

CHAPTER 26 VIBRATION

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INTRODUCTION

Exposure to vibration is frequently associated with exposure to noise in industrial processes since the two often originate from the same operation. However, the adverse effects resulting from exposure to noise and to vibration are quite different in nature, the former having a more substantial basis than the latter for establishing a cause-and-effect relationship both qualitatively and quantitatively. As more information concerning industrial exposures to vibration becomes available, particularly within the United States, and appropriate exposure criteria are established and standards adopted, the now common practice of taking noise surveys in industrial situations will likely be extended by the use of a vibration sensor to assist the investigator in evaluating the exposures of workers to both noise and vibration.

The effects of exposure to noise have been thoroughly investigated and the results of these studies are reflected in current legislation. Although a significant amount of research is underway on the relationship between exposure to vibration and the health and well-being of the persons exposed, sufficient evidence for the establishment of occupational health standards has not yet been developed.

Therefore the purpose of this chapter is to acquaint the reader with the general principles involved in recognition, evaluation and control of workers' exposure to vibration. Except to the extent necessary, the chapter will not discuss considerations of vibration in noise control efforts, since this is done in detail in Chapter 37.

EFFECTS OF VIBRATION ON MAN

The human body is an extremely complex physical and biological system. When looked upon as a mechanical system, it contains a number of linear and non-linear elements, the mechanical properties of which differ from person to person. Biologically, and certainly psychologically, the system is by no means any simpler than it is mechanically. On the basis of experimental studies, as well as documented reports of industrial experience, it is apparent that exposure of workers to vibration can result in profound effects on the human body — mechanically, biologically, physiologically and psychologically.

It should be noted at this point that relatively few studies of industrial exposures to vibration have been conducted in the United States; most of the available literature on documentations of effects of vibration in industrial situations has been

published in European countries. There have been considerable numbers of military and, relatively recently, agriculturally applied research programs in the United States. The application of such studies to general industrial situations is obviously limited. However, they have been valuable in determining some of the parameters of importance in investigating the response of people exposed to vibration and, for this reason, results of some of these studies will be discussed later in this chapter.

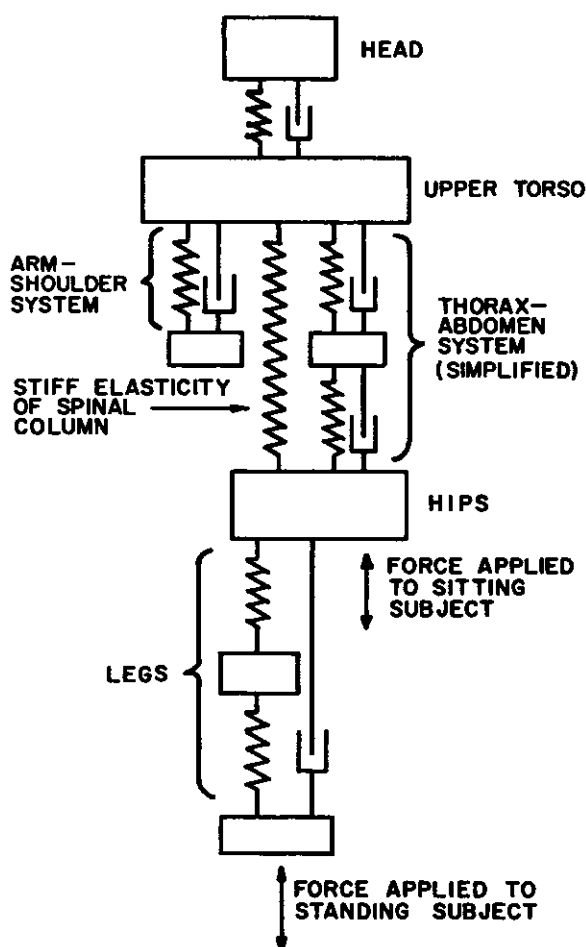


Figure 26-1. Simplified Mechanical System Representing the Human Body Standing (or Sitting) on a Vertically Vibrating Platform.¹

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When considering the effects of vibration on man, it is necessary to classify the type of vibration exposure into one of two categories on the basis of the means by which the worker contacts the vibrating medium. The first category is referred to as "whole body" vibration and results when the whole body mass is subjected to the mechanical vibration as, for example, from a supporting surface such as a tractor seat. The second category is usually referred to as "segmental" vibration and is defined as vibration in which only part of the body, for example the hand or hands operating a chain saw, is in direct contact with the vibrating medium and the bulk of the body rests on a stationary surface. This classification of vibration does not necessarily mean that parts of the body other than those in direct contact with the vibrating surface are not affected.

If the whole body is considered as a mechanical system, at low frequencies and low vibration levels it may be approximated roughly by a simplified mechanical system such as that depicted in Figure 26-1.

Results of some of the research studies conducted in the United States are presented in Figures 26-2 and 26-3.^{2, 3, 4} These studies have shown that, for whole body vibration, the tolerance of a seated man is lowest in the frequencies between approximately 3 and 14 Hertz. As with any tangible object, it is possible to apply externally generated vibrations to the human body at certain frequencies and in such a way that the body becomes more in resonance with the vibrating source than at other frequencies. These studies have indicated that such whole body resonances occur

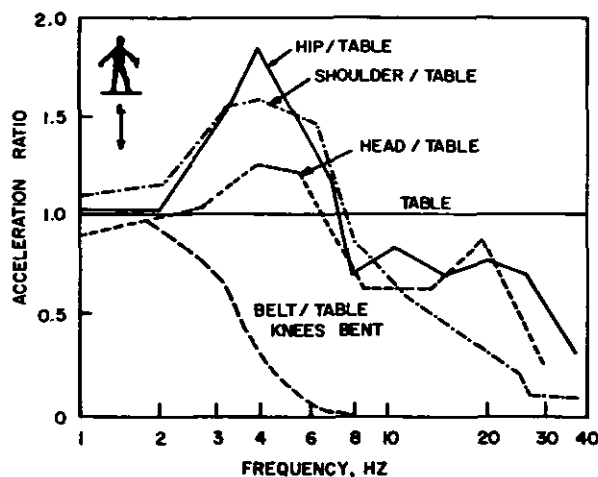


Figure 26-2. Transmissibility of Vertical Vibration from Supporting Surface to Various Parts of the Body of a Standing Human Subject as a Function of Frequency.^{2, 3, 4}

