HANDBOOK
OF
NOISE CONTROL

Edited by

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PREFACE

People do not like noise. By definition, it is *unwanted* sound. It may interfere with speech communication on jobs or in leisure activities; in certain respects it may affect behavior; it may produce a temporary hearing loss, and if the noise level is high enough, it may be responsible for permanent damage to hearing.

Noise control is therefore a matter of considerable social and economic importance. This has become increasingly true in recent years. In consequence it has brought together individuals of widely varying vocations who share a vital interest in the problem: acoustical engineers, physicists, electrical engineers, designers of military equipment, aeronautical engineers, mechanical engineers, ventilation engineers, builders, architects, city planners, public health officials, industrial hygienists, otologists, physiologists, psychologists, transportation authorities, industrial designers, business executives, lawyers, and compensation experts. This range of interests is reflected in the contributors who have cooperated in the writing of this handbook. They are divided equally among government, university, and industrial organizations.

Although there have been many scientific articles on various aspects of noise, and lengthy technical reports have been issued by government agencies and industrial organizations, this is the first book to be published in the United States on the general subject of noise control.

Over the years there has been an increasingly large quantity of material published on noise, some of which is more popularly than accurately written. A need has therefore developed for an authoritative work covering the entire field. Consideration was given to the division of the field into separate volumes, each with its own author. But since all areas of noise control are interrelated, such separate volumes cannot treat these interrelationships as effectively as can a single work; furthermore, useless duplication of material would result. A handbook type of presentation has permitted a highly unified treatment of the specialized areas—each one covered by an expert in his field.

The chapters in this handbook are included in the following general groupings: properties of sound, effects of noise on man, vibration control, instrumentation and noise measurement, techniques of noise control, noise control in buildings, sources of noise and examples of noise control, noise control of machinery and electrical equipment, noise control in transportation, community noise, and the legal aspects of noise problems.

In the writing of this book many authorities have spent much time and effort preparing their respective chapters. Their labor, willing collaboration, diligence, and patience have been immense. Thanks are due also to their colleagues who read and commented on the chapters during their preparation.

Many of the authors are with the Department of Defense in either a civilian or military capacity. Some are with other departments of the government. The material which they present has been released for publication, but the opinions expressed are not official and therefore do not necessarily reflect views of the relevant agency.

The wealth of technical information contained in this volume has been gathered through diligent effort on the part of the contributors. In this regard, publications of the Acoustical Society of America have been particularly helpful. Much of the material is heretofore unpublished; we are greatly indebted to the many industrial organizations, government agencies, and engineering consultants who have been credited throughout the book. Special thanks are due to the Department of Defense, to the American Standards Association, to the Controller of Her Brittanic Majesty's Stationery Office, and to the Director of Building Research for permission to reproduce material in this handbook.

Cyril M. Harris

HANDBOOK OF NOISE CONTROL

CONTENTS

Chapter 1

INTRODUCTION AND TERMINOLOGY

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INTRODUCTION

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.*

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 affects man in a number of ways—his hearing, his ability to communicate, and his behavior—noise control, from both economic and medico-legal standpoints, has become tremendously important. In addition, noise control has become a matter of significance because it can make the world a pleasanter place in which to live. The chapters that follow will consider the various effects of noise on man, noise measurements, methods of noise control, practical applications of noise-control techniques, and the legal aspects of the noise problem.

How Noise Is Transmitted. Noise may reach a listener by any one of a number of paths. Suppose, for example, he 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 his 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.

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.

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.

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. In a technical sense, we say that when the output of a noise source has been so influenced by its surroundings, the "radiation impedance" of the source has been altered by its environment. Another type of influence of the environment on the output of a source may take place when the source is a person speaking. If he talks to a nearby listener in a small room, his speech power may be relatively low, but in a large hall or at some distance out of doors, his power will automatically increase. In fact, the talker is influenced by the receiver as well as the path. If he knows the listener is hard of hearing, he will raise his voice. 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 he may annoy 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, it is shown in Chap. 21 that the attenuation provided by mufflers and acoustic filters 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. For example, 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.

