NOISE CONTROL IN INDUSTRY

A Practical Guide

by

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NOTICE

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

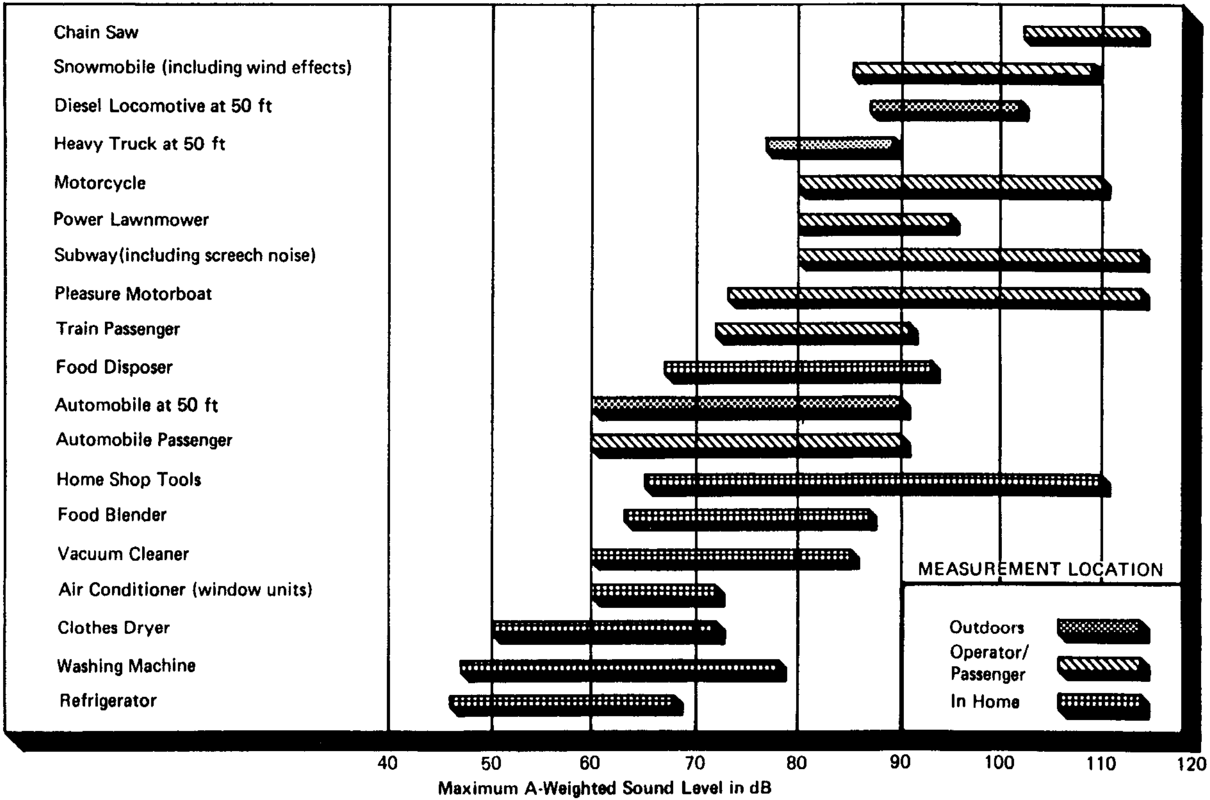


Figure 1. Typical range of common sounds [2].

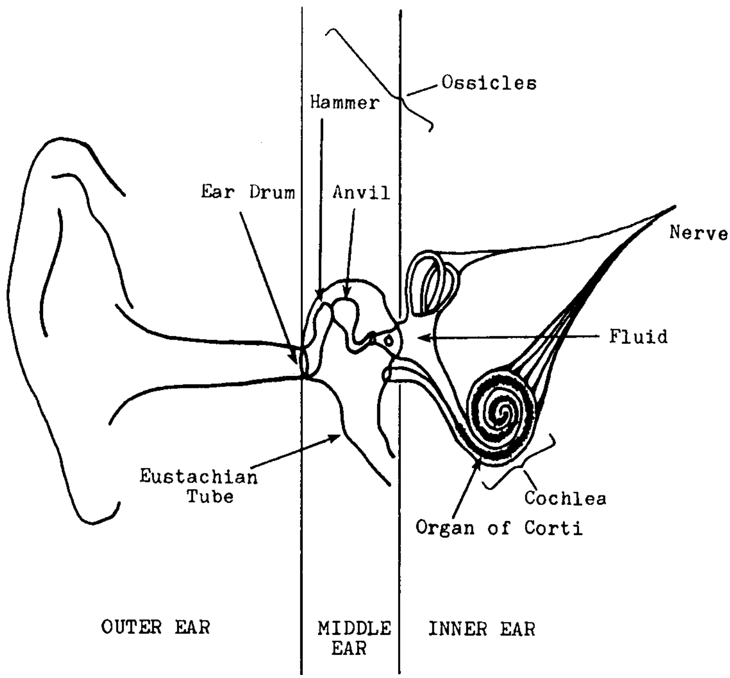


Figure 2. The human ear.