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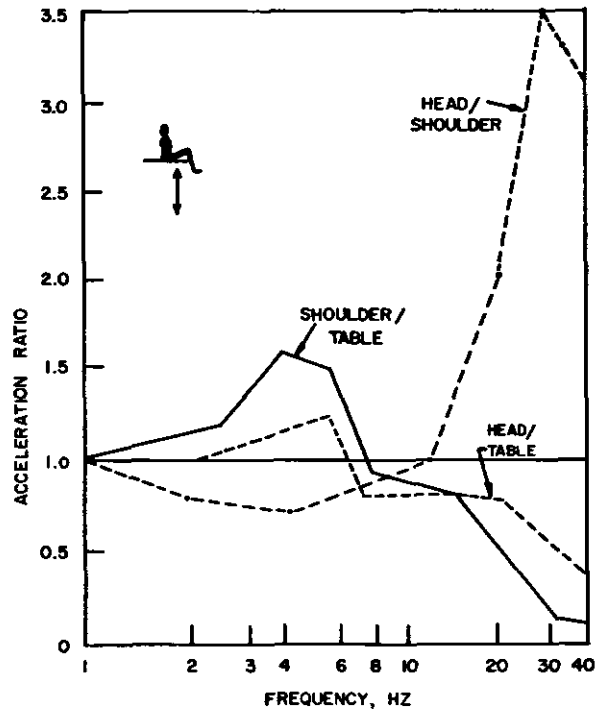


Figure 26-3. Transmissibility of Vertical Vibration from Supporting Surface to Various Parts of a Seated Human Subject as a Function of Frequency.^{2, 4}

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in the frequency range 3-6 Hertz and 10-14 Hertz. The studies have also indicated the presence of resonant effects in some of the sub-systems of the body as a result of exposure to whole body vibration. For example, resonance of the head-shoulder sub-system has been found in the 20-30 Hz range; disturbances which suggest eyeball resonance have been indicated in the 60-90 Hz range; and a resonance effect in the lower jaw and skull sub-system has been reported for the 100-200 Hz range.

The preceding discussion has dealt with mechanical responses to vibration, however, there are pronounced physiological and psychological effects resulting from exposures to whole body vibration as well. Although these effects are rather complex and usually difficult to measure, the subjective responses of man to whole body vibration have been fairly well documented in the European literature. A few causal relationships between the biomechanical effects of whole body vibration and consequent physiological changes in the body are apparent. These physiological observations have included evidence of a slight acceleration in the rate of oxygen consumption, pulmonary ventilation and cardiac output.^{5, 6, 7, 8} There is evidence of an

inhibition of tendon reflexes and an impairment in the ability to regulate the posture, possibly by actions through both the vestibular and spinal reflex pathways.^{9, 10} Alterations have been recorded in the electrical activity of the brain and there has been evidence of effects on visual acuity and performance at various levels of motor activity and task complexity during exposure to whole body vibration.^{11, 12} These and other studies conducted in Europe have indicated that whole body vibration has effects on the endocrinological, biochemical and histopathological systems of the body as well.

The most extensive investigations of industrial exposures of workers to vibration have been concerned with repeated exposure to low frequency vibration transmitted through the upper extremities of the worker; that is, during the use of hand-held power tools which incorporate rapidly rotating or reciprocating parts. Such studies therefore consider the effects of "segmental" vibration on the worker. Unfortunately, most of these studies present only general descriptions of the clinical evidence of overexposure to vibration and very few contain any controlled observations by quantitative techniques; consequently there is a large variability between the observations reported by different investigators. However, the main features of what can be called a vibration syndrome are evident.

The clinical evidence of overexposure to vibration during the use of hand tools can be conveniently grouped into four categories.¹³ These four types of disorders, in decreasing order of their appearance in the published literature, are:

1. A traumatic vaso-spastic syndrome in the form of Raynaud's phenomenon (discussed in more detail below);
2. Neuritis and degenerative alterations, particularly in the ulnar and axillar nerves, that is, a loss of the sense of touch and thermal sensations as well as muscular weakness or even paralysis, and abnormalities of the central nervous system;
3. Decalcification of the carpal and metacarpal bones; fragmentation, deformation and necrosis of carpal bones; and
4. Muscle atrophy, tenosynovitis.

As indicated earlier, the prevalence of the different symptom groups varies tremendously in the reports of different investigators. However, a fair estimate of the average overall prevalence of the vibration syndrome, at least as typified by the Raynaud phenomenon, appears to be around 50%; that is, about half of the workers exposed to segmental vibration exhibit clinical symptoms characteristic of the Raynaud phenomenon.

Raynaud's Syndrome

Raynaud's syndrome or "dead fingers" or "white fingers" occurs mainly in the fingers of the hand used to guide a vibrating tool. The circulation in the hand becomes impaired and, when exposed to cold, the fingers become white and void of sensation, as though mildly frosted. The condition usually disappears when the fingers are warmed for some time, but a few cases have been suffi-

ciently disabling that the men were forced to seek other types of work. In some instances, both hands are affected.

This condition has been observed in a number of occupations involving the use of fairly light vibrating tools such as the air hammers used for scarfing and chipping in the metal trades, stone-cutting, lumbering and in the cleaning departments of foundries where men have a good deal of overtime work. Obviously, prevention of this condition is much more desirable than treatment. Preventive measures include directing the exhaust air from the air-driven tools away from the hands so they will not become unduly chilled, use of handles of a comfortable size for the fingers, and in some instances, substituting mechanical cleaning methods for some of the hand methods which have produced many of the cases of "white fingers." In many instances, simply preventing the fingers from becoming chilled while at work has been sufficient to eliminate the condition.

The appearance of the syndrome appears to be a function of the cumulative absorption of vibration energy, its harmonic content and on personal factors such as the age of the worker. Vibration in the frequency range 40-125 Hz has been implicated most frequently in reported cases of vibration disorders.^{14, 15} In most studies it appeared that an exposure time of several months was generally needed before symptoms appeared. With continued exposure there was a progressive diversification and intensification of the symptoms; some improvement of symptoms has been reported, but rarely complete recovery, with cessation of exposure to vibration. It is the opinion of many investigators in Europe that the vibration syndrome is a widespread and alarmingly common occupational disorder.¹³ Symptoms of overexposure are reportedly grave or moderately grave in about half of those affected, and in all cases result in a varying loss of working capacity.

Results of the European studies of industrial vibration exposures are summarized in Table 26-1. These data were obtained from reports issued by investigators in several countries: Austria, Czechoslovakia, France, Finland, Germany, Great Britain, Italy, the Netherlands, Russia, Sweden and others. In general, these studies revealed abnormal changes in the vascular, gastric, neurological, skeletal, muscular and endocrine systems as well as definite effects on visual acuity and task performance. The presence of Raynaud's syndrome was common to practically all studies of exposures to segmental vibration. It is beyond the intent of this chapter to discuss any of the hundreds of articles published in the literature on these studies; bibliographies on the subject have been published and should be reviewed by the interested reader.^{13, 16}

As can be seen from Table 26-1 the vibration syndrome does indeed appear to be a widespread occupational disorder in European industry. It must be noted here again that similar studies in industries in the United States have been very limited. However, it is reasonable to assume that United States workers employed in occupations