WHAT NOISE CONTROL IS

Noise control is the technology of obtaining an acceptable noise environment, at a receiver, consistent with economic and operational considerations; the receiver may be a person, 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 this procedure may be unnecessarily costly and wasteful, and it may result in needless interference with normal operations. In contrast, from the standpoint of good noise-control technique, the same problem would 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 his consultation room by a partition which provides so little sound insulation that private conversations can be overheard in the waiting room. Acceptable conditions in the waiting room could be achieved by the construction of a partition providing greater air-borne 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

Because noise can affect man's ability to communicate with his neighbors by speech, because noise may affect his behavior, because noise may have some permanent damaging effect on his hearing, and because he simply may regard it as being annoying, noise is a problem of very great economic importance in modern society. For example, quantitative relationships can be obtained to show how one's ability to understand speech is reduced by the influence of noise (Chap. 9). 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. 38). 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 (Chap. 37). 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 their 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. During the past 10 years in the United States, the total dollar sales of acoustical materials have increased from about 10 to 60 million dollars. 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. They are willing to pay for it.

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

* In some industries it is important that noises associated with their products have a certain quality. For example, automobile manufacturers consider it desirable that the noise produced by the slamming of an automobile door have a "big-car quality."

reduction 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. For example, a method is described in Chap. 29 for controlling noise from transformer substations which is based on the principle of "noise cancellation." Here, the reduction in noise at the receiving position is achieved by generating a second sound source which is just "out of phase" with the original source of disturbance, so as to cancel it. Although this technique has limited application (primarily for steady, pure-tone sources, such as transformer noise), it has been used successfully over small areas.

Noise Control at the Source. Important methods of controlling noise at its source include (1) the reduction of the amplitude of the exciting forces, (2) the reduction of the response of various components of the system to these exciting forces (components that generate noise when excited or that transmit vibratory energy to surfaces that will radiate sound), and (3) changes in operating procedure. It may be impractical for the purchaser of equipment to employ any of the measures listed below which involve equipment modification. In this case, he may best reduce the noise at its source by the selection of the quietest source or the quietest components of which the source is comprised, consistent with other requirements.

Reduction of the Exciting Forces.

a. REDUCTION OF IMPACTS OR IMPULSIVE FORCES.

b. BALANCING OF MOVING MASSES. (See Chaps. 12 and 30 for a discussion of the balancing of shafts of rotating machinery.)

c. BALANCING OF MAGNETIC FORCES. (In electric motors and generators, both *b* and *c* must be considered. See Chap. 30.)

d. REDUCTION OF FRICTIONAL FORCES BY PROPER ALIGNMENT AND LUBRICATION. (See Chap. 23.)

e. THE USE OF DYNAMIC COMPENSATION. So-called "dynamic absorbers" provide a compensating force which is out of phase with the exciting force and hence reduce the total energy transmitted to the structure (Chap. 14).

f. VIBRATION ISOLATION. The vibration isolation of the components of a source, or of the entire source itself, can be effective in greatly reducing the exciting forces (see Chaps. 12 and 13).

Reduction of the Response of Noise-radiating Components in the System to the Exciting Forces. When components in a system are set into vibration, they will radiate sound. Application of the following techniques can reduce this noise at its source.

a. ALTERATION OF THE NATURAL FREQUENCY OF A RESONANT ELEMENT. A panel may be set into strong vibration when the frequency of the exciting force corresponds with, or is near, the natural frequency of the panel. Under these conditions, the vibration of the panel, and hence the noise which is produced by it, may be reduced by altering the natural frequency of the panel. For example, this may be done by increasing the mass of the panel (which will lower the natural frequency), by increasing its stiffness (which will raise the natural frequency), or by changing the dimensions of the panel.

b. INCREASING THE ENERGY DISSIPATION. Vibration-damping materials (Chap. 14) may be applied to the radiating surfaces. In this way, very substantial reductions in noise output may be obtained.

