Handbook of Noise Control

SECOND EDITION

Edited by
CYRIL M. HARRIS, Ph.D.

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PREFACE

People do not like *noise*, by definition *unwanted sound*. It may be annoying, it may interfere with speech communication on their jobs or in their leisure activities; under certain conditions, it may affect their behavior. At very high levels, it may produce temporary hearing loss—and if the exposure is prolonged at these levels, it may produce permanent hearing loss.

Twenty-two years have passed since publication of the first edition of the *Handbook of Noise Control*. During this time, noise control has become a matter of considerable social and economic importance. Because of this concern, many countries have enacted some type of noise control legislation (in the U.S.A., for example, the Noise Control Act of 1972). As a result of such legislation and administrative regulations, and because of recent technological developments, many noise control techniques are now being employed that would not have been considered economically feasible a generation ago. Usually (but not always) the public has shown itself willing to pay the additional costs which usually (but not always) accompany any form of pollution control, and which as a rule are passed on to the general public.

When the first edition was published, interest in noise control was restricted primarily to those people working in acoustics. In contrast, today there are many people in widely diverse fields whose work requires some knowledge of noise control. They need access to authoritative material on noise control, written in terms which they can understand. They include: city planners, environmentalists, government administrators, industrial hygienists, public health officials, audiologists, physiologists, psychologists, builders, business executives, law enforcement officers, lawyers, union officials, aeronautical engineers, architects, electrical engineers, equipment design engineers, mechanical engineers, physicists, plant maintenance engineers, and many others.

Because of this diversity of field and background, the second edition is written so as to make technical information accessible without diminishing its value to the specialist—often by the use of written explanation and simple charts in place of highly technical mathematical formulas which do not contribute significantly to the basic understanding of the problem. Such a presentation does not require a lowering of the substantive level of the Handbook's contents. But it has required the rewriting of the chapters, often many times, in order to achieve our objective; as well as considerable effort and cooperation between the Contributors and Editor. I am deeply grateful for their patience and their skill.

Each member of the staff of Contributors is an expert in his or her special area. A handbook-type presentation makes this expertise possible. No individual (or group of individuals working as coauthors), however able, can be expert in all the subjects in a field as broad as noise control. By careful editorial supervision and control, a unified treatment is presented here, employing uniform terminology, symbols, and abbreviations which probably represent as close to an international consensus as is possible to obtain. The millenium when all standards organizations, professional societies, writing groups, and professionals who work in the field agree has not yet arrived.

Both the International System of Units and the U.S. Customary System of Units are employed throughout the handbook (except for a few illustrative examples of noise control regulations which apply only in the U.S.A.).

The chapters in this handbook are grouped as follows:

- Properties of sound and sound sources; sound propagation in the open air and in enclosed spaces.
- Noise measurement instrumentation, methods, and standards.
- Hearing characteristics, hearing loss from noise exposure, hearing testing, hearing conservation programs, hearing protective devices, and liability for hearing loss.
- Effects of noise on speech communication, physiology, annoyance, and human performance.
- Criteria for noise and vibration exposure.
- Methods of noise control—including vibration control, use of acoustical materials and sound insulation.
- Control of noise in buildings.
- Machinery and equipment noise.
- Transportation noise.
- Community noise.
- Noise control and the law; noise control legislation and regulation.

ACKNOWLEDGMENTS

The wealth of technical information contained in this volume has been gathered from many sources. Much of the material, heretofore unpublished, has been provided by manufacturers, government agencies, and engineering consultants. Material has been reproduced, by permission, from copyrighted publications of a number of technical societies, including the Journal of the Acoustical Society of America, Noise Control Engineering, Psychophysiology, Journal of Experimental Psychology, and publications of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

Where reference is made to books, all such material is copyrighted, and is reproduced by permission. Special acknowledgment is made herein to the McGraw-Hill Book Company and the Oxford University Press.

Other valuable sources include publications of the standards organizations of various countries such as the American National Standards Institute, and international organizations including the International Organization for Standardization and the International Electrotechnical Commission. Copies of these publications may be obtained by writing the appropriate organizations at the addresses listed in Chapter 7.

Many of the authors work for a department for the United States government. Material included in their chapters has been released for publication, but because these are private contributions, the contents do not necessarily reflect the official view of the relevant department.

