Fluid Noise Control

Silencers (or mufflers) are of two basic designs:

1. Reflective–contains baffles and chambers that tend to block the transmission of sound waves downstream. They are most effective on low-frequency noise sources, such as compressors.
2. Absorptive–contains porous material (steel wool or fiberglass), which absorbs the sound energy and converts it into heat energy. They are most effective on high-frequency noise sources (400–8000 Hz), such as valves controlling compressible fluid flow.

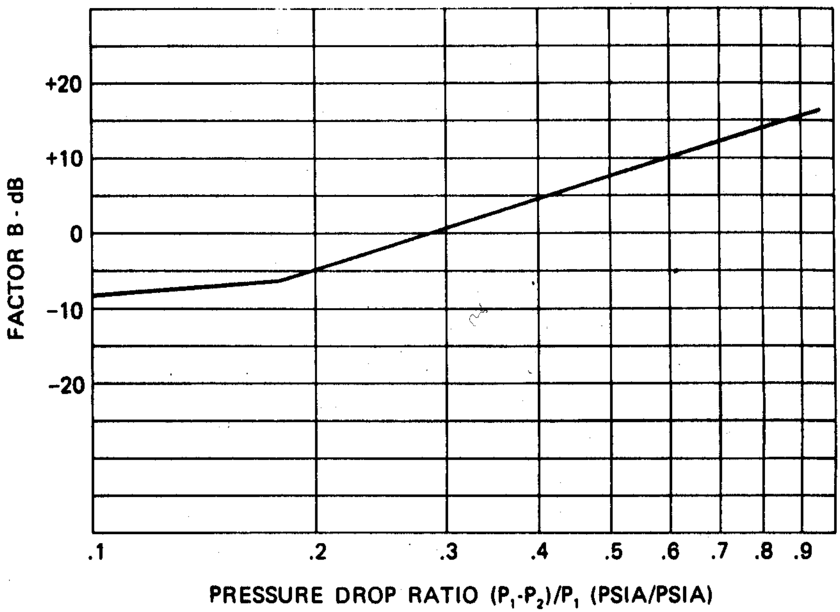


Figure 2. Factor B—pressure drop ratio—for globe- and cage-type valves with contoured, ported or quick-opening main valves only.

It is important to remember that a silencer does not stop the generation of noise but merely reduces the noise transmitted to the surroundings or downstream piping.

Silencers can provide up to 30-dB noise attenuation when used on the downstream side of a valve having a supercritical pressure drop. Less attenuation is obtained when valve pressure drops are subcritical: noise under this condition, however, is generally less of a problem.

Caution must be exercised when applying silencers for the following reasons:

1. A silencer is not a substitute for good piping practice. Proper piping techniques must be observed to assure that high noise levels will not be created elsewhere in the system.
2. A silencer will not reduce upstream noise levels, some of which may be transmitted upstream from a valve. Thus, in some extreme cases, silencers may be required on both upstream and downstream sides of a valve.
3. In all cases, upstream and downstream pipes must be sized to limit approach and exit velocities to prevent noise generation in other parts of the system.

From the above, it is obvious that selection and application of silencers must be done with care to ensure that optimum results are obtained.

Acoustic Pipe Insulation

Generally, any material applied over the surface of a pipe will provide some sound attenuation. The amount of attenuation depends on the type of materials used, the thickness and the method of application.

Acoustic insulation does not reduce the sound energy produced within the valve or pipe. Rather, it absorbs or blocks the transmission of a portion of the sound energy, reducing the external noise level. The noise created by a valve or other restrictions in the pipeline can be transmitted for relatively long distances through the pipe wall and fluid stream. For this reason, it is often necessary to treat the entire piping system to eliminate the noise problem completely. Where the piping system passes through separate enclosures or rooms, it is often possible to reduce the noise level within a given room by insulating only that portion of the piping contained within the room.

Selecting Materials

Noise in compressible fluid systems generally predominates in the frequency range of 1000 to 8000 Hz. In this frequency range, the most effective acoustic materials are porous or fibrous materials such as fiberglass, Rockwool or foam materials. Fiberglass blankets are commonly used to wrap pipelines and are available for temperatures up to 1000°F. Generally, the attenuation of a given material increases with thickness, density and the frequency of the sound. Some typical attenuation properties are given below.

Typical Attenuation Values of Noncovered Insulation

Material	Density (lb/ft^3)	Attenuation (dB) per inch of Thickness 1000 Hz	8000 Hz
Fiberglass	10	6-8	11-13
Rock Wool	4	4	9-13

Values for other materials or densities are available from the manufacturers of the material. The values given above are applicable over a limited range of thickness (generally 2-4 in.) Greater thickness generally will provide greater attenuation per inch at low frequencies and may provide lower attenuation per inch at high frequencies.

COVER MATERIALS

The attenuation values above are for insulation with no outer cover, or with a porous outer cover such as untreated cloth. A significant increase in attenuation can be achieved by using an impervious cover such as thin sheet steel, aluminum, lead, rubber or cloth coated with an airtight material. For maximum attenuation, at low frequencies (below 1000 Hz) the cover material should be dense and limp. Lead and lead-coated cloths are ideal in this respect. At higher frequencies the limpness and density are not as critical.

The peak frequency of fluid-generated noise decreases as the valve or pipe size increases. For valves and piping systems over 8 inches, high-density limp cover materials can produce a significant increase of attenuation over stiff lightweight materials.

The additional attenuation provided by the impervious cover can be calculated using methods described in various handbooks. One example of the additional attenuation provided by an *impervious* cover is a 3-in.-thick fiberglass insulation with a thin sheet metal cover having a mass of 0.5 lb/ft^2. The addition of the cover provides an approximate attenuation of 20 dB at 1000 Hz and 40 dB at 8000 Hz, in addition to the attenuation of the fiberglass.

The outer cover must be supported only by the insulation. If it is in contact with the pipe or valve, the sound energy will bypass the insulation and cause the cover to vibrate and radiate additional noise.

DOUBLE REDUCING STATION

The specification of a single reducing station, its piping arrangement and location, as well as valve class and size for each particular job, provide optimum consideration from a control point of view and will not be the cause of excessive noise in the line, under normal conditions.

This selection from both control and noise point of view, will be a better choice by far than an arbitrary specification of a double reducing station. There are very few cases where the addition of fittings, their possible misalignment and the doubling of restrictions in the line will be of any help to eliminate noise.

Why then are double reduction valves sometimes less noisy? In the case of double reduction, the valve handling lower-pressure drops will have to be larger, therefore requiring larger pipes, resulting in lower pipe velocities. Also, more distance must be provided between valves to approach stability of operation so that there would be *less* tendency toward *abrupt* expansions.

An installation of a properly sized valve planned to keep approach and exit velocities low, utilizing tapered expansions and specified straight lengths of pipe, is a better way of assuring a quieter reducing station.