Changes in Operating Procedure. Changes in the usual procedure of operation may be effective as a 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 general background noise is decreased. Without this background noise to "mask" it, the factory noise becomes more noticeable. Because of this and because of possible interference with sleep, factories that would otherwise operate on a 24-hour-a-day basis 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:

a. SITING. In the open air, maximum attenuation should be provided by increasing—in so far 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. For example, 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.

b. 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 where quiet conditions are desired, may result in a considerable economy by reducing the extent of the noise-control measures that would otherwise be required.

c. PATH DEFLECTION. Barriers in the open air can be effective when they are large in size compared with the wavelength of the noise to be deflected (Chap. 3). For example, deflecting surfaces 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 upward toward the sky. The use of barriers or partial partitions in rooms is discussed in Chap. 22.

d. ENCLOSURES. Considerable attenuation may be provided by the use of a properly designed enclosure around a noise source or around the receiver (Chap. 20).

e. ABSORPTION. One of the most effective means of attenuating sound in its transmission path is by means of absorption. For example, 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 will have been reflected by the ceiling, walls, and floor. Therefore, the use of sound absorption in the form of acoustical materials on the ceiling, or carpet on the floor, will provide attenuation in the path between the source and receiver (Chap. 18). If noise is communicated by a ventilating duct, attenuation along this path may be employed in the form of a sound-absorptive lining (Chap. 27).

f. IMPEDANCE MISMATCH (acoustic filters, mufflers). The flow of acoustic energy along the path from source to receiver can be impeded by discontinuities which reflect the energy back toward the source (i.e., by an "impedance mismatch"). In dwellings, this may be provided by a break in the building construction (Chap. 19). Sound transmission in the open air can be similarly impeded. For example, the stack of an exhaust blower can be designed to provide the greatest reflection of acoustic fan-noise energy at its outlet, in order to minimize the radiation of blower noise from the stack. Acoustic filters and mufflers operate on this principle, although some mufflers may also include absorption in the transmission path (Chap. 21).

Protective Measures at the Receiver. The following noise-control techniques may be employed where the noise level at the receiver is considered to be excessive.*

Use of Personal Protective Equipment. Where noise levels in an environment are excessive, the use of earplugs, earmuffs, noise helmets, or small booths may reduce the levels to a point where the noise hazard will be reduced to a condition of acceptability (Chap. 8).

Education and Public Relations. 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 by showing the com-

* One manufacturer found that for a particularly noisy operation in his factory, the combination of all the techniques described above, including that of personal protective measures, would not provide sufficient protection for his workmen at an economical price. The most practical solution was the use of a closed-circuit television system for monitoring the operation and the use of appropriate remote-controlled devices in the noisy areas. Such extreme measures are seldom necessary.

munity that constructive steps were being taken to minimize the disturbance. A dramatic example of this took place at an Air Force base in Wisconsin, where public discontent was turned to public pride as the result of the application of noise-control techniques, public education to the problem, and a good public-relations policy.

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 Chap. 34, a noise level that is unacceptable for one 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 only.

HOW MUCH NOISE REDUCTION IS REQUIRED

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

1. *Determine the noise level in the environment where the receiver is located, under existing or expected conditions.* This may be done by measurements or from estimates based on available data.
2. *Determine what noise level is acceptable.* This information is provided by an appropriate criterion.
3. *Use the difference between* 1 *and* 2 *as the noise reduction that must be provided to obtain an acceptable environment.* This noise reduction is usually determined as a function of frequency.

Determination of Noise Level in the Receiver Environment. Noise measurements should furnish data that is statistically significant for the selection or evaluation of noise-control procedures. This requires the use of the appropriate equipment for the job, accurate calibration, the taking of data in the various frequency bands under properly controlled conditions, and the evaluation of other factors which influence the measurements—for example, the effects of the environment (Chaps. 16 and 17).

Under some circumstances it is impracticable or impossible to make noise measurements on various sources. In such cases one frequency can obtain a useful engineering estimate from information provided by existing data, which specifies the conditions of measurement. Many noise analyses are given throughout this handbook. By way of illustration in this chapter, data from one type of noise survey are shown in Appendix 1.1.