CONTENTS

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Chapter 1

Introduction, Terminology, Abbreviations, and Symbols

CYRIL M. HARRIS

WHAT NOISE IS

A sonorous melody pouring forth from a radio may be very pleasant to one family in a dwelling, but it is a nuisance to those neighbors who are trying to sleep; it is unwanted, it is noise. By definition, noise is *unwanted sound.**

Ambient noise is the all-encompassing noise associated with any given environment, and is usually a composite of sounds from many sources—near and far. For example, suppose there is no traffic on a city street and no other significant noise sources at a given location. Then the ambient noise at this location is pervasive noise (a composite derived from many noise sources) which reaches this location from many directions.

Unfortunately, most of the machines that have been developed for industrial purposes, for high-speed transportation, or to make life more enjoyable by furnishing additional comfort, reducing the drudgery of everyday living, and speeding up our daily routines to provide additional leisure hours, are accompanied by noise. Since noise can affect humans in a number of ways—their hearing, their ability to communicate, and their behavior—noise control has become tremendously important from both economic and medico-legal standpoints. Noise control is also a matter of significance because it can make the world a pleasanter place in which to live.

To ensure that the benefits of noise control are enjoyed by the general public and to protect the general welfare in the U.S.A., the federal government, the states, and most municipalities have enacted legislation and established noise control regulations which are described in the last nine chapters of the handbook. Earlier chapters describe the general properties of sound waves, how sound is propagated, sound waves in rooms, noise measurement equipment and techniques, noise standards, the effects of noise on humans, vibration control, control of noise in buildings, practical application of noise control techniques to specific types of equipment, characteristics and control of transportation noise sources, and the measurement of, and reaction to, community noise.

*Noise also may be defined as sound, generally of a random nature, the spectrum of which does not exhibit distinct frequency components.

WHAT NOISE CONTROL IS

Noise control is the technology of obtaining an acceptable noise environment, consistent with economic and operational considerations. The acceptable environment may be required for an individual, a group of people, an entire community, or a piece of equipment whose operation is affected by noise. When the word "acceptable" is employed, such questions as the following are raised: Acceptable under what conditions? Acceptable to whom? There is usually no unique answer to such questions for a given noise problem because of the complexity of the economic and operational considerations which are involved, and because all the elements may vary with time.

Noise control is not the same as noise reduction. In a specific problem, the amount of noise reduction required to achieve acceptable results sometimes may be obtained simply by applying all the various noise-reduction techniques listed in a following section. But, as illustrated in Chap. 26, this procedure may be unnecessarily costly and wasteful, and it may result in needless interference with normal operations. The problem should be analyzed systematically to determine how acceptable conditions might be achieved in the most economical way. In unusual cases the solution to some noise control problems may even suggest a noise *increase*, rather than a noise reduction. Consider, for example, the waiting room in a physician's office that is separated from the consultation room by a partition which provides so little sound insulation that private conversation can be overheard in the waiting room. Acceptable conditions in the waiting room could be achieved by the construction of a partition providing greater airborne sound insulation. A possible alternate solution is to *increase* the noise level in the waiting room by installing another noise source there (for example, a fan) so as to "mask" the conversation that would otherwise be overheard. While this latter solution has its disadvantages, it is much more economical—and therefore may be more desirable under some circumstances. It illustrates once again that "noise control" and "noise reduction" are not always synonymous.

ECONOMIC IMPORTANCE OF NOISE CONTROL

Noise is a problem of very great economic importance in modern society. Thus when the noise level in business or educational institutions is high enough to interfere with speech communication, economic losses are sustained. Compensation cases involving claims for many millions of dollars as a result of permanent hearing damage are now in the courts (Chap. 13). Another aspect of the economic importance of noise is shown by the effects of noise on property values. For example, the noise from the operation of an airfield or from a factory may influence the value of the land in the surrounding area. For economic reasons, a considerable effort is being made by industry to develop products that are quiet, and by the business world to achieve quiet conditions in offices and factories. While it is not always possible to state explicit relationships between noise and its effects on man, or for the laboratory scientist—at this time—to demonstrate that some of these effects even exist, it is of utmost significance that business and industry are spending considerable amounts of money annually to achieve conditions of quiet. It has been estimated that during the past decade in the United States, the total annual dollar sales of acoustical materials have increased tenfold. It may be argued that this increase is the result of sales promotional effort; to some extent this is true, as it is with most products. On the other hand, such rapid growth can be fully accounted for only on the basis of the fact that people do not like noise. They are annoyed by it. They are distracted by it. Noise is a public nuisance. Many business firms find their customers object to noise. Furthermore, their employees prefer not to work in a noisy environment. People like quiet. Usually they are willing to pay for it.