TABLE 26-1
EUROPEAN INDUSTRIES IN WHICH
CLINICAL EVIDENCE OF OVEREXPOSURE
OF WORKERS TO VIBRATION
HAS BEEN REPORTED

Industry	Type of Vibration	Common Vibration Sources
Agriculture	Whole body	Tractor operation
Boiler Making	Segmental	Pneumatic tools
Construction	Whole body Segmental	Heavy equipment vehicles, pneumatic drills, jackhammers, etc.
Diamond cutting	Segmental	Vibrating hand tools
Forestry	Whole body Segmental	Tractor operation chain saws
Foundries	Segmental	Vibrating cleavers
Furniture manufacture	Segmental	Pneumatic chisels
Iron and steel	Segmental	Vibrating hand tools
Lumber	Segmental	Chain saws
Machine tools	Segmental	Vibrating hand tools
Mining	Whole body Segmental	Vehicle operators rock drills
Riveting	Segmental	Hand tools
Rubber	Segmental	Pneumatic stripping tools
Sheet metal	Segmental	Stamping equipment
Shipyards	Segmental	Pneumatic hand tools
Stone dressing	Segmental	Pneumatic hand tools
Textile	Segmental	Sewing machines, looms
Transportation (operators and passengers)	Whole body	Vehicle operation

similar to those listed in Table 26-1 are being potentially exposed to excessive levels of vibration during their routine work activities. The National Institute for Occupational Safety and Health (NIOSH) has initiated a comprehensive program in which the occupational exposures to vibration in American industries is being investigated.¹⁶

VIBRATION EXPOSURE CRITERIA

It is obvious from the preceding discussion that the occurrence of vibration disorders in a wide

cross section of industry is significant enough, both in terms of prevalence and magnitude, that appropriate standards for allowable exposure to vibration are desirable. However, at the present time there are no generally accepted limits for safe vibration levels and, in fact, the available literature, because of the variability of reported findings, does not permit the reliable construction of a vibration exposure standard. All this is not to say that individual standards and criteria, as well as corrective methods for dealing with excessive levels of industrial vibration, have not been attempted; in fact, they have. However, the approaches to establishment of criteria and/or im-

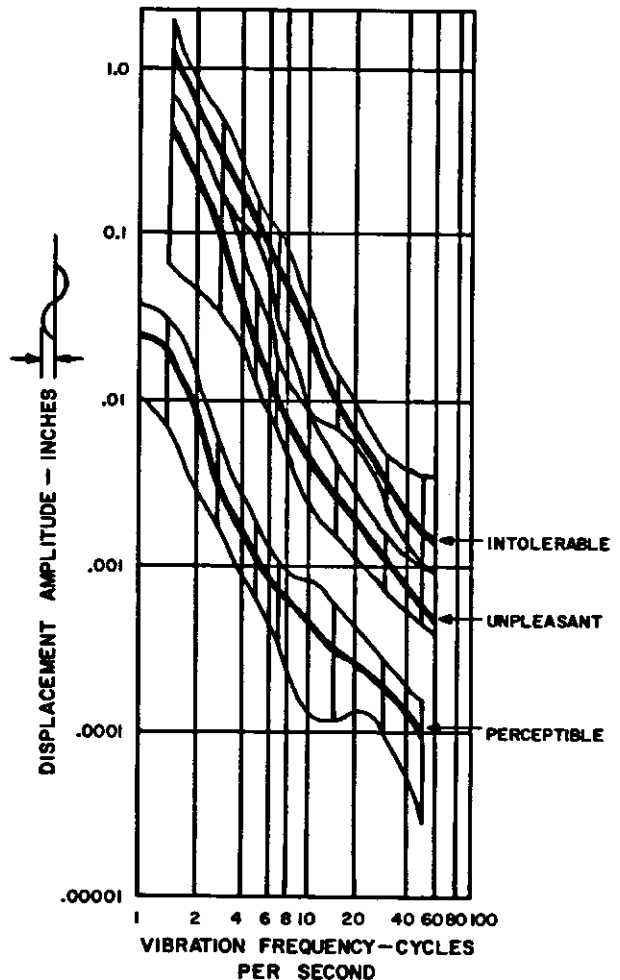


Figure 26-4. Subjective Responses to Vibratory Motion. The chart is based on the averaged values of various investigators and is valid for exposures up to a few minutes. The vertical arrows represent one standard deviation above and below the means.

McFarland RA Human engineering and industrial safety.

Reprinted from Vol. 1, F. A. Patty "Industrial Hygiene and Toxicology", 2nd edition. Courtesy Interscience Publishers, Inc., New York, N.Y., 1958.

plementation of corrective methods have been quite variable even within a given country.

Many studies have been conducted in which the subjective responses of exposed personnel to various levels of vibration have been documented. The results of experimental studies with human volunteers conducted by three different investigators are presented in Figure 26-4.¹⁷ It must be emphasized that these data and, in fact, all such data in which *experimental* exposures have been documented are useful only over a very limited time duration. Most of these studies have been conducted for military and/or aerospace programs and are concerned primarily with acute exposures; that is, relatively short duration exposure such as impact or shock type of vibrations encountered in military situations. The subjects selected for such studies, therefore, are normal young, physically fit men, such as pilots. There are obvious pitfalls, therefore, in using such information as a basis for establishment of standards for industrial exposures to vibration. In the occupational workplace the normal work force is comprised of persons constituting a wide spectrum of characteristics. The industrial worker can be female as well as male, is not necessarily as physically fit as the subjects

used in experimental studies, and certainly encompasses a greater range of age and other physical characteristics. Perhaps of more significance, however, is the fact that these experimental investigations represent acute or short-term exposures to vibration and certainly do not permit direct extrapolation to the typical industrial exposure which is comprised, for the most part, of exposure to relatively low frequency vibration of varying amplitudes for extended periods of time. In the case of the industrial worker then, one must be concerned with the cumulative effects of exposure to vibration over a working lifetime which can be comprised of exposure to vibration for, in an extreme example, 40 hours per week, 50 weeks per year for 40 years. Suffice to say, therefore, that the types of human exposure studies that have been conducted in the United States have limited application in the industrial environment.