Noise Control Criteria. A *criterion* is defined as a standard of judging. Noise control criteria provide standards for judging the acceptability of noise levels under various conditions and for various purposes.

Criteria can be stated for man's tolerance to vibration, for risk of damage to hearing as a result of exposure to high-intensity noise, for reliable speech communication in the presence of noise, for acceptable noise levels in different types of buildings, for community reaction to noise, etc. Such criteria are statistical in nature. For example, 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. Thus how they react depends to a large extent on their previous history and how they intercommunicate. A community may react to airplane noise entirely differently after a series of airplane crashes than it did before.

To illustrate the statistical aspect of such criteria, consider a factory in which there is a continuous noise level of very high intensity, in an area where men spend eight hours a day. A damage-risk criterion could be established here which would indicate a "safe" upper limit for the noise spectrum. If the noise level does not exceed this limit, 99 per cent of the factory population would be protected against risk of damage to their hearing; but if, for example, this limit were raised by x db, then only 90 per cent would be protected. After the noise-control engineer has been provided with information which specifies the percentage of the group that is to be protected, the length of exposure time per man, and the amount of hearing loss that is considered significant, he may use such a criterion to determine the level to which the noise must be reduced. Thus the difference between this level and the existing level, obtained by appropriate measurements, indicates the noise reduction in decibels that must be provided. The desired results then may be obtained by application of noise-control techniques described in detail in the chapters which follow.

TERMINOLOGY

Throughout this handbook, definitions of terms used in noise-control work are given in various chapters. (In particular, see Chap. 2, *Physical Properties of Noise*, and Chap. 12, *Principles of Vibration Control*.) For convenience definitions of terms which are used frequently in the general field of noise control are assembled here. Many of these definitions are quotations, with permission, from *American Standard Terminology* (Z24.1-1951), American Standards Association.† These definitions have been denoted by an asterisk(*). Others have been modified from this standard or are proposed revisions. For terms which are not listed below, the reader is referred to the index.

Absorption Coefficient (Acoustical Absorptivity) (α). The sound-absorption coefficient of a surface which is exposed to a sound field is the ratio of the sound energy absorbed by the surface to the sound energy incident upon the surface. The absorption coefficient is a function of both angle of incidence and frequency. Tables of absorption coefficient which are given in the literature usually list the absorption coefficients at various frequencies, the values being those obtained by averaging over-all angles of incidence.

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 designates 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.

Acoustics. Acoustics is the science of sound, including (*a*) its production, transmission, and effects, or (*b*) the qualities that determine the value of a room or other enclosed space with respect to distinct hearing.

Acoustic Impedance. The acoustic impedance of a sound medium on a given surface lying in a wave front is the impedance obtained from the ratio of the sound pressure (force per unit area) on that surface by the flux (volume velocity, or linear velocity multiplied by the area) through the surface. When concentrated rather than distributed impedances are considered, the impedance of a portion of the medium is based on the pressure difference effective in driving that portion and the flux (volume velocity). The acoustic impedance may be expressed in terms of mechanical impedance divided by the square of the area of the surface considered. (Velocities in the direction along which the impedance is to be specified are considered positive.)

Acoustical Ohm.* An acoustic resistance, reactance, or impedance has a magnitude of 1 acoustical ohm when a sound pressure of 1 microbar produces a volume velocity of 1 cu cm per sec.

Acoustic Power. (See *Sound Power.*)

Acoustic Power Level. (See *Sound Power Level.*)

Acoustic Reactance. Acoustic reactance is the imaginary component of the acoustic impedance.

Acoustic Refraction. Acoustic refraction is the process by which the direction of sound propagation is changed because of spatial variation of the wave velocity in the medium.

Acoustic Resistance.* Acoustic resistance is the real component of the acoustic impedance.

Acoustic Scattering. Acoustic scattering is the irregular and diffuse reflection, refraction, or diffraction of a sound in many directions.

Ambient Noise. Ambient noise is the all-encompassing noise associated with a given environment, being usually a composite of sounds from many sources near and far.