HOW MUCH NOISE REDUCTION IS REQUIRED

The following steps are taken to determine the amount of noise reduction required for a specific problem:

1. *Evaluate the noise environment, under existing or expected conditions.* Existing conditions may be evaluated from noise measurements which furnish data that are statistically significant. This process requires the appropriate selection and use of meas-

urement equipment, accurate calibration, the taking of data under properly controlled conditions, and the evaluation of any environmental factors which affect the measurements (see Chaps. 5, 6, and 35). Under some conditions it is impractical or impossible to evaluate existing conditions. In such cases, or where the noise environment must be estimated for expected or future conditions, an estimate must be made either from empirical engineering formulas or from existing data. Such information is given in many chapters of this handbook.

2. *Determine what noise level is acceptable.* This information is provided by an appropriate criterion. A criterion may be defined as a standard or rule for judging. Such a standard may be used, for example, for establishing an acceptable limit or restriction that is to be imposed. Noise control criteria provide standards for judging the acceptability of noise levels under various conditions and for various purposes. For example: Chap. 14 gives a criterion for reliable speech communication in the presence of noise; Chap. 18 describes criteria for risk of damage to hearing as a result of exposure to high-level noise for long periods of time, for acceptable noise levels in buildings, for exposure to infrasonic and ultrasonic frequencies, and for human tolerance to vibration; Chap. 36 describes criteria for community response to noise. Such criteria are statistical in nature. A noise level that may constitute a damage risk to the hearing of one person may not have a significant effect on another. Furthermore, the reactions of people are not time-invariant. A community may react to airplane noise entirely differently after several airplane crashes at a nearby airport than it did before. How people react depends to a large extent on their previous history.

3. *The difference between the levels in Steps 1 and 2 represents the noise reduction that must be provided to obtain an acceptable environment.* This difference usually is determined as a function of frequency.

HOW NOISE IS TRANSMITTED

Noise may reach a listener by any one of a number of paths. Suppose, for example, the listener hears a piano in the apartment overhead. Some of the sound may be transmitted to the listener along a direct air path out of the window of the apartment overhead, along an outside path, and through the listener's window. Some of the sound radiated by the piano will strike the walls, forcing them into minute vibration; a fraction of this vibratory energy will travel through the building structure, forcing other wall surfaces elsewhere in the building to vibrate and to radiate sound. Alternatively, some of the vibratory energy may be communicated through the frame of the piano to the floor, entirely along a solid path, setting the floor into vibration and thereby radiating sound in the apartment below.

For convenience, in engineering problems, one may represent the transmission of sound from a source to a listener by the diagram shown in Fig. 1.1. Actually, the block labeled *source* may represent not one, but many sources of vibratory energy, e.g., it may include all the airplanes in the sky above a specified area. As indicated above, the *paths* may be numerous. Finally, the block labeled *receiver* may represent a single person, a group of people, an entire community, or a delicate piece of equipment whose operation is affected by noise.

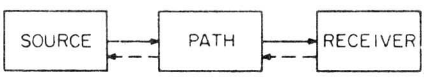

Fig. 1.1 Schematic diagram in which the heavy solid arrows represent the transmission of sound from a source to a listener. The block labeled *source* may represent more than one sound source; the *paths* may be numerous; and the *receiver* may represent a single person, a group of people, an entire community, or equipment whose operation is affected by noise. The broken arrows indicate interaction between the various elements of the block diagram.

Statistical Aspect of the Source, Path, and Receiver In the field of noise control it is always important to bear in mind the statistical aspect of the elements of the block diagram of Fig. 1.1. First, the noise generators represented by the block labeled *source* may vary in number and their outputs may vary in time—as, for example, the case of vehicular traffic at an intersection.

The *path* by which noise reaches our ears from a source is also statistical in nature. For example, consider an airplane circling a listener on the ground. Because of inhomogeneities in the atmosphere, there will be a multitude of variations in the transmission path. These statistical variations in the propagation characteristics of the atmosphere may result in a wide fluctuation in sound level at the listener's ears. As another illustration, consider the noise level in an office which is separated from a noisy factory by a partition with a door in it. When the door is opened, the transmission path is altered. Thus, the noise level in the office varies statistically, depending among other factors on the frequency with which the door to the factory area is opened.

The *receiver* in Fig. 1.1 has its statistical aspects as well. Suppose it represents a large group of people. The actual number in the group may vary from time to time, the threshold of each person in the group will be different, and each of these thresholds may vary with time.

Interaction between Source, Path, and Receiver Although the source, path, and receiver are shown as separate elements in the block diagram of Fig. 1.1, there is considerable interaction among them—they are not independent elements.