Attempts have been made to establish vibration exposure standards and, of these, perhaps the single best vibration exposure criteria guides are those proposed by the International Standards Organization.¹⁸ These criteria, presented in Figure 26-5 as a family of curves, are valid for vibrations transmitted to the torso of a standing or sit-

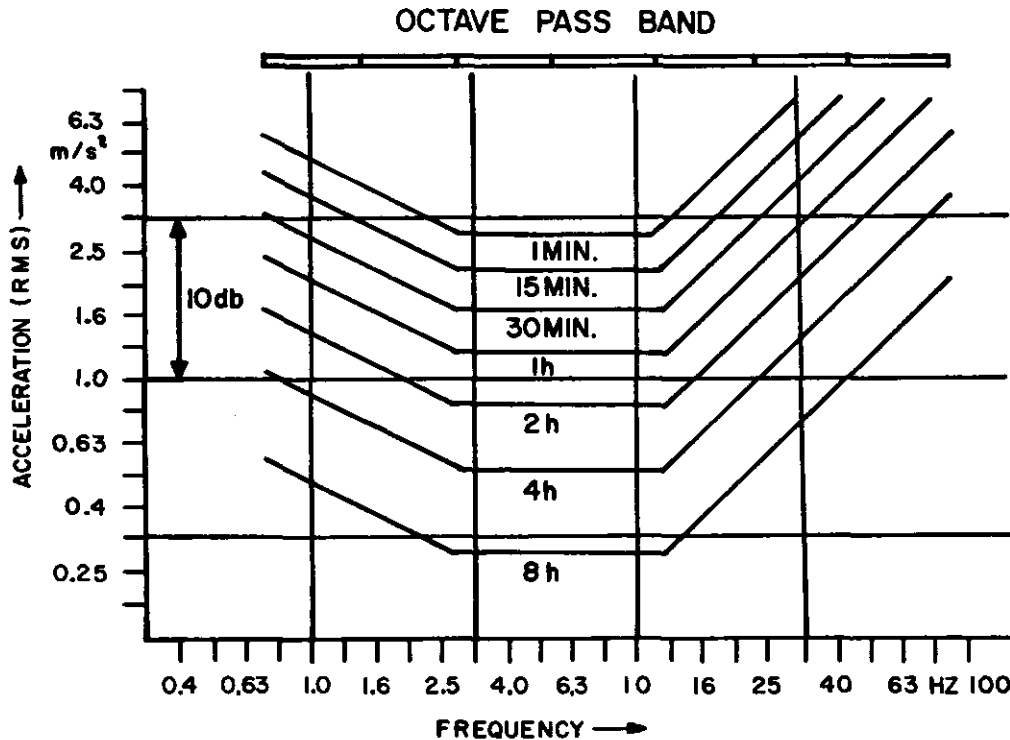


Figure 26-5. *Vibration Exposure Criteria Curves.* The vibration levels indicated by the curves in Figure 26-5 are given in terms of RMS acceleration levels which produce equal fatigue-decreased proficiency. Exceeding the exposure specified by the curves, in most situations, will cause noticeable fatigue and decreased job proficiency in most tasks. The degree of task interference depends on the subject and the complexity of the task.

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ting person and are, therefore, to be considered a guide for whole body vibration. A tentative ISO vibration guide has been proposed for segmental (hand-arm system vibrations).¹⁹ The ISO whole body vibration guide is based to a great extent on studies conducted in the aerospace medical research laboratories in formulating guides for short-term exposures, usually of a military nature and thus again may have only limited application in industrial work environments.

The vibration levels indicated in Figure 26-5 are given in terms of the root mean square acceleration levels which produce equal "fatigue-decreased proficiency" over the frequency range of 1-100 Hz. Vibrations in frequencies below 1 Hz produce annoyances which are individually unique; for instance, cinetosis or air sickness. For frequencies above 100 Hz the vibrational perceptions are mainly effective on the skin and depend greatly upon the influenced body part and on the damping layer; for example, clothing or shoes. It seems, therefore, practically impossible to state generally valid vibration exposure criteria for frequencies outside the range indicated in Figure 26-5, that is, 1-100 Hertz. Exceeding the exposures specified by the curves in most situations will cause noticeable fatigue and decreased job efficiency. The degree of task interference depends on the subject and the complexity of the task being performed. The curves indicate the general range for onset of such interferences and the time dependency observed. An upper exposure

considered hazardous to health as well as performance is considered to be twice as high (6 decibels higher) as the "fatigue-decreased efficiency" boundary shown in Figure 26-5 while the "reduced comfort" boundary is assumed to be about $\frac{1}{2}$ (10 decibels below) the illustrated levels.

Again, these criteria are presented as recommended guidelines or trend curves, rather than firm boundaries of classified quantitative biological or psychological limits. They are intended solely for situations involving healthy, normal people considered fit for normal living routines and stress of an average work day. A program for establishing vibration exposure based upon identification and characterization of exposed workers in industries in the United States and implementation of relevant studies to ascertain the extent of the industrial vibration hazard and determination of criteria for these standards to prevent adverse exposures to industrial vibration has been initiated.¹⁶

CHARACTERISTICS OF VIBRATION

In general, vibration can be described as an oscillatory motion of a system. The "motion" can be simple harmonic motion, or it can be extremely complex. The "system" might be gaseous, liquid or solid. When the system is air (gaseous) and the motion involves vibration of air particles in the frequency range of 20 to 20,000 Hertz (Hz), sound is produced. For the purposes of this chapter, only the effects on the worker caused by mo-

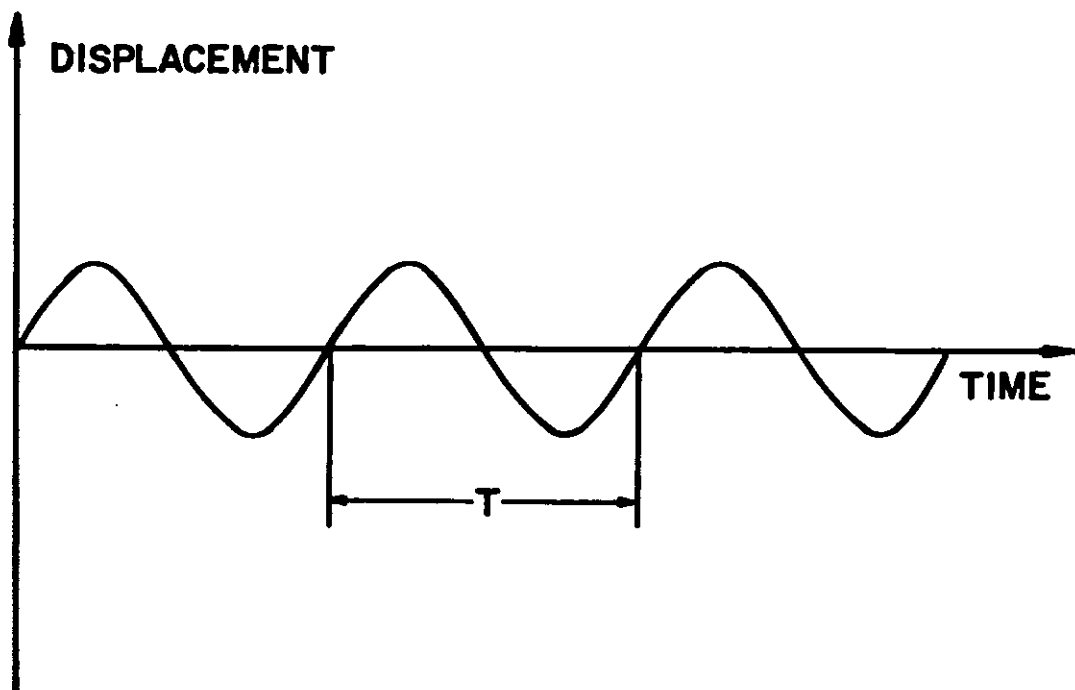


Figure 26-6. Representation of Pure Harmonic (Sinusoidal) Vibration.