VALVE/PIPING DESIGN CONSIDERATIONS

Noise Consideration in the Specification of a Reducing Station

1. Follow standard procedure in selecting valve size.
2. Inlet and outlet pipe are to be sized for velocities as follows:

4000/6000 ft/min (70-100 ft/sec)	- Heating mains for locations where surrounding noise level is 60 dB max.
6000-8000 ft/min (100-135 ft/sec)	- Heating mains for locations where surrounding noise level is 80 dB max.
8000-10,000 ft/min (135-170 ft/sec)	- Heating mains for locations where surrounding noise level is over 80 dB.

The internal area of the pipe may be calculated to meet above velocity limits by the following formula:

$$A = \frac{(q)(u)(.04)}{V}$$

where A = pipe flow area (in.^{2})
q = flowrate (lb/hr)
u = specific volume at flowing conditions (ft^3/lb)
V = fluid velocity (ft/sec)

The valve body outlet connection should be selected such that the fluid velocity in that region is less than sonic. The formula below provides a means of determining the correct size by giving the minimum outlet diameter to avoid sonic velocity:

$$D = 0.006\sqrt{q \times u}$$

where D = minimum valve outlet connection to avoid sonic velocity (in.)
q = flowrate (lb/hr)
u = specific volume of outlet steam (ft^3/lb)

If sonic velocity is unavoidable, then an abrupt expander should be used in lieu of a tapered expander. However, sound levels will be somewhat higher than with properly sized valves.

3. Strainer sized same as inlet piping.

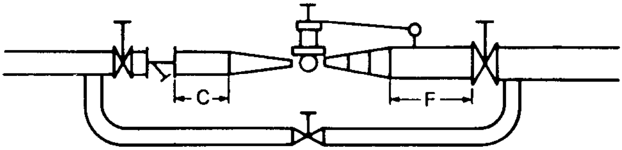
4. Straight run of pipe after strainer of equal size–see Table below under "C."

*5. Swage down to valve through tapered fitting of 15-20° included angle.

*6. Taper expander (included angle of 15–20°) right out of reducing valve outlet to pipe of size to keep velocity to values recommended.

7. Straight run of pipe after expander and before outlet stop valve for pressure connection as follows:

Valve Size	C	F
½-1½	1 ft 6 in.	3 ft
2-4	3 ft	5 ft
5-8	4 ft	8 ft



8. If downstream pipe: valve diameter ratio is greater than 2.5 or 3, install a section of straight pipe twice the valve size, with tapered expander between the regulating valve and downstream stop valve. This section of pipe should be equal to "F" in the above table. Expanders should have a 15°–20° included angle. Make pressure control connection in the straight double-expanded section at least 2 ft from end of the expander and no closer than 12–18 in. to the outlet stop valve. Final expansion should be made beyond stop valve with tapered expander.

9. Avoid abrupt change in flow direction. Consult chart to avoid possible generation of noise due to piping.

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*It is possible to make these expansions by using standard fittings, and the angle and length can vary by the number of fittings and the ratio used due to standard face to face dimensions. This does not give quite as smooth an interior and increases the possibility of sharp edges and gasket projections. Also, angle might be discontinuous if sections are not selected properly.

9.

FAN NOISE CONTROL

Thomas M. Bordas
Occupational Health Consultant
New Jersey Department of Labor
Trenton, New Jersey

This chapter deals with establishing basic guidelines to be able to control noise generated by a fan in a typical ventilation system. Therefore, it is advisable that the noise control engineer or industrial hygienist become familiar with the basic types of fans commonly used and the particular noise characteristics associated with each.

TYPES OF FANS

Fans can be divided into two major groups: the *axial fan* and the *centrifugal fan*. The axial, or propeller-type, fan includes:

1. *The Vaneaxial Fan*. This fan can be used in clean air in such operations as paint spray booths and dry ovens.
2. *The Tubeaxial Fan*. This fan is very similar to the vaneaxial fan. It is capable of moving contaminated air having condensable fumes, paint and any material that will collect on the blades.
3. *Propeller*. This is used typically for roof exhaust or windows, for general ventilation or dilution ventilation. It is characterized by low-pressure and high-volume airflow (Figure 1).

The centrifugal fans include basically two types: tangential and blade type (Figure 2):

1. *Centrifugal, Forward-Curve Blade*. This fan is good for low-pressure applications, such as in heating and air-conditioning work, or any other clean operation in which the short, curved blades would not be exposed to contaminants.

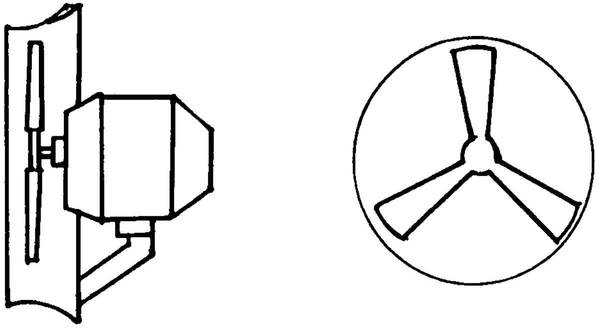

Figure 1. Propeller fan.

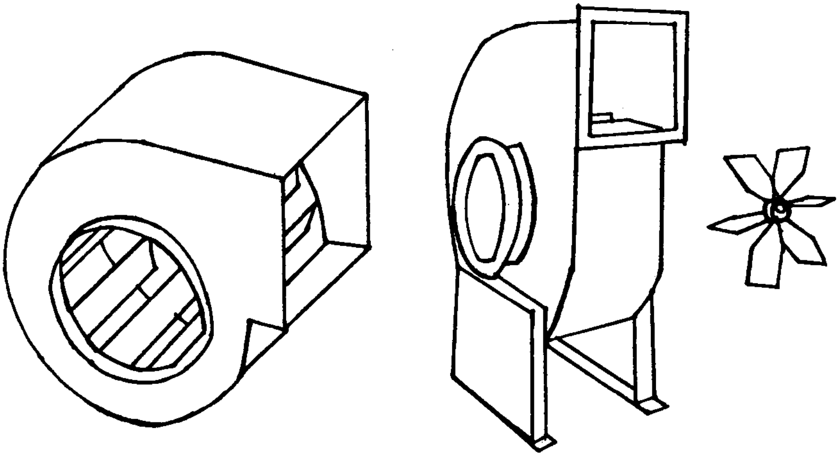

Figure 2. Tangential- and blade-type fans.

2. *Centrifugal, Backward Curve Blade.* This fan is used for general heating, ventilating and air conditioning systems. The fan blades in this type of fan are inclined in the direction opposite to the fan rotation.
3. *Centrifugal, Radial Blade Type.* This is a heavy-duty fan for high-pressure applications. They are used for systems handling material capable of clogging the fan wheel, such as sand, wood, dust-laden air, etc.

NOISE SOURCE

The noise associated with axial fans is composed of:

1. discrete tones at the fundamental blade passing frequency and integer-ordered harmonics of it; and
2. broad random aerodynamic noise due to vortex shedding from the blades.