Amplitude of a Periodic Quantity. The amplitude of a periodic quantity is the maximum value of the quantity.

Anechoic Room. (See *Free-field Room.*)

† Copies of this standard, as well as others in the field of acoustics, vibration, and mechanical shock, are available from the American Standards Association, Inc., New York 17, N.Y.

Angular Frequency (ω). The angular frequency of a periodic quantity is its frequency in radians per unit time, usually radians per second. It is thus the frequency multiplied by 2π.

Antinodes. An antinode is a point, line, or surface in a vibrating body or system at which the amplitude of motion, relative to that at a node, is a maximum.

Antiresonant Frequency.* An antiresonant frequency is a frequency at which antiresonance exists.

Articulation (Per Cent Articulation) and Intelligibility (Per Cent Intelligibility). Per cent articulation or per cent intelligibility of a communication system is the percentage of the speech units spoken by a talker or talkers that is understood correctly by a listener or listeners. The word "articulation" is customarily used when the contextual relations among the units of the special material are thought to play an unimportant role; the word "intelligibility" is customarily used when the context is thought to play an important role in determining the listener's perception. The kind of speech material used is identified by an appropriate adjective in phrases such as "syllable articulation," "individual sound articulation," "vowel (or consonant) articulation," "word articulation," "discrete word intelligibility," "discrete sentence intelligibility."

Articulation Score. (See *Discrimination for Speech.*)

Audio Frequency (Sonic Frequency). An audio frequency is any frequency corresponding to a normally audible sound wave, roughly from 15 to 20,000 cps.

Audiogram (Threshold Audiogram).* An audiogram is a graph showing hearing loss, per cent hearing loss, or per cent hearing as a function of frequency.

Audiometer.* An audiometer is an instrument for measuring hearing acuity. Measurements may be made with speech signals, usually recorded, or with tone signals.

Aural Critical Band. The aural critical band is that frequency band of sound, being a portion of a continuous-spectrum noise covering a wide band, that contains sound power equal to that of a simple (pure) tone centered in the critical band and just audible in the presence of the wide band noise. In order to be just audible in a wideband continuous noise, the level of a simple tone in decibels must exceed the spectrum level of the continuous noise (at the same frequency) by 10 times the logarithm to the base 10 of the ratio of the critical bandwidth to unit bandwidth.

Aural Harmonic.* An aural harmonic is a harmonic generated in the auditory mechanism.

Band Pressure Level.* The band pressure level of a sound for a specified frequency band is the effective sound pressure level for the sound energy contained within the band. The width of the band and the reference pressure must be specified. The width of the band may be indicated by the use of a qualifying adjective: e.g., octave-band (sound pressure) level, half-octave band level, third-octave band level, 50-cps band level. If the sound pressure level is caused by thermal noise, the standard deviation of the band pressure level will not exceed 1 db if the product of the bandwidth in cycles per second by the integration time in seconds exceeds 20.

Beats. Beats are periodic variations that result from the superposition of two simple harmonic motions of different frequencies f_1 and f_2. They involve the periodic increase and decrease of the amplitude at the beat frequency $(f_1 - f_2)$.

Characteristic Impedance. The characteristic impedance of a medium is the ratio of the effective sound pressure at a given point to the effective particle velocity at that point in a free plane progressive sound wave. The characteristic impedance is equal to the product of the density by the speed of sound in the medium, i.e., (ρc).

Characteristic Impedance of Air ($\rho_0 c$). (See *Characteristic Impedance.*) Values of the characteristic impedance of air for various temperatures and pressures are given in Fig. 2.8.

Circular Frequency. (See *Angular Frequency.*)

Compliance. Compliance is the reciprocal of stiffness.

Compressional Wave.* A compressional wave is a wave in an elastic medium which causes an element of the medium to change its volume without undergoing rotation.

Continuous Spectrum.* A continuous spectrum is the spectrum of a wave, the components of which are continuously distributed over a frequency region.

Coupled Modes. Coupled modes are modes of vibration which are not independent but which mutually influence one another because of energy transfer from one mode to the other.