The output of a sound *source* is not always a constant but may depend on both the path and the receiver, and on the environment in which the sound source is located. Another type of influence of the environment on the output of a source may take place when the source is a person speaking. When talking to a nearby listener in a small room, a speaker's speech power may be relatively low, but in a large hall or at some distance out of doors, the speaker's power will automatically increase. In fact, the talker is influenced by the receiver as well as the path. The talker who knows the listener is hard of hearing, speaks louder. Another illustration of the influence of the path and receiver on the source is provided by the operator of a noisy machine who varies its operation according to the environmental conditions in which this source of disturbance is placed and the people who may be annoyed by its operation.

It is not always realized that the characteristics of the *path* may be influenced by both the source and receiver. For example, the attenuation provided by a muffler depends to a considerable extent on the characteristics of both the source and the receiver, i.e., the attenuation of the path is not a constant independent of the source and receiver.

Likewise, the reaction of the *receiver* depends upon the characteristics of the path and source. A housewife may go about her chores unaffected by the sound from airplanes that pass overhead. She may be uninfluenced by the rattle of dishes in her cupboard if they are set into vibration by a noisy refrigerator. However, should the rattle of the dishes be caused by airplane noise, her reaction may be entirely different. Thus, it is apparent that there is considerable interaction among the source, path, and receiver, just as there may be among the many components of which the source, path, or receiver may be constituted.

NOISE-CONTROL TECHNIQUES

Throughout this handbook, various methods for controlling noise are considered in detail. In general, these measures may be classified in three categories: (1) noise control at the *source*, (2) noise control of the *transmission* path, and (3) the use of noise protective measures at the *receiver*. Which method, or which combination of methods, is employed depends on the amount of noise reduction that is required and on economic and operational considerations. In solving a specific noise-control problem, the relative benefit to be gained from the application of each technique must be evaluated from the system point of view and compared with its respective cost.

In addition to the techniques described below, which have general application in the field of noise control, measures that may be employed in special problems are described in the specific chapters where they have application.

Noise Control at the Source

One important method of controlling noise at the source is to reduce the amplitude of the forces which result in the generation of noise, for example, by balancing rotating masses or by isolating vibrating components of the source. Another method is to reduce the motion of the components which are set into vibration; for example, the vibration of panels which are set into vibration may be reduced by application of vibration-damping materials or by alteration of the resonance frequencies of the panels, as described in Chaps. 20 and 26.

Changes in the usual procedure of operation may be an effective noise control technique. Thus some factories, adjacent to residential areas, suspend or reduce noise operations at night, when the normal activity in a community diminishes and the ambient noise level in the community is decreased. Without this ambient noise to "mask" it, the factory noise becomes more noticeable. Because of this and possible interference with sleep, factories that would otherwise operate on a 24-hour-a-day basis may curtail their operations at night.

Control of the Transmission Path

Another general technique of noise reduction is that of controlling the transmission path so as to reduce the energy that is communicated to the receiver. This may be done in a number of ways:

Siting In the open air, maximum attenuation should be provided by increasing—insofar as possible—the distance between the source and the receiver. Since many noise sources do not radiate uniformly in all directions, by altering the relative orientation of the source and receiver a considerable reduction in noise level at the receiver may be possible. Thus the orientation of an airport runway may be an important consideration in reducing noise in an adjacent community. Where possible, a site should be chosen that will take advantage of the natural terrain to provide additional shielding of the receiver from the source.

Building Layout The careful planning of the location of rooms within a building, with respect to the relative position of the noise sources and those areas in which quiet conditions are desired, may result in considerable economy by reducing the extent of the noise control measures that otherwise would be required (see Chap. 24).

Barriers Barriers in the open air can be effective when they are large in size compared with the wavelength of the sound to be deflected (see Chap. 3). For example, barriers which make an angle of 45° with respect to the horizontal have been used in the noise field of jet aircraft engines to reflect the high frequencies toward the sky. The use of barriers or partial enclosures in rooms is discussed in Chaps. 24 and 26.

Enclosures Considerable attenuation may be provided by the use of a properly designed enclosure around a noise source or around the receiver (Chap. 26).

Absorption One of the most effective means of attenuating sound in its transmission path is by means of absorption. Suppose a number of machines are in operation in a large office. Most of the noise from these sources that reaches workers on the opposite side of the room is reflected by the ceiling, walls, and floor. Therefore the use of sound absorption in the form of acoustical materials (see Chap. 21) on the ceiling provides attenuation in the path between the source and receiver. Such absorption also reduces the level of the sound which reaches the workers after a multiplicity of reflections from the walls, ceiling, and floor (see Chap. 4). If noise is communicated by a ventilation duct, attenuation along this path may be employed in the form of sound absorptive lining (Chap. 28).