To determine the noise generated by an axial or a centrifugal fan, the following expression can be applied [1]:

$$Lw = 10 \text{ Log } Fr + 20 \text{ Log } Ps + K_f$$

where Fr = volume flowrate, ft^2/min
Ps = static pressure, in. H_2O
K_f = sound power level constant, which is dependent on fan type and number of blades

The sound power calculated by this technique is the total power of the fan. The basic assumption is made that the fan is well designed; therefore, 3 dB can be subtracted from the number obtained.

By looking at the above equation, one can see that the fan noise is proportional to the volume of air moved and the pressure developed by the fan. Also, the number of blades or type of fan will contribute to the frequency being generated.

The following is an example of how to calculate the sound power level generated by a vaneaxial fan:

F = 200,000 cfm
Speed = 700 rpm
Pressure = 2.0 H_2O
Number of blades = 8

The following relationship also holds true when

$$Lw = Lw(B) + 10 \text{ log } F + 20 \text{ Log } P$$

where $Lw(B)$ = basic sound power level
F = volume flowrate, cfm
P = pressure, in. H_2O
Lw = sound power level, dB re 10^{-12} W
$Lw(C) = 10 \text{ Log } F + 20 \text{ Log } p$
B_t = blade tone component

Therefore,

$$\begin{aligned} Lw(C) &= 10 \text{ Log } 200{,}000 \text{ cfm} + 20 \text{ Log } 2.0 \\ &= 10 \quad 5.3 \quad + 20 \quad 0.301 \\ &= \quad 59 \quad \text{dB} \end{aligned}$$

The frequency for the discreted blade passing tone is calculated from

$$F = \frac{\text{rpm} \times N}{60}$$

Therefore,

$$F = \frac{700 \times 8}{60}$$

$$F = 93 \text{ Hz}$$

Table I shows how to correct for octave band distribution for axial fan.

Once the source has been identified, its sound power level calculated and its blade passing tone calculated, then specific noise reduction techniques can be applied to best reduce the propagation of noise. This can be accomplished by:

- Equipment relocation
- Fan modification
- Isolators
- Mufflers
- Proper location of fan
- Balancing
- Maintenance

RELOCATION OF EQUIPMENT

The noise generated by a fan or air-moving equipment can be eliminated, or at least controlled, by locating or relocating the device in a basement, separate room, on the roof or in any isolated location. The point should be made that according to an Occupational Safety and Health Administration (OSHA) regulation, if no one is exposed to damaging noise a violation of the standard has not taken place. Therefore, as long as the room or area is posted with a noise hazard sign, the noise would be under control.

Table I. Octave Band Center Frequency, Hz

Octave Band	63	100	250	500	1000	2000	4000	8000
Lw	42	39	41	42	40	37	35	25
$Lw_{(C)}$	59	59	59	59	59	59	59	59
Bt	8	0	0	0	0	0	0	0
Lw Total	109	98	100	101	99	96	94	84

FAN MODIFICATION

The second technique for noise reduction would be a simple modification on the fan, such as changing the number of blades. This can alter the frequency of the noise emitted by the fan based on the following expression:

$$f = \frac{NK}{60}$$

where N = shaft rotational speed revolution per second
K = number of blades

Therefore, if a situation existed in which the fan were located outside the building and the low frequency noise from the fan were disturbing the adjacent community by simply increasing the number of blades in the fan, the low-frequency tones would be eliminated. This modification will produce less low-frequency noise. However, it will increase the high-frequency noise. However, these high frequencies are easily stopped by some type of barrier and are also reduced more effectively than low frequency by passing through air.

ISOLATORS

A third method of controlling the noise generated by air moving equipment would be by properly mounting the device. In many instances the fan itself is not the source of the noise; rather, the base to which it is mounted acts as a noise amplifier. An excellent example would be the vibration of the string in a guitar. The vibrations of the strings are transmitted from the bridge to the body. Therefore, mechanical isolation between the fan and the supporting base would be the simplest solution. There are three major types of isolators: springs, elastomeric mounts and resilient pads.

The spring system has wide applications. This type of spring (Figure 3) can be placed in almost any piece of equipment provided that such things as the natural frequency of the equipment is taken into account. This new frequency can be calculated by the following equation [2]:

$$f_n = 3.13\sqrt{\frac{1}{d}}$$

where d = static deflection of the spring, in. under load

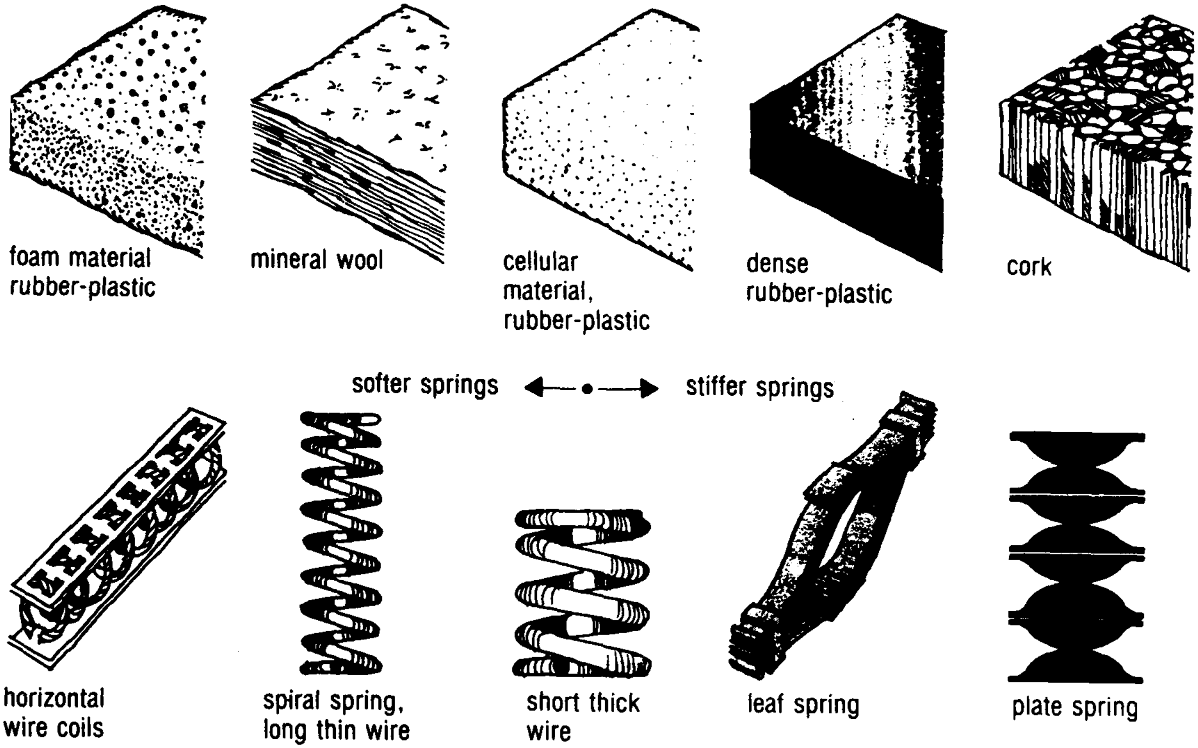

Figure 3. Isolators: spring and resilient pads.