Critical Band. (See *Aural Critical Band.*)

Critical Speed. Critical speed is the rotating speed of a system which corresponds to a resonant frequency of the system.

Cycle.* A cycle is the complete sequence of values of a periodic quantity which occur during a period.

Cycle per Second (cps). A unit of frequency. In many European countries the cycle per second is called the *Hertz.*

Cylindrical Wave.* A cylindrical wave is a wave in which the wavefronts are coaxial cylinders.

Damage-risk Criterion. A damage-risk criterion specifies the maximum sound pressure levels of a noise, as a function of frequency, to which people should be exposed if risk of hearing loss is to be avoided. This criterion includes a specification of the time of exposure, amount of hearing loss considered significant, and the percentage of the population to be protected.

Dead Room.* A dead room is a room which is characterized by an unusually large amount of sound absorption.

Decibel (db). The decibel is a unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels corresponding to the ratio of two amounts of power is 10 times the logarithm to the base 10 of this ratio. In many sound fields, the sound-pressure ratios are not proportional to the square root of the corresponding power ratios, so that strictly speaking the term *decibel* should not be used in such cases; however, it is common practice to extend the use of the unit to these cases (see, for example, *Sound Pressure Level*).

Degrees of Freedom. The number of degrees of freedom of a mechanical system is equal to the number of independent displacements which are possible. In general, it is equal to the minimum number of independent coordinates required to define completely the position of the system at any given instant.

Difference Limen (Differential Threshold) (Just Noticeable Difference).* A difference limen is the increment in a stimulus which is just noticed in a specified fraction of the trials. The relative difference limen is the ratio of the difference limen to the absolute magnitude of the stimulus to which it is related.

Diffracted Wave. A diffracted wave is one whose front has been changed in direction by an obstacle or other nonhomogeneity in a medium, otherwise than by reflection or refraction.

Diffraction.* Diffraction is that process which produces a diffracted wave.

Diffuse Sound Field (Random-incidence Sound Field). A diffuse sound field is a sound field such that the sound pressure level is everywhere the same, and all directions of energy flux are equally probable.

Discrimination for Speech (Articulation Score). The discrimination for speech, or articulation score, of an ear is the percentage of items in an appropriate form of test, usually monosyllabic words, that is correctly repeated, written down, or checked by the listener. This form of test is usually administered at an acoustic level well above the threshold for speech. The normal value of discrimination (or articulation score) for each test must be determined empirically.

Discrimination Loss. Discrimination loss is the difference between the normal discrimination score for the test and the score obtained for the ear under test.

Distortion.* Distortion is a change in wave form. Noise and certain desired changes in wave form, such as those resulting from modulation or detection, are not usually classed as distortion.

Doppler Effect.* The Doppler effect is the phenomenon evidenced by the change in the observed frequency of a wave in a transmission system caused by a time rate of change in the effective length of the path of travel between the source and the point of observation.

Doppler Shift.* The Doppler shift is the magnitude of the change in the observed frequency of a wave due to the Doppler effect.

Double Amplitude. (See *Peak-to-peak Amplitude.*)

Echo. An echo is a wave which has been reflected or otherwise returned with sufficient magnitude and delay to be perceived as a wave distinct from that directly transmitted.

Efficiency. The efficiency of a device with respect to a physical quantity which may be stored, transferred, or transformed by the device is the ratio of the useful output of the quantity to its total input.

Effective Sound Pressure (p) **(Root-mean-square Sound Pressure).** The effective sound pressure at a point is the root-mean-square value of the instantaneous sound pressures, over a time interval at the point under consideration. In the case of periodic sound pressure, the interval must be an integral number of periods or an interval long compared to a period. In the case of nonperiodic sound pressures, the interval should be long enough to make the value obtained essentially independent of small changes in the length of the interval. The term "effective sound pressure" is frequently shortened to "sound pressure."

Flutter Echo.* A flutter echo is a rapid succession of reflected pulses resulting from a single initial pulse.

Forced Oscillation (Forced Vibration). The oscillation of a system is forced if the response is imposed by the excitation. If the excitation is periodic, the oscillation is steady-state.