Mismatch The flow of acoustic energy along the path from the source to the receiver can be impeded by discontinuities which reflect energy back toward the source. In dwellings, this may be provided by a discontinuity in the building construction, as described in Chap. 23. Sound transmission in air can be similarly impeded. Mufflers operate on this principle, although some mufflers also may include absorption in the transmission path (Chap. 26).

Protective Measures at the Receiver

The following noise-control techniques may be employed where the noise level at the receiver is excessive:

Ear Protectors Ear plugs, ear muffs, and helmets (described in Chap. 12) provide an economical means of reducing the noise exposure of industrial workers.

Booths In many cases it is impractical or uneconomical to reduce the noise level to which a worker is exposed; it is better to provide a booth or partial enclosure for the worker.

Hearing Conservation Programs and Education The value of hearing conservation programs in industry is discussed in Chap. 11. Education forms an important component of such a program. In some cities where noise has been a serious problem, both industrial and government installations have improved their relations with the community by interesting it in their noise problem and showing the community the constructive steps taken to minimize the disturbance.

Exposure Control Under some circumstances it is impracticable to reduce extremely intense noise levels in areas where people must work to levels which are considered acceptable for the usual working period. As indicated in Chaps. 18 and 40, a noise level that is not acceptable for a specific period of time may be acceptable for a shorter period. Therefore one noise control technique is the rotation of personnel so that work assignments in the intense noise area are for a limited period of time.

TERMINOLOGY*

This handbook contains many definitions, used in noise control and allied fields, which are not given below. The reader is referred to the index. Also see *Levels* in Chap. 2 for definitions of various kinds of levels.

absorption coefficient: See *sound absorption coefficient.*

acoustic, acoustical: The qualifying adjectives *acoustic* and *acoustical* mean: containing, producing, arising from, actuated by, related to, or associated with sound. *Acoustic* is used when the term being qualified designated something that has the properties, dimensions, or physical characteristics associated with sound waves; *acoustical* is used when the term being qualified does *not* designate explicitly something which has such properties, dimensions, or physical characteristics.

acceleration: See *vibration acceleration.*

acceleration of gravity: The acceleration produced by the force of gravity at the surface of the earth. It varies with the latitude and elevation of the point of observation. Unit symbol: g. (By international agreement, the value of g is 9.80665 m/sec^2 = 980.665 cm/sec^2 = 386.089 in./sec^3 = 32.1740 ft/sec^2. Acceleration magnitude is frequently expressed as a multiple of g.)

acoustical insulation material: Material used in insulating against the transmission of airborne sound into a room.

acoustics: The science and technology of sound, including its production, transmission, and effects.

acoustic trauma: A hearing injury which is caused by exposure to a sudden intense sound, such as that produced by an explosion, or a blow to the head.

ambient noise: All-encompassing noise associated with a given environment, being usually a composite of sounds from many sources, near and far. No particular sound is dominant.

ambient vibration: The all-encompassing vibration associated with a given environment, being usually a composite of vibration from many sources near and far.

amplitude: The maximum value of a sinusoidal quantity.

anechoic room: Same as *free-field room.*

artificial ear: A device for the measurement of characteristics of an earphone which presents an acoustic impedance equivalent to the impedance presented by the average human ear. It is equipped with a microphone for the measurement of the sound pressure developed by the earphone.

audible sound: (1) Acoustic oscillations of such a character as to be capable of exciting the sensation of hearing. (2) Sensation of hearing excited by an acoustic oscillation.

audio frequency: Any frequency of a normally audible sound wave. (Audio frequencies generally lie between 20 and 20,000 Hz.)

audiogram: A graph showing hearing (threshold) level as a function of frequency.

audiologist: A person trained in the specialized problems of hearing and deafness.

air conduction: The process by which sound travels to the inner ear via a pathway through the air in the outer ear canal, then utilizing the tympanic membrane and the ossicles. See Chap. 10.

audiometer: An instrument for the measurement of hearing acuity and hearing level.

audiometric room: A room insulated against outside noise and having some sound absorption, intended for testing of hearing.

average sound pressure level: See *Levels*, Chap. 2.

A-weighted sound level: See *Levels*, Chap. 2.

A-weighted sound power level: See *Levels*, Chap. 2.

*Many of these definitions are in conformity with those contained in standards available from the American National Standards Institute, Inc., 1430 Broadway, New York, NY 10018, and/or the American Society for Testing Materials, 1916 Race St., Philadelphia, PA 19103.