The following example will illustrate the concept. If a fan is mounted on a roof with four spring mounts at the corner, the static deflection of each mount is $^1/_8$ in. What is the natural resonance frequency? From the above equation,

$$f_n = 3.13 \sqrt{\frac{1}{d}}$$

$$= 3.13 \sqrt{\frac{1}{0.125}}$$

$$= 8.88 \text{ Hz}$$

If the forcing frequency of the fan were in the 8 Hz range, a resonant situation would occur and would be intensified to a point that it might break away from its fastening. However, if the forcing frequency were 24 Hz or higher, a high degree of isolation could be achieved and transmissibility would be less than 10%. A rule of thumb to follow is that the spring mount selected should have a static deflection such that the natural frequency (fn) is one-third or less than the lowest anticipated forcing frequency.

Elastomeric or rubber mounts are the second technique used to minimize vibration. They are generally selected by "the weight, the deflection required, and the lowest vibratory frequency of the unit to be isolated" [3] (Figure 4).

The same calculation outlined previously for springs is also applicable in the proper selection of rubber mounts. It must be mentioned that rubber mounts have some advantages over spring mounts, such as easy installation, cost and limited space. However, they also have some major disadvantages such as limited life span and endurance characteristics.

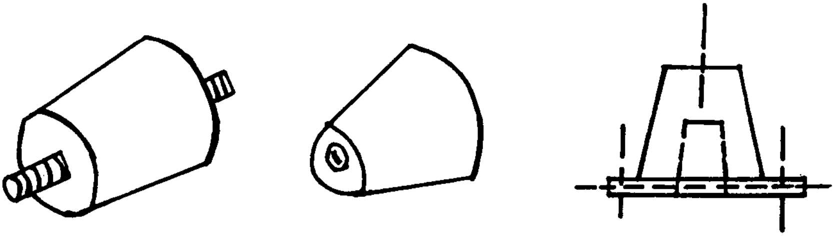

Figure 4. Elastomeric or rubber mounts.

They can be seriously affected by high changes in temperatures, acid, oils and solvents.

Resilient pads are the third type of isolators (refer to Figure 3). These pads generally consist of rubber, cork, felt, fiberglass or any combination thereof. In general, the selection of the pad follows the same approach discussed earlier in rubber mounts and spring selection. In each case the manufacturer will provide tables of recommended loading per unit area, range of stiffness and density of material to make it possible to calculate the static deflection or stiffness needed.

Table II lists the damping factors of isolator pads, as well as pad resistance to common industrial products.

MUFFLERS

There are basically two types or classifications of mufflers: absorptive or reactive. Absorptive-type mufflers have fibrous or porous material as sound absorbers to reduce noise. The reactive muffler does not depend on the absorptive properties of the material but on the reflection of the sound waves.

The reduction of noise generated by the blades passing frequency, vortex shedding from the blades and formation of eddies downstream of the discharge can be accomplished by the addition of a muffler at the inlet, the outlet, or both.

A typical problem would be the selection of a muffler for a fan, rotary blower or compressor, where space is limited and low-frequency noises are generated. If this situation exists, a reactive-type muffler would be the choice because it tends to be smaller than absorptive-type mufflers. As mentioned previously, the reactive-type muffler operates on the principle of sound wave self-destruction. As the cross-sectional areas of the duct change, it causes reflection of the sound waves within the muffler (Figure 5).

Table II. Isolator Pads Damping Factor

Damping Factor, ξ	Resistance			
	Oil	Acid	Temperature	Solvent
Rubber 0.05–0.4	Bad	Bad	Average	Bad
Cork 0.05–0.06	Good	Good	Good	Good
Felt 0.3	Bad	Average	Good	Bad
Fiberglass 0.1–0.2	Good	Good	Good	Good

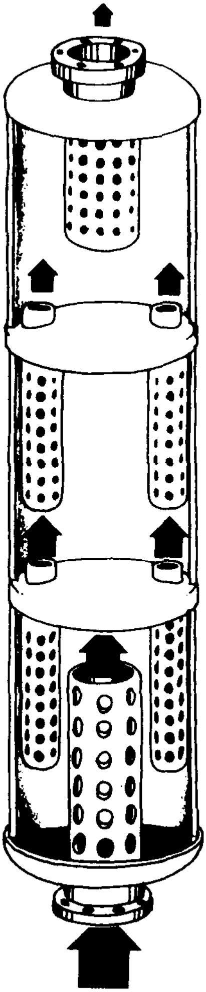

Figure 5. Reactive muffler with three stages.

Two drawbacks associated with this type of muffler are: (1) high pressure drop and (2) low mass flow.

Another type of reactive muffler is just a simple expansion in the duct. Once again, this type of muffler is best suited for noise-containing discrete tones, preferably low-frequency noise. The design expansion size depends on the wavelength of the incident sound. The length is determined to cancel a narrow band of frequencies. The transmission loss (TL) associated with this type of reactive muffler can be calculated by the following equation [4].

$$\mathrm{TL} = 10\ \mathrm{Log}\left[1 + \frac{1}{4}\left(\mathrm{M} - \frac{1}{\mathrm{M}}\right)^2 \mathrm{SIN}^2\mathrm{KL}\right]$$

where $\mathrm{M} = \dfrac{\text{muffler cross-sectional area}}{\text{duct cross-sectional area}} = \dfrac{S_2}{S_1}$

$\mathrm{K} = \text{wave number} = \dfrac{2\pi}{\tau} = \dfrac{2\pi f}{C}$

$\mathrm{L} = \text{muffler length}$

This equation is valid as long as the greatest transverse dimension of the muffler cross-sectional area is less than about 0.8τ. Maximum transmission loss occurs when

$$\mathrm{KL} = \frac{\eta\pi}{2}\ ; \quad \eta = 1, 3, 5, 7, \ldots$$

Zero transmission loss occurs at

$$\mathrm{KL} = \eta\pi\ ; \quad \eta = 1, 2, 4, 6, \ldots$$

Because of this selectivity, this muffler is known as a quarter-wave muffler. Some of the advantages of this type of muffler are as follows:

1. It is economical.
2. Its design is simple.
3. It can be used in dirty air.
4. It has a small pressure drop.

Disadvantages associated with reactive (expansion) mufflers are as follows:

1. It has limited application (narrow band).
2. There is performance breakdown as high frequencies come into play.
3. Performance also breaks down when used with a large-diameter duct.