Free Field. A free sound field is a field in a homogeneous, isotropic medium free from boundaries. In practice it is a field in which the effects of the boundaries are negligible over the region of interest. The actual pressure impinging on an object (e.g., a microphone) placed in an otherwise free sound field will differ from the pressure which would exist at that point with the object removed, unless the acoustic impedance of the object matches the acoustic impedance of the medium.

Free-field Room (Anechoic Room). A free-field room is a room in which essentially free-field conditions exist.

Free Oscillation (Free Vibration). Free oscillation of a system is the oscillation of some physical quantity of the system when there are no externally applied driving forces. Such *oscillation is maintained by the transfer of energy between elastic restoring forces and* inertia forces. The oscillation may arise from initial displacements, velocities, or a force suddenly applied and withdrawn.

Free Progressive Wave (Free Wave).* A free progressive wave is a wave in a medium free from boundary effects. A free wave in a steady state can only be approximated in practice.

Frequency (*f*). The frequency of a function periodic in time is the reciprocal of the period. The unit is the cycle per unit time, e.g., cycles per second (cps) or kilocycles per second (kc or kcps).

Fundamental Mode of Vibration.* The fundamental mode of vibration of a system is the mode having the lowest frequency.

Fundamental Frequency. The fundamental frequency of a periodic quantity is equal to the reciprocal of the shortest period during which the quantity exactly reproduces itself.

g. The quantity g is the acceleration produced in a mass by the force of gravity; it is *approximately equal to 32.2 ft per sec*^{2} $=$ *386 in. per sec*^{2} $=$ *981 cm per sec*^{2}.

Harmonic.* A harmonic is a sinusoidal quantity having a frequency which is an integral multiple of the fundamental frequency of a periodic quantity to which it is related.

Hearing Loss. The hearing loss of an ear at a specified frequency is the amount, in decibels, by which the threshold of audibility for that ear exceeds the normal threshold.

Hearing Loss for Speech.* Hearing loss for speech is the difference in decibels between the speech levels at which the average normal ear and the defective ear, respectively, reach the same intelligibility, often arbitrarily set at 50 per cent.

Hertz (Hz). (See *Cycle per Second.*)

Impedance. An impedance is the complex ratio of a forcelike quantity (force, pressure, voltage) to a related velocitylike quantity (velocity, volume velocity, or current).

Infrasonic Frequency (Subsonic Frequency).* An infrasonic frequency is a frequency lying below the audio-frequency range.

Instantaneous Sound Pressure.* The instantaneous sound pressure at a point is the total instantaneous pressure at that point minus the static pressure at that point.

Intensity (*I*). The sound *intensity measured in a specified direction at a point is the* average rate at which sound energy is transmitted through a unit area perpendicular to the specified direction at the point considered. Only in plane or spherical free progressive sound waves is the intensity related to the average pressure p by the equation $I = p^2/\rho_0 c$, where $\rho_0 c$ represents the characteristic impedance of air.

Intensity Level (Sound-energy Flux-density Level) (L_I). The intensity level, in decibels, of a sound is 10 times the logarithm to the base 10 of the ratio of the intensity of this sound to the reference intensity. The reference intensity shall be stated explicitly; however, a commonly used reference is 10^{-16} watt per sq cm in a specified direction. In a plane progressive wave, there is a known relationship between sound-energy flux density and sound pressure, so that sound-energy flux-density level can be deduced from a measurement of sound pressure level. In general, however, there is no simple relationship between the two and a measurement of sound pressure level should not be reported as intensity level.

Jerk. Jerk is a vector which specifies the time rate of change of the acceleration of a *particle; jerk is the third derivative of the displacement of the particle with respect to time.*

Just Noticeable Difference. (See *Difference Limen.*)

Level. In communication and 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.

Level above Threshold (Sensation Level) (L_S). The level above threshold of a sound is the pressure level of the sound in decibels above its threshold of audibility for the individual observer.

Line Spectrum.* A line spectrum is the spectrum of a wave, the components of which are confined to a number of discrete frequencies.