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tion of *solid* systems will be considered.

The oscillation of the system may be periodic or completely random; steady-state or transient; continuous or intermittent. In any event, during vibration one or more particles of the system oscillate about some position of equilibrium.

Periodic (Sinusoidal) Vibration

Vibration is considered periodic if the oscillating motion of a particle around a position of equilibrium repeats itself *exactly* after some period of time. The simplest form of periodic vibration is called pure harmonic motion which as a function of time, can be represented by a sinusoidal curve. Such a relationship is illustrated in Figure 26-6, where T = period of vibration.

The motion of any particle can be characterized at any time by (1) displacement from the equilibrium position, (2) *velocity*, or rate of change of displacement, or (3) *acceleration*, or rate of change of velocity. For pure harmonic motion, the three characteristics of motion are related mathematically.

Displacement

The instantaneous displacement of a particle from its reference position under influence of harmonic motion can be described mathematically as:

$$s = S \sin \left(2\pi \frac{t}{T} \right) = S \sin (2\pi ft) = S \sin \omega t$$

where s = instantaneous displacement from reference position

S = maximum displacement

t = time

T = period of vibration

f = frequency of vibration

ω = angular frequency ($2\pi f$)

Of the possible vibration measurements, displacement probably is the easiest to understand and is significant in the study of deformation and bending of structures. However, only if the rate of motion, i.e. frequency of vibration, is low enough, can displacement be measured directly.

Velocity

In many practical problems, displacement is not the most important property of the vibration. For example, experience has shown that the velocity of the vibrating part is the best single criterion for use in preventive maintenance of rotating machinery.

Although peak-to-peak displacement measurements have been widely used for this purpose, it is necessary to establish a relationship between the limits for displacement and rotational speed for each machine.

Since the velocity of a moving particle is the change of displacement with respect to time, the particle's velocity can be described as:

$$v = \frac{ds}{dt} = \omega S \cos(\omega t) = V \cos(\omega t) = V \sin\left(\omega t + \frac{\pi}{2}\right)$$

where

v = instantaneous velocity

V = maximum velocity

Acceleration

In many cases of vibration, especially where mechanical failure is a consideration, actual forces

set up in the vibrating parts are critical factors. Since the acceleration of a particle is proportional to these applied forces and since equal-and-opposite reactive forces result, particles in a vibrating structure exert forces on the total structure that are a function of the masses and accelerations of the vibrating parts. Thus, acceleration measurements are another means by which the motion of vibrating particles can be characterized.

The instantaneous acceleration, i.e., the time rate of change of velocity of a particle in pure harmonic motion, can be described as:

$$a = \frac{dv}{dt} = \frac{d^2s}{dt^2} = -\omega^2 S \sin(\omega t) = A \sin(\omega t + \pi)$$

where a = instantaneous acceleration and

A = maximum acceleration.

Other terms, such as "jerk," defined as the time rate of change of acceleration, are sometimes used to define vibration. At low frequencies, jerk is related to riding comfort of automobiles and elevators and is also important for determining load tie-down in airplanes, trains and trucks. However, from the equations and definitions presented in the preceding discussion, it is apparent that, regardless of the parameter being studied, i.e., displacement, velocity, acceleration or jerk, the form and period of the vibration are the same.

As noted above, the instantaneous magnitudes of the various parameters have been defined in terms of their peak values, that is, the maximum values obtained. This approach is quite useful in the consideration of pure harmonic vibration because it can be applied directly in the above equations. However, in the consideration of more complex vibrations it is desirable to use other descriptive quantities. One reason for this is that the peak values describe the vibration in terms of a quantity dependent only upon an instantaneous vibration magnitude, regardless of the previous history of the vibration. One descriptive quantity which does take the time history into account is the "average absolute value" defined as:

$$S \text{ (average)} = \frac{1}{T} \int_0^T |s| dt$$

Although the above quantity does take the time history of the vibration into account over one period, it has very limited practical usefulness. The root mean square (rms) value is a much more useful descriptive quantity which also takes the time history of the vibration parameter into account. This quantity is defined as:

$$S_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T s^2(t) dt}$$

The importance of the rms value as a descriptive quantity lies mainly in its direct relationship to the energy content of the vibration. For example, in the case of pure harmonic motion the relationship between the various values is:

$$S_{\text{rms}} = \frac{\pi}{2\sqrt{2}} S \text{ (average)} = \frac{1}{\sqrt{2}} S$$

Or, in a more general form:

$$S_{\text{rms}} = F_f \quad S \text{ (average)} = \frac{1}{F_c} S$$

The factors, F_f and F_c , are called "form factor" and "crest factor," respectively, and give an indication of the wave shape of the vibration being studied. For pure harmonic motion

$$F_f = \frac{\pi}{2\sqrt{2}} = 1.11$$

and

$$F_c = \sqrt{2} = 1.414$$

There have been attempts to introduce the concept of "acceleration level" and "velocity level." These terms, similar in concept to the sound pressure level used in expressing noise levels, indicate the acceleration and velocity in decibels; that is, the logarithm of the ratio of the acceleration or velocity to a reference acceleration

or velocity. Although several references have been proposed, the most common velocity reference value is 10^{-8} meters per second; i.e., 10^{-6} centimeters per second. The acceleration reference value is 10^{-6} meters per second squared or 10^{-4} centimeters per second squared. Suitable "standard reference values" for acceleration, velocity and displacement are still being studied.

The discussion and certainly the equations which have been presented to this point have dealt exclusively with the periodic vibrations, and more specifically with pure harmonic periodic vibrations. It must be pointed out that most of the vibrations encountered in industry and in fact, practically anywhere, are not pure harmonic motions, even though many of them certainly can be characterized as periodic. A typical nonharmonic periodic vibration is illustrated in Figure 26-7.

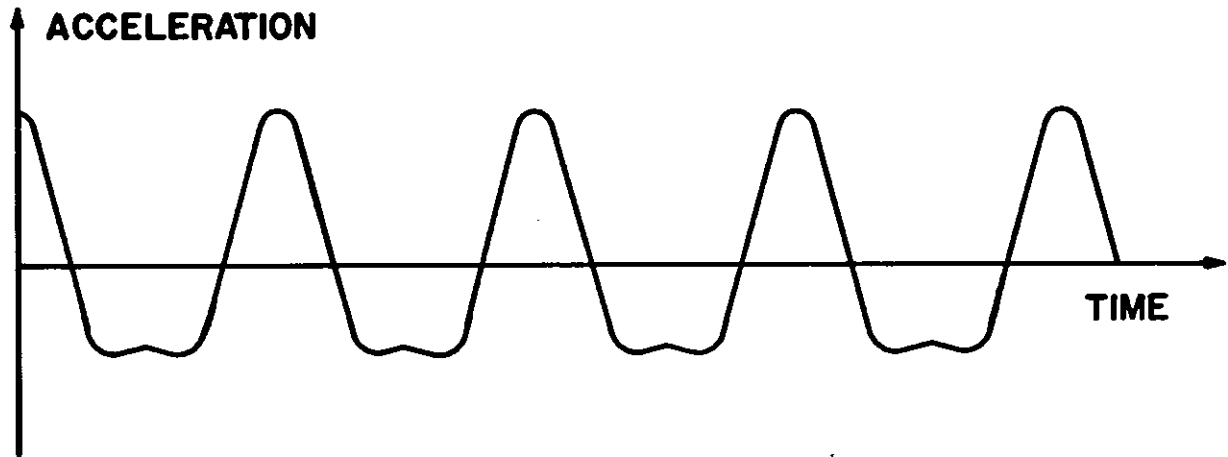


Figure 26-7. Example of a *Non-Harmonic Periodic Motion* (Piston Acceleration of a Combustion Engine).

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By examining this curve and determining the peak absolute and root mean square values of this vibration as well as the form factor and crest factor, it is obvious that the motion is not harmonic. However, on the basis of this information, it would be practically impossible to predict all of the various effects the vibration might produce in connected structural elements. Obviously, other methods of description must be used; one of the most powerful descriptive methods is that of frequency analysis, which is based on a mathematical theorem first formulated by Fourier, which states that "any periodic curve no matter how complex may be looked upon as a combination of a number of pure sinusoidal curves with harmonically related frequencies."

As the number of elements in the series increases, it becomes an increasingly better approximation to the actual curve. The various elements

constitute the vibration frequency spectrum and in Figure 26-8 the non-harmonic periodic vibration illustrated in Figure 26-7 is re-illustrated, together with two important harmonic curves which represent its frequency spectrum. A more convenient method of representing this spectrum is shown in Figure 26-9. This characteristic of periodic vibrations is evident in examining Figure 26-10. Their spectra consist of discrete lines when represented in the so-called "frequency domain"; random vibrations show continuous frequency spectra when represented in similar fashion.

Random Vibrations

Random vibrations occur quite frequently in nature and may be defined as motion in which the vibrating particles undergo irregular motion cycles that *never* repeat themselves exactly. Theoretically then, obtaining a complete description of the vi-

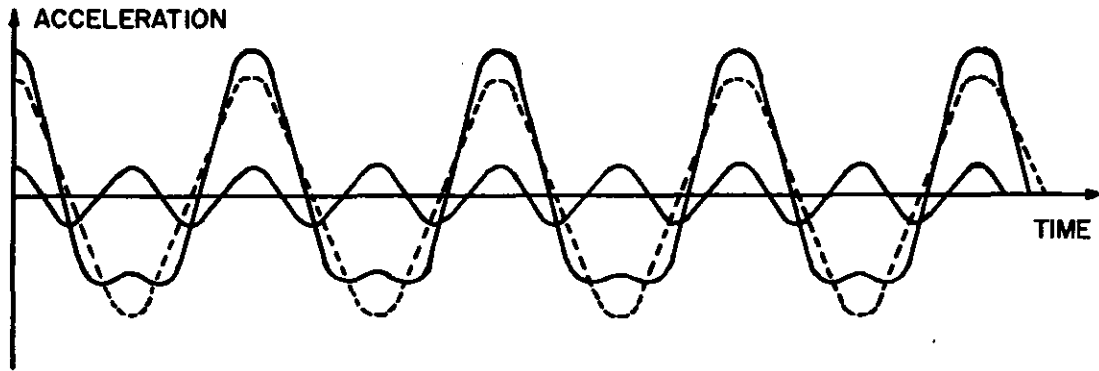


Figure 26-8. Illustration of How the Waveform Shown in Figure 26-7 Can Be "Broken Up" into a Sum of Harmonic Related Sinewaves.

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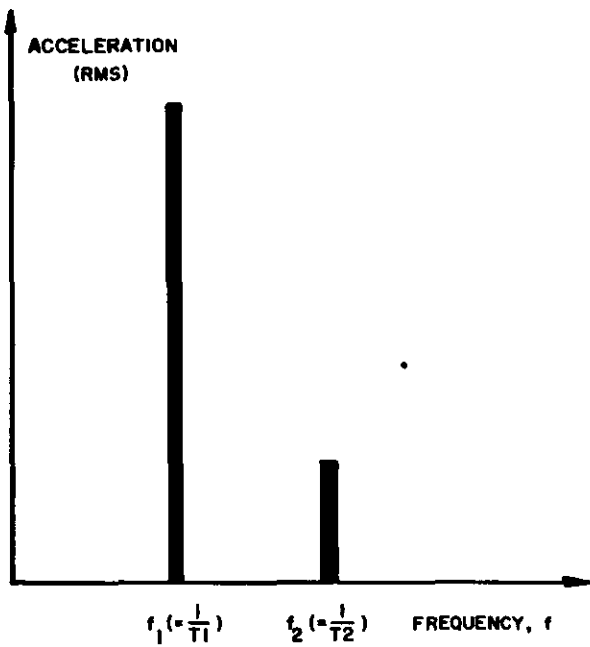


Figure 26-9. Examples of Periodic Signals and their Frequency Spectra.

- a) Description in the time domain.
- b) Description in the frequency domain.

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brations requires an infinitely long time record. This, of course, is an impossible requirement and finite time records would have to be used in practice. Even so, if the time record becomes too long, it also will become a very inconvenient means of describing the vibration, and other methods there-

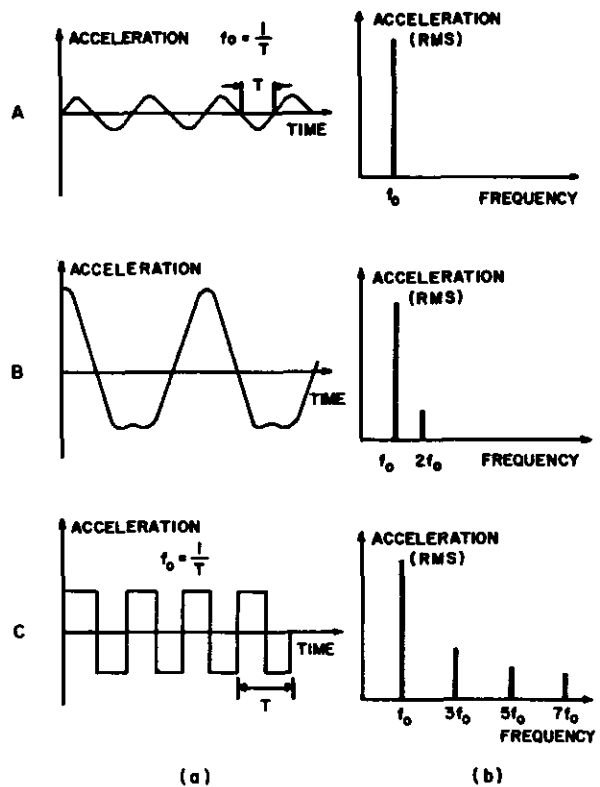


Figure 26-10. Examples of Periodic Signals and their Frequency Spectra.

- a) Description in the time domain.
- b) Description in the frequency domain.

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fore have to be devised, and are commonly used. It is beyond the purpose and intent of this chapter to discuss the theoretical and mathematical models necessary to describe complex vibrations; this information is presented in several well-written scientific and engineering texts.

VIBRATION MEASUREMENTS

Basic Elements In a Measurement System

A wide variety of component systems, consisting of mechanical or a combination of mechanical, electrical and optical elements are available to measure vibration. The most common system uses a vibration pick-up to transform the mechanical motion into an electrical signal, an amplifier to enlarge the signal, an analyzer to measure the vibration in specific frequency ranges and a metering device calibrated in vibrational units.

Vibration Pick-ups

The vibration pick-up measures the displacement, the velocity, or the acceleration of the vibration. These parameters are all inter-related by differential operations so that it does not normally matter which variable is measured. If the result is desired in terms of velocity or displacement, electronic integrators are added at the output of an accelerometer, an instrument which measures the acceleration of a mass due to the vibration signal.

Accelerometers, the most common type of vibration pick-up, are normally smaller than velocity pick-ups and their useful frequency range is wider. An accelerometer is an electromechanical transducer which produces an output voltage signal proportional to the acceleration to which it is subjected.

The most common type of accelerometer is the piezoelectric type, such as the one shown in Figure 26-11, in which two piezoelectric discs

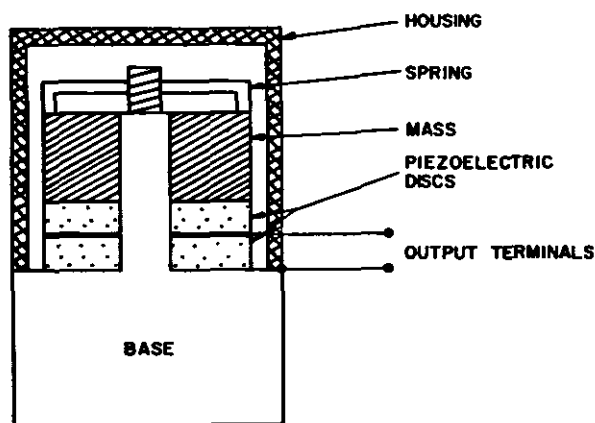


Figure 26-11. Sketch Showing the Basic Construction of the Bruel & Kjaer Compression Type Piezo-Electric Accelerometers (Single-Ended Version).

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produce a voltage on their surfaces due to the mechanical strain on the asymmetric crystals which make up the discs. The strain is in the form of vibrational inertia from a moving mass atop the discs. The output voltage is proportional to the acceleration, and thus to the vibration signal. The upper limit of the accelerometer's useful frequency range is determined by the resonant frequency of the mass and the stiffness of the whole accelerometer system. The lower limit of the frequency range varies with the cable length and the properties of the connected amplifiers. The accelerometer's sensitivity and the magnitude of the voltage developed across the output terminals depends upon both the properties of the materials used in the piezoelectric discs and the weight of the mass. The mechanical size of the accelerometer, therefore, determines the sensitivity of the system; the smaller the accelerometer, the lower the sensitivity. In contrast, a decrease in size results in an increase in frequency of the accelerometer resonance and thus, a wider useful range.²⁰

Other factors to consider in the selection of a suitable accelerometer include:

1. The transverse sensitivity, which is the sensitivity to accelerations in a plane perpendicular to the plane of the discs.
2. The environmental conditions during the accelerometer's operation, primarily temperature, humidity, and varying ambient pressure.

Often two types of sensitivities are stated by the manufacturer—the voltage sensitivity and the charge sensitivity. The voltage sensitivity is important when the accelerometer is used in conjunction with voltage measuring electronics, while the charge sensitivity, an indication of the charge accumulated on the discs for a given acceleration, is important when the accelerometer is used with charge-measuring electronics.

Preamplifier

The preamplifier is introduced in the measurement circuit for two reasons:

1. To amplify the weak output signal from the accelerometer; and
2. To transform the high output impedance of the accelerometer to a lower, acceptable value.

It is possible to design the preamplifier in two ways, one in which the preamplifier output voltage is directly related to the input voltage, and one in which the output voltage is proportional to the input charge, with the preamplifier termed a voltage amplifier or charge amplifier, respectively.

The major differences between the two types of amplifiers rest in their performance characteristics. When a voltage amplifier is used, the overall system is very sensitive to changes in the cable lengths between the accelerometer and the preamplifier, whereas changes in cable length produce negligible effects on a charge amplifier. The input resistance of a voltage amplifier will also affect the low frequency response of a system. Voltage amplifiers are generally simpler than charge amplifiers, with fewer components and are, therefore, less expensive. In selecting the appro-

appropriate preamplifier for vibration work, these above-mentioned factors should all be considered.

Analyzers

The analyzer element in a vibration measuring arrangement determines what signal properties are being measured and what kind of data can be obtained in the form of numbers or curves.

The simplest analyzer consists of a linear amplifier and a detection device measuring some characteristic vibration signal value such as the peak, root mean square, or average value of the acceleration, velocity, or displacement. The phase response of a system must be taken into account, in addition to the frequency response in choosing the correct analyzer. A signal reaching the detection device may look completely different from the signal input to the linear amplifier, due to possible distortions during linear attenuation of a complex signal's various frequency components. Serious waveshape distortion of the signal may be avoided when the fundamental vibration frequency is higher than 10 times the low frequency limit of the measuring system, and the highest significant vibration frequency component has a frequency which is lower than 0.1 times the high frequency limit of the system.²⁰ Phase response can be disregarded for measurement of only RMS values.

In most practical cases it will be necessary to determine the frequency composition of the vibration signal, which is done with a frequency analyzer. Two types of frequency analyzers are commonly available, the constant bandwidth analyzer and the constant percentage bandwidth-type analyzer. If the vibrations are periodic, the constant bandwidth-type analyzer is preferred because the frequency components are harmonically related. If the signal is not quite stable and only the first few harmonics are significant, such as characteristic of a shock signal, a constant percentage bandwidth-type analyzer is suitable. If the vibration signal is random in nature, the type of analyzer will depend on the use to be made of the measurement as well as the frequency spectrum itself.

If the vibrations are periodic, the frequency spectra are presented in terms of the RMS value of the signal, defined earlier.

In random vibrations, the RMS-value fluctuates during measurement because the averaging time is limited to a practical time limit and the time of observation is greater than the averaging time of the instrument. A decrease in averaging time will cause considerable fluctuations in the RMS values.

Vibration Recorders

Many types of metering or recording devices are available to exhibit the analyzer output. These are divided into three classes: the strip-chart recorder which prints the output on preprinted calibrated recording paper; the vibration meter which indicates some characteristic value (RMS, peak, etc.) on a precalibrated scale; and an oscilloscope, which projects the wave form on a screen for analysis and measurement.

When a strip-chart recorder is used, the aver-

aging time is determined by the writing speed of the recording pen, the input range potentiometer, and other internal properties of the recorder instead of observation time. The choice of averaging time affects the recording of a random vibration frequency spectrum.

The oscilloscope presents measurements as a function of time, and makes possible the study of instantaneous values of vibration. An oscilloscope with slow sweep rates, long-persistence screen, and a DC amplifier is recommended for most studies.

Accessories

The accessories used with vibration meters are determined by customer needs and usually can be built into any specified instrument. Integrators to interconvert displacement, velocity, and acceleration can be specified in the basic circuit design of measuring devices. Often, a series of ranges can be requested for a frequency analyzer, depending on the accuracy of the measurements required.

Additional analyzers including the third-octave-bandwidth, tenth-octave-bandwidth, one-percent-bandwidth, and a wave analyzer are available. Different recorders, dependent on desired output, can be used in conjunction with any analyzer. For peak or high speed impacts, the signal can be recorded on tape and then replayed at varied speeds to give the optimum measurement on an electric output signal.

A calibrator is an important accessory for checking the overall operation of a vibration-measuring system. The common calibrator is nothing more than an accelerometer, driven by a small, electromechanical oscillator mounted within the mass, operated at a controlled frequency and RMS acceleration. Provisions can be made for additional calibration of transducers, insert voltage, and reciprocity.

Field Measurements

The arrangement of the vibration equipment for typical field use is shown in Figure 26-12. Sources of error in field measurements must be recognized by the investigator and avoided or minimized, at least. Common sources of error are incorrect mounting, incorrect calibration, connecting cable noises, and thermal effects. In the field, consideration must be given to the location and mounting of the accelerometer in order to record the original motion and resonant frequencies of the structure. The vibration transducer should load the structural member as little as possible, since any loading effects will invalidate the measurement results. In most practical situations, the mass loading effect is negligible but can be checked by the formula:

$$AR = AS \left(\frac{MS}{MS + MA} \right)$$

where AR = Response of structure with accelerometer

AS = Response of structure without accelerometer

MS = Weight of the structure member to which the accelerometer is attached

MA = Weight of the accelerometer

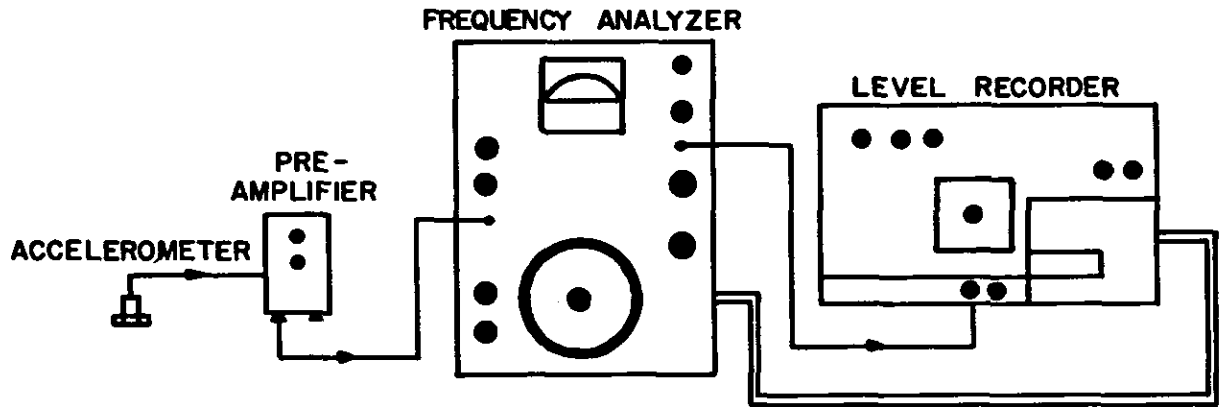


Figure 26-12. Arrangement of Equipment for Automatic Frequency Analysis.

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A number of methods can be used to mount the accelerometer, including mounting by means of a steel stud, an isolated stud and mica washer, a permanent magnet, wax or soft glue, or hand-held with a probe. Use of a steel stud gives the best frequency response, approaching the actual calibration curve supplied with the accelerometer. When electrical isolation is required between the accelerometer and vibrator, a mica washer is used because of its hardness and transmission characteristics. A permanent magnet also gives electrical isolation, but magnetic mass, and temperature effects on the accelerometer can be introduced. Handheld probes are convenient but should not be used for frequencies higher than 1000 Hz where mass loading effects begin. Wax, because of its stiffness, gives a good frequency response but should not be used at high temperatures.

Another source of error, cable noise, originates either from mechanical motion of the cable or from ground loop-induced electrical hum and noise. Mechanical noises originate from local capacity and charge changes due to dynamic compression and tension of the cable, affecting low-frequency readings. A ground loop (see Figure 26-13) induces a current and small voltage drop which adds directly to the sometimes weak accelerometer signal. Insuring that grounding of the installation is made only at one point eliminates ground looping.

In ordinary vibration measurements, temperature effects need not be considered. However, measurements of very low frequency, very low amplitude vibration will be disturbed by even small temperature changes due to the variance of the accelerometer output at a rate determined by the time constant of the accelerometer preamplifier input circuit.

Calibration of a typical vibration measuring arrangement can be made directly from curves and figures supplied by the manufacturer. Special

measuring arrangements can be calibrated using a vibration calibrator.

The following general outline points out the important considerations in a field measurement:

1. Determine placement of the vibration transducer with consideration for possible mass loading effects.
2. Estimate the types and levels of vibrations likely at the mounting point.
3. Select a suitable vibration transducer considering the mass loading effect, types of vibrations, temperature, humidity, acoustic and electric fields.
4. Determine what type of measurement would be most appropriate for the problem at hand.
5. Select suitable electronic equipment, considering frequency and phase characteristics, dynamic range and convenience.
6. Check and calibrate the overall system.
7. Make a sketch of the instrumentation system, including types and serial numbers.
8. Select the appropriate mounting method, checking vibration levels, frequency range, electrical insulation, ground loops, and temperatures.
9. Mount the accelerometer, carry out the measurements, and record the results. Record any octave band analysis of the vibrations, if necessary.
10. Note the setting of various instrument control knobs.

The apparent vibration level, similar to a background reading, should be recorded by mounting the accelerometer on a nonvibrating object in the measured system. Apparent vibrations should be less than one-third of the measured vibrations for accuracy in the actual vibration measurements.

Analysis should include measurements at different points on the machine or system to determine the areas of greatest vibration and their