If space is not a limiting factor and low static pressure drop is important, then an absorptive-type muffler may be used. Basically, this type of muffler consists of an aerodynamically streamlined entrance and exits with perforated walls backed by highly absorbent acoustical material (Figure 6). The absorbing material can be fiberglass, mineral wool, foam belt, resinated cotton, powder metal or any combination thereof.

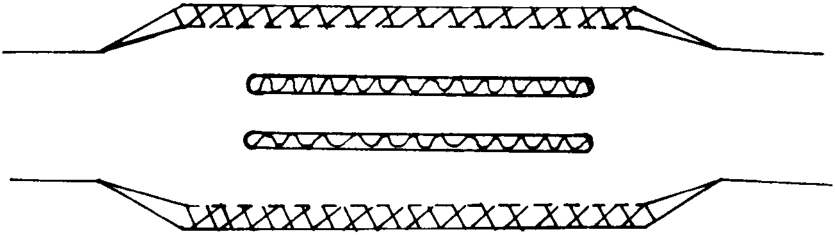

Figure 6. Absorptive expansion muffler.

The acoustical performance associated with this type of muffler depends on:

1. thickness of absorbing materials,
2. spacing of baffles, and
3. length of baffles.

One drawback associated with this type of muffler is that as flow velocities increase, its acoustical performance decreases. The performance of this type of muffler can be estimated by the following empirical equation [5]:

$$TL = 4.2\ \alpha\ 1.4 \frac{L}{d}$$

where α is the absorption coefficient of the acoustic material.

FAN LOCATION

The location of a fan in a ventilation system becomes an important factor if maximum noise control is to be achieved (Figure 7).

This noise can be attributed to:

- Abrupt entry
- Abrupt exits
- Fan orientation
- Upstream interference
- Sharp turns

It is assumed that some noise will be generated as the blades pass through air. However, if turbulence is present in the incoming air already, the sound will be intensified. Therefore, the entry to a ventilation system should be streamlined aerodynamically. The literature indicates that when an axial fan is run without a ducted inlet, the measured sound power

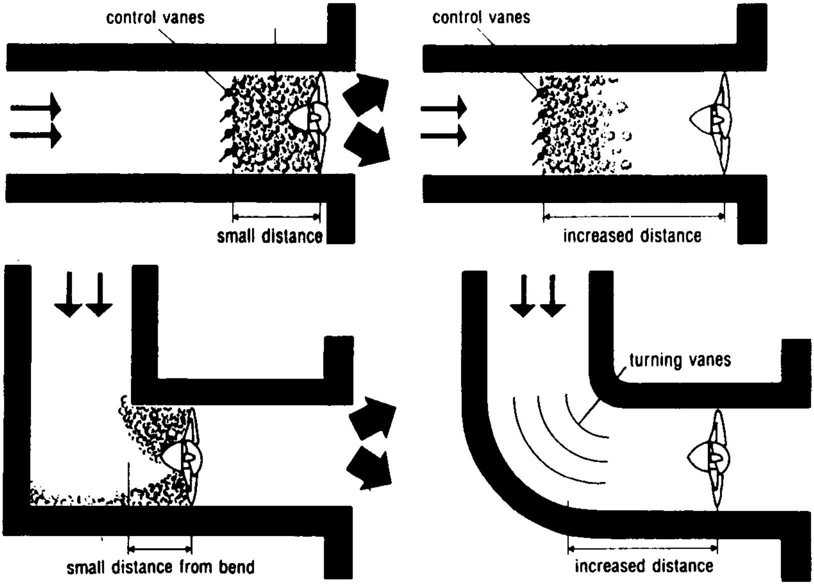

Figure 7. Fan location.

levels will be increased by as much as 6 dB over most of the middle- to high-frequency ranges. Additional noise will occur if the air flows over the motor before passing through the blades. Therefore, the fan orientation should be considered when installation is made. Upstream interference such as control vanes being too close to the fan can produce enough turbulence that the sound will be intensified once it passes the fan. Therefore, their location and distance from the fan should be considered. The same problem previously mentioned will be produced by a sharp turn. Therefore, turns should be made gradually, and turning vanes should be used to help minimize any turbulence.

BALANCING

Properly balancing a fan is a factor in keeping the fan quiet. One of the major sources of noise associated with a fan is its being on an imbalanced condition. A large fan rotating at high speed causes vibration, which, in turn, will produce noise. Imbalanced conditions can be caused by misalignment of coupling or bearings, blade wear, uneven tension in the belts, or accumulation of particulates, paint, oil or grease in the fan blades. It is very important that all significant rotating parts be balanced when the fan is in its final operating position.

MAINTENANCE

By reducing the amount of sound energy released by the source (fan), it is possible to control the noise, or at least to minimize it. A poorly maintained fan makes more noise than one that is maintained properly. This line of thinking can be applied to practically any piece of equipment, such as motor, pumps, compressors, etc. Therefore, bad bearings, insufficient lubrication, slapping belts, loose guards, bent shafts, rubbing parts and resonant conditions should be monitored periodically.

SUMMARY AND CONCLUSIONS

The elimination of noise in the work environment is not an easy undertaking because every situation or process generation of a potential pollutant is probable, whether in the form of dust, fumes, smoke or noise. The noise control engineer or industrial hygienist must be able to make recommendations based on predictable noise control data. The topics discussed in this chapter, such as fan modification, isolators, location, balancing and maintenance, will provide the proper tools to reduce the noise generated by any fan or air-moving device to the desired levels. Also, the section of the paper outlining the different types of mufflers, their advantages, disadvantages and limitations, will provide added edge in quieting any air-moving device to an even higher degree.

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GLOSSARY

The following explanations of terms are provided to assist the reader in understanding some terms used in this book:

A-weighted sound level–The ear does not respond equally to frequencies, but is less efficient at low and high frequencies than it is at medium or speech range frequencies. Thus, to obtain a single number representing the sound level of a noise containing a wide range of frequencies in a manner representative of the ear's response, it is necessary to reduce, or weight, the effects of the low and high frequencies with respect to the medium frequencies. The resultant sound level is said to be A-weighted, and the units are dB. A popular method of indicating the units is dBA. The A-weighted sound level is also called the noise level. Sound level meters have an A-weighting network for measuring A-weighted sound level.

abscissa–The horizontal axis on a chart or graph.

acoustics–The science of sound.

acoustic reflex–The involuntary contraction of muscles (stapedius and/or tensor tympani) of the middle ear in response to acoustic or mechanical stimuli.

acoustic trauma–Damage to the hearing mechanism caused by a sudden burst of intense noise, or by blast. *Note*: The term usually implies a single traumatic event.

airborne sound–Sound propagated through air.

air conduction (AC)–The process by which sound is normally conducted to the inner and middle ear through the air in the external auditory meatus.

ambient noise (residual noise; background noise)–Noise of a measurable intensity that is normally present in the background in a given environment.

articulation index (AI)–A numerically calculated measure of the intelligibility of transmitted or processed speech. It takes into account the limitations of the transmission path and the background noise. The articulation index can range in magnitude between 0 and 1.0. If the AI is less than 0.1, speech intelligibility is generally low. If it is above 0.6, speech intelligibility is generally high.

audible range of frequency (audio-frequency range)–The frequency range 20 Hz to 20,000 Hz (20 kHz). *Note*: This is conventionally taken to be the normal frequency range of human hearing.

audiogram–A chart, table or graph showing hearing threshold level as a function of frequency.

audiometer–An instrument for measuring the threshold or sensitivity of hearing.

audiometry–The measurement of hearing.

auditory trauma–Damage to the hearing mechanism resulting in some degree of permanent or temporary hearing loss. *Note*: Auditory trauma may be caused by agents other than noise, e.g., head injury; burns; sudden or excessive changes of atmospheric pressure (cf. acoustic trauma).

aural–Of or pertaining to the ear or hearing.

background noise–The total of all noise in a system or situation, independent of the presence of the desired signal. In acoustical measurements, strictly speaking, the term "background noise" means electrical noise in the measurement system. However, in popular usage the term "background noise" is also used with the same meaning as "residual noise."

band center frequency–The designated (geometric) mean frequency of a band of noise or other signal. For example, 1000 Hz is the band center frequency for the octave band that extends from 707 Hz to 1414 Hz, or for the third-octave band that extends from 891 Hz to 1123 Hz.

band pressure (or power) level–The pressure (or power) level for the sound contained within a specified frequency band. The band may be specified either by its lower and upper cut-off frequencies, or by its geometric center frequency. The width of the band is often indicated by a prefactory modifier; e.g., octave band, third-octave band, 10-Hz band.

baseline audiogram–An audiogram obtained on testing after a prescribed period of quiet (at least 12 hours).

bone conduction (BC)–The process by which sound is transmitted to the inner ear through the bones of the skull (cf. air conduction).

boom carpet–The area on the ground underneath an aircraft flying at supersonic speeds that is hit by a sonic boom of specified magnitude.

broadband noise–Noise whose energy is distributed over a broad range of frequency (generally speaking, more than one octave).

C-weighted sound level (dBC)–A quantity, in decibels, read from a standard sound-level meter that is switched to the weighting network labeled "C". The C-weighting network weights the frequencies between 70 Hz and 4000 Hz uniformly, but below and above these limits frequencies are slightly discriminated against. Generally, C-weighted measurements are essentially the same as overall sound-pressure levels, which require no discrimination at any frequency.

central hearing loss–Hearing loss resulting from injury or disease involving the auditory pathways or the auditory center of the brain or from a psychoneurotic disorder. *Note*: Central hearing loss can occur in the absence of any damage or deficiency in the peripheral hearing mechanism.

cochlea–A spirally wound tube, resembling a snail shell, which forms part of the inner ear and contains the end organ of hearing.

community noise equivalent level–Community noise equivalent level (CNEL) is a cumulative measure of community noise. It uses the A-weighted sound level and applies weighting factors which place greater importance upon noise events occurring during the evening hours (7:00 PM to 10:00 PM) and even greater importance upon noise events at night (10:00 PM to 6:00 AM).

composite noise rating–Composite noise rating (CNR) is a noise exposure used for evaluating land use around airports. It is in wide use by the Department of Defense in predicting noise environments around military airfields.

conductive hearing loss (conductive deafness)–Hearing loss resulting from a lesion in the air-conduction mechanism of the ear.

continuous noise–On-going noise, the intensity of which remains at a measurable level (which may vary) without interruption over an indefinite period or a specified period of time. Loosely, nonimpulsive noise.

cycles per second–A measure of frequency numerically equivalent to hertz.

damage risk criterion (DRC)–A graphical or other expression of sound levels above which a designated or a general population incurs a specified risk of noise-induced hearing loss.

deafness–100 percent impairment of hearing associated with an otological condition. *Note*: This is defined for medicological and cognate purposes in terms of the hearing threshold level for speech or the average hearing threshold level for pure tones of 500, 1000, and 2000 Hz in excess of 92 dB.

decibel–One-tenth of a bel. Thus, the decibel is a unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power. Note 1: Examples of quantities that qualify are power (any form), sound pressure squared, particle velocity squared, sound intensity, sound energy density, voltage squared. Thus the decibel is a unit of sound-pressure-squared level; it is common practice, however, to shorten this to sound pressure level because ordinarily no ambiguity results from so doing. Note 2: The logarithm to the base the tenth root of 10 is the same as ten times the logarithm to the base 10: e.g., for a number x^2, $\log_{10}{}^{0.1}x^2 = 10 \log_{10}x^2 = 20 \log_{10}x$. This last relationship is the one ordinarily used to simplify the language in definitions of sound pressure level, etc.

dosimeter (noise dosimeter)–An instrument which registers the occurrence and cumulative duration of noise exceeding a predetermined level at a chosen point in the environment or on a person.

ear defender (ear protector)–A device inserted into or placed over the ear in order to attenuate air-conducted sounds.

earmuff–An ear defender that encloses the entire outer ear (pinna). *Note*: Earmuffs are customarily mounted as a pair on a headband or in a helmet.

earplug–An ear defender, having specified or standard acoustic characteristics, which upon insertion occludes the external auditory meatus. *Note*: Earplugs should be properly designed, made of suitable material and correctly fitted to insure that they are acoustically effective and do not harm the ear.

effective perceived noise level (EPNL)–A calculated measure designed to estimate the effective "noisiness" of a single noise event, usually an aircraft flyover. It is derived from instantaneous Perceived Noise Level (PNL) values by applying corrections for pure tones and for the duration of the noise.

fence–(Slang) An arbitrary hearing level, greater than 0 dB, below which no hearing impairment is deemed to have occurred ("low fence") or at which complete (100%) hearing impairment is deemed to have occurred ("high fence").

filter–A device for separating components of a signal on the basis of their frequency. It allows components in one or more frequency bands to pass relatively unattenuated, and it attenuates components in other frequency bands.

fluctuating noise–Continuous noise whose level varies appreciably (more than ±5 dB) with time.

free sound field (free field)–An isotropic, homogeneous sound field free from bounding surfaces.

frequency–The number of times per second that a sine-wave repeats itself. It is expressed in hertz (Hz), formerly in cycles per second (cps).

hair cell–Sensory cells in the cochlea which transform the mechanical disturbance into a nerve impulse.

handicap (hearing handicap)–The occupational and social difficulty experienced by a person who has a hearing loss.

hard of hearing–Having more than zero but less than 100 percent impairment of hearing for everyday speech or for pure tones of 500, 1000 and 2000 Hz. *Note*: This is defined, according to various standards, in terms of an elevated hearing threshold level of which the elevation is less than that defining deafness.

hearing conservation (hearing conservation program)–Those measures which are taken to reduce the risk of noise-induced hearing loss.

hearing disability–Hearing handicap prejudicing employment at full wages.

hearing impairment–Hearing loss exceeding a designated criterion (commonly 25 dB, re ISO standard averaged from the threshold levels at 500, 1000 and 2000 Hz).

hearing loss–Impairment of auditory sensitivity: an elevation of a hearing threshold level with respect to the standard reference zero.

hearing threshold level–The amount by which the threshold of hearing for an ear exceeds a standard audiometric reference zero. Units: decibels.

hearing threshold level for speech–An estimate of the amount of socially significant hearing loss in decibels. *Note*: This is measured by speech audiometry or estimated by averaging the hearing threshold level for pure tones of 500, 1000 and 2000 Hz.

hertz–Unit of measurement of frequency, numerically equal to cycles per second.

impulse noise (impulsive noise)–Noise of short duration (typically, less than one second) especially of high intensity, abrupt onset and rapid decay, and often rapidly changing spectral composition. *Note*: Impulse noise is characteristically associated with such sources as explosions, impacts, the discharge of firearms, the passage of supersonic aircraft (sonic boom) and many industrial processes.

industrial deafness–Syn. occupational hearing loss.

infrasonic–Having a frequency below the audible range for man (customarily deemed to cut off at 20 Hz).

intermittent noise–Fluctuating noise whose level falls one or more times to very low or unmeasurable values during an exposure.

interrupted noise–Syn. Intermittent noise (deprecated).

L_{10} level–The sound level exceeded 10 percent of the time period during which measurement was made.

L_{50} level–The sound level exceeded 50 percent of the time period during which measurement was made.

L_{90} level–The sound level exceeded 90 percent of the time period during which measurement was made.

level–In acoustics, the level of a quantity is the logarithm of the ratio of that quantity to a reference quantity of the same kind. The base of the logarithm, the reference quantity and the kind of level must be specified.

loudness–An attribute of an auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud. Loudness is chiefly a function of intensity but it also depends upon the frequency and waveform of the stimulus. The unit is the sone.

loudness level–The loudness level of a sound, in phons, is numerically equal to the median sound pressure level, in decibels, relative to 0.0002 microbar, of a free progressive wave of frequency 1000 Hz presented to listeners facing the source, which in a number of trials is judged by listeners to be equally loud.

masking–(1) The process by which the threshold of audibility for one sound is raised by the presence of another (masking) sound. (2) The amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. The unit customarily used is the decibel.

microbar–A microbar is a unit of pressure, equal to one dyne per square centimeter.

microphone–An electroacoustic transducer that responds to sound waves and delivers essentially equivalent electric waves.

middle ear–A small cavity next to the ear drum in which is located the ossicular chain and associated structures.

mixed hearing loss–Hearing loss due to a combination of conductive and sensorineural deficit.

narrow-band noise–A relative term describing the pass-band of a filter or the spectral distribution of a noise. *Note*: The term commonly implies a bandwidth of 1/3 octave or less (cf. Broad-band noise).

noise–(1) Disturbing, harmful or unwanted sound. (2) An erratic, intermittent or statistically random oscillation.

noise exposure–The integrated effect over a given period of time of a number of different events of equal or different noise levels and durations. The integration may include weighting factor for the number of events during certain time periods.

noise exposure forecast–A method currently used for making noise exposure forecasts utilizing a perceived noise level scale with additional corrections for the presence of pure tones. Two periods are used to weight the number of flights.

noise hazard (hazardous noise)–Acoustic stimulation of the ear which is likely to produce noise-induced permanent threshold shift in some fraction of a population.

noise-induced hearing loss (NIHL)–A sensorineural hearing loss caused by acoustic stimulation.

noise-induced permanent threshold shift (NIPTS)–Permanent threshold shift caused by noise exposure.

noise-induced temporary threshold shift (NITTS)–Temporary threshold shift caused by noise exposure.

noise level–(Slang) An averaged sound level (weighted sound pressure level). *Note*: The weighting must be specified.

noise limit (noise emission standard)–A graphical, tabular or other numerical expression of the permissible amount of noise which may be produced by a practical source (e.g., a vehicle or an appliance) or which may invade a specified point in a living or working environment (e.g., in a workingplace or residence) in prescribed conditions of measurement.

noise and number index (NNI)–A measure based on Perceived Noise Level, with weighting factors added to account for the number of noise events, and used (in some European countries) for rating the noise environment near airports.

noise pollution level (L_{NP} or NPL)–A measure of the total community noise, postulated to be applicable to both traffic noise and aircraft noise. It is computed from the "energy average" of the noise level and the standard deviation of the time-varying noise level.

noise rating (NR) numbers (contours)–An empirically established set of standard values of octave-band sound pressure level, expressed as functions of octave-band center frequency, intended as general noise limits for the protection of populations from hazardous noise, speech interference and community disturbance. *Note*: The NR number is numerically equal to the sound pressure level in decibels at the intersection of the so designated NR contour with the ordinate at 1000 Hz.

noise susceptibility–A predisposition to noise-induced hearing loss, particularly of an individual compared with the average.

non-organic hearing loss (NOHL)–That portion of a hearing loss for which no otological or organic cause can be found. Hearing loss other than conductive or sensorineural.

nonsteady noise–Noise whose level varies substantially or significantly with time (e.g., aircraft flyover noise). Syn: fluctuating noise.

normal hearing–The standardized range of auditory sensitivity of a specified population of healthy, otologically normal people determined in prescribed conditions of testing. (Deprecated.)

normal threshold of hearing–Syn. Standard audiometric threshold.

occupational hearing loss–A permanent hearing loss sustained in the course of following an occupation or employment. *Note*: While noise is usually presumed to be the cause, other causes are possible (e.g., head injury).

octave–The interval between two sounds having a basic frequency ratio of two. For example, there are 8 octaves on the keyboard of a standard piano.

ordinate–The vertical axis on a chart or graph.

organ of corti–The end organ of hearing made up of hair cells and their associated and supportive structures.

otologically normal–Enjoying normal health and freedom from all clinical manifestations and history of ear disease or injury; and having a patent (waxfree) external auditory meatus.

peak sound pressure–The absolute maximum value (magnitude) of the instantaneous sound pressure occurring in a specified period of time. The unit is the N/m^2.

perceived noise level (PNL)–A quantity expressed in decibels that provides a subjective assessment of the perceived "noisiness" of aircraft noise. The units of perceived noise level are perceived noise decibels, PNdB.

percent handicap–Syn. Percent impairment of hearing.

percent impairment of hearing (overall) (PIHO)–The estimated percentage by which a person's hearing is impaired, based upon audiometric determinations of the hearing threshold level at 500, 1000 and 2000 Hz (cf. Percent impairment of hearing for speech).

percent impairment of hearing for speech (PIHS)–An estimate of the percentage by which a person's hearing is impaired, particularly at the frequencies (500, 1000 and 2000 Hz) deemed important for the perception of speech. *Note*: The scale 0 to 100 percent is arbitrarily set to correspond linearly with a standard range of values of hearing threshold level for speech in decibels (more than one standard has been used). The percent impairment of hearing increases by approximately 1.5 percent for each decibel of elevation of the estimated hearing threshold level for speech (average of 500, 1000 and 2000 Hz) in the standard ranges.

perceptive hearing loss–Syn. Sensorineural hearing loss. (Obs.)

permanent hearing loss–Hearing loss deemed to be irrecoverable.

permanent threshold shift (PTS)–That component of threshold shift which shows no progressive reduction with the passage of time when the putative cause has been removed.

persistent threshold shift–Threshold shift remaining at least 48 hours after exposure of the affected ear to noise.

phon–The unit of measurement for loudness *level*.

pink noise–Noise having a noise-power-per-unit frequency that is inversely proportional to frequency over a specified range.

pitch–That attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch depends primarily upon the frequency of the sound stimulus, but it also depends upon the sound pressure and wave form of the stimulus.

presbycusis–The decline in hearing acuity that normally occurs as a person grows older.

pure tone–A sound wave whose waveform is that of a sine-wave.

recruitment–The unusually great increase in loudness with rising sound levels.

resonance–Resonance of a system in forced oscillation exists when any change, however small in the frequency of excitation, causes a decrease in the response of the system. *Note*: Velocity resonance, for example, may occur at a frequency different from that of displacement resonance.

risk–That percentage of a population whose hearing level, as a result of a given influence, exceeds the specified value, minus that percentage whose hearing level would have exceeded the specified value in the absence of that influence, other factors remaining the same. *Note*: The influence may be noise, age, disease or a combination of factors.

semi-insert ear defender–An ear defender which, supported by a headband, occludes the external auditory meatus at the entrance to the ear canal.

sensorineural hearing loss–Hearing loss resulting from a lesion of the cochlear end-organ (organ of Corti) or its nerve supply.

short-lived noise–Noise of measurable intensity lasting without interruption (although the level may vary) for more than half one second but less than one minute (cf. Continuous noise; impulsive noise).

sociocusis–Elevation of hearing threshold level resulting from or ascribed to non-occupational noise exposure associated with environmental noise and exclusive of hearing loss associated with aging.

sone–The unit of loudness.

sonic boom–The pressure transient produced at an observing point by a vehicle that is moving faster than the speed of sound.

sound–(1) An oscillation in pressure, stress, particle displacement, particle velocity, etc., in a medium with internal forces (e.g., elastic, viscous), or the superposition of such propagated alterations. (2) An auditory sensation evoked by the oscillation described above. Note 1: In case of possible confusion, the term "sound wave" or "elastic wave" may be used for concept (1), and the term "sound sensation" for concept (2). Not all sound waves can evoke an auditory sensation: e.g., ultrasound. Note 2: The medium in which the source exists is often indicated by an appropriate adjective: e.g., airborne, waterborne, structureborne.

sound level (noise level)–The A-weighted sound pressure level obtained by use of a sound level meter having a standard frequency-filter for attenuating part of the sound spectrum.

sound level meter–An instrument, comprising a microphone, an amplifier, an output meter and frequency-weighting networks, that is used for the measurement of noise and sound levels in a specified manner.

sound power–Of a source of sound, the total amount of acoustical energy radiated into the atmospheric air per unit time.

sound power level–The level of sound power, averaged over a period of time, the reference being 10^{-12} watts.

sound pressure level (SPL)–20 times the logarithm to the base 10 of the ratio of the sound pressure in question to the standard reference pressure of 0.00002 N/m^2. Units: decibels (dB).

spectrum–Of a sound wave, the description of its resolution into components, each of different frequency and (usually) different amplitude and phase.

speech audiometry–A technique in which speech signals are used to test a person's aural capacity to perceive speech in prescribed conditions of testing.

speech discrimination–The ability to distinguish and understand speech signals.

speech-interference level (SIL)–A calculated quantity providing a guide to the interfering effect of a noise on reception of speech communication.

The speech-interference level is the arithmetic average of the octave-band sound-pressure levels of the interfering noise in the most important part of the speech frequency range. The levels in the three octave-frequency bands centered at 500, 1000 and 2000 Hz are commonly averaged to determine the speech-interference level. Numerically, the magnitudes of aircraft sounds in the Speech-Interference Level scale are approximately 18 to 22 dB less than the same sounds in the Perceived Noise Level scale in PNdB, depending on the spectrum of the sound.

speed (velocity) of sound in air–The speed of sound in air is 344 m/sec or 1128 ft/sec at 78°F.

standard–(1) A prescribed method of measuring acoustical quantities. Standards in this sense are promulgated by professional and scientific societies like ANSI, SAE, ISO, etc., as well as by other groups. (2) In the sense used in federal environmental statutes, a standard is a specific statement of permitted environmental conditions.

standard audiometric threshold–A standardized set of values of sound pressure level as a function of frequency serving as the reference zero for determinations of hearing threshold level by pure-tone audiometry.

stapedius reflex (stapedial reflex)–(Likewise, tensor tympani reflex.) The reflex response of the stapedius (likewise, tensor tympani) muscle to acoustic or mechanical stimulation. Commonly, synonymous with acoustic reflex.

steady noise (steady-state noise)–Noise whose level varies negligibly within a given period of time.

temporary threshold shift (TTS)–That component of threshold shift which shows a progressive reduction with the passage of time after the apparent cause has been removed.

threshold of hearing (audibility)–The minimum effective sound pressure level of an acoustic signal capable of exciting the sensation of hearing in a specified proportion of trials in prescribed conditions of listening.

threshold of feeling (tickle)–The minimum effective sound pressure level of an auditory signal capable of exciting a sensation of feeling or tickle in the ear which is distinct from the sensation of hearing.

threshold of pain (aural pain)–The minimum effective sound pressure level of an auditory signal at the external auditory meatus which is capable of eliciting pain in the ear as distinct from sensations of feeling, tickle or discomfort.

threshold shift–An elevation of the threshold of hearing of an ear at a specified frequency. Units: Decibels.

tinnitus–Ringing in the ear or noise sensed in the head. Onset may be due to noise exposure and persist after a causative noise has ceased, or occur in the absence of acoustical stimulation (in which case it may indicate a lesion of the auditory system).

tone–A sound of definite pitch. A pure tone has a sinusoidal waveform.

TTS–See temporary threshold shift.

ultrasonic–Pertaining to sound frequencies above the audible sound spectrum (in general, higher than 20,000 Hz).

vasoconstriction–The diminution of the caliber of vessels, arteris and arterioles.

vestibular mechanism (system)–The sensory mechanism which has to do with balance, locomotion, orientation, acceleration and deceleration.

weighting (frequency weighting)–The selective modification of the values of a complex signal or function for purposes of analysis or evaluation, in accordance with prescribed or standardized rules or formulas. *Note*: This may be done by computation or by the use of specified weighting networks inserted into electronic instrumentation so as to transform input signals.

INDEX