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

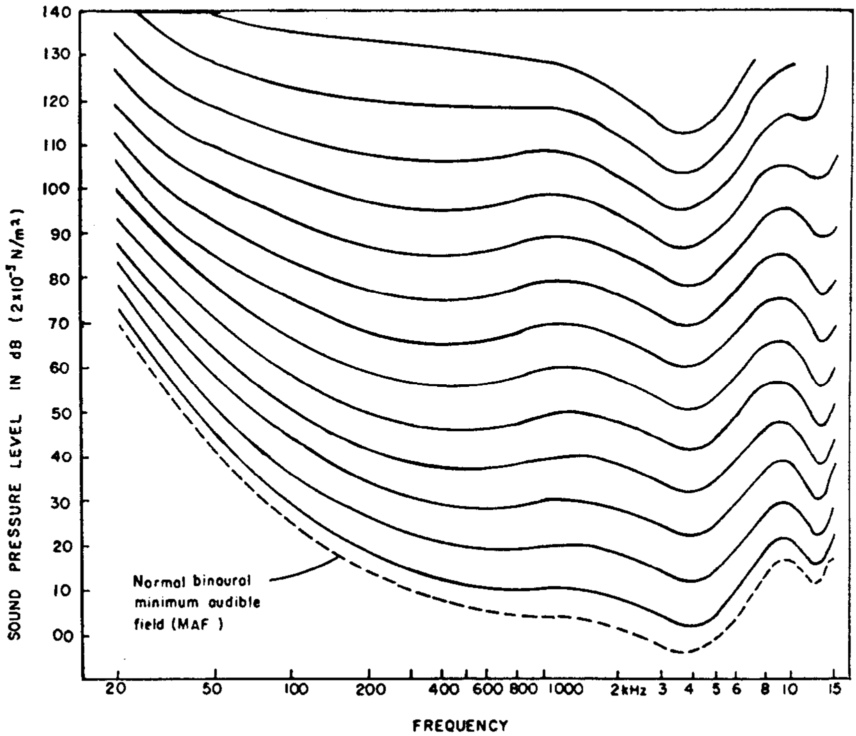


Figure 3. Normal equal-loudness contours for pure tones [9].

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

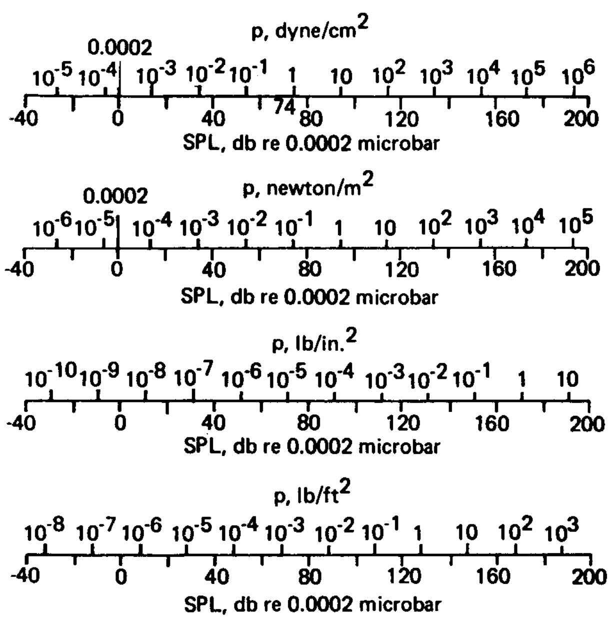
As stated above, vibrations in a medium result in sound. The vibration produces alternating waves of relatively dense and sparse particles—compression and rarefaction, respectively—which travel away from the source as longitudinal waves, much like ripples in water. The resultant variation to normal ambient 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 X 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 $\mu N/m^2$,
- 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

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

or

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

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 1 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 } Peak rms levels in 1/8-second intervals
3	125	Small aircraft engine
1.0	120	Large chipping hammer Piano } Peak rms levels in 1/8-second intervals BB♭ tuba } Peak rms levels in 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.

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

in terms of pressure.

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

in terms of intensity.

$$\text{Sound power} = W = IA \qquad (4)$$

Therefore,

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

in terms of sound pressure.

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

in terms of sound power.

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

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

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

$$Lw = Lp + 10 \log A \qquad (11)$$

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

$$Lw = Lp + 10 \log A - 10.5 \qquad (12)$$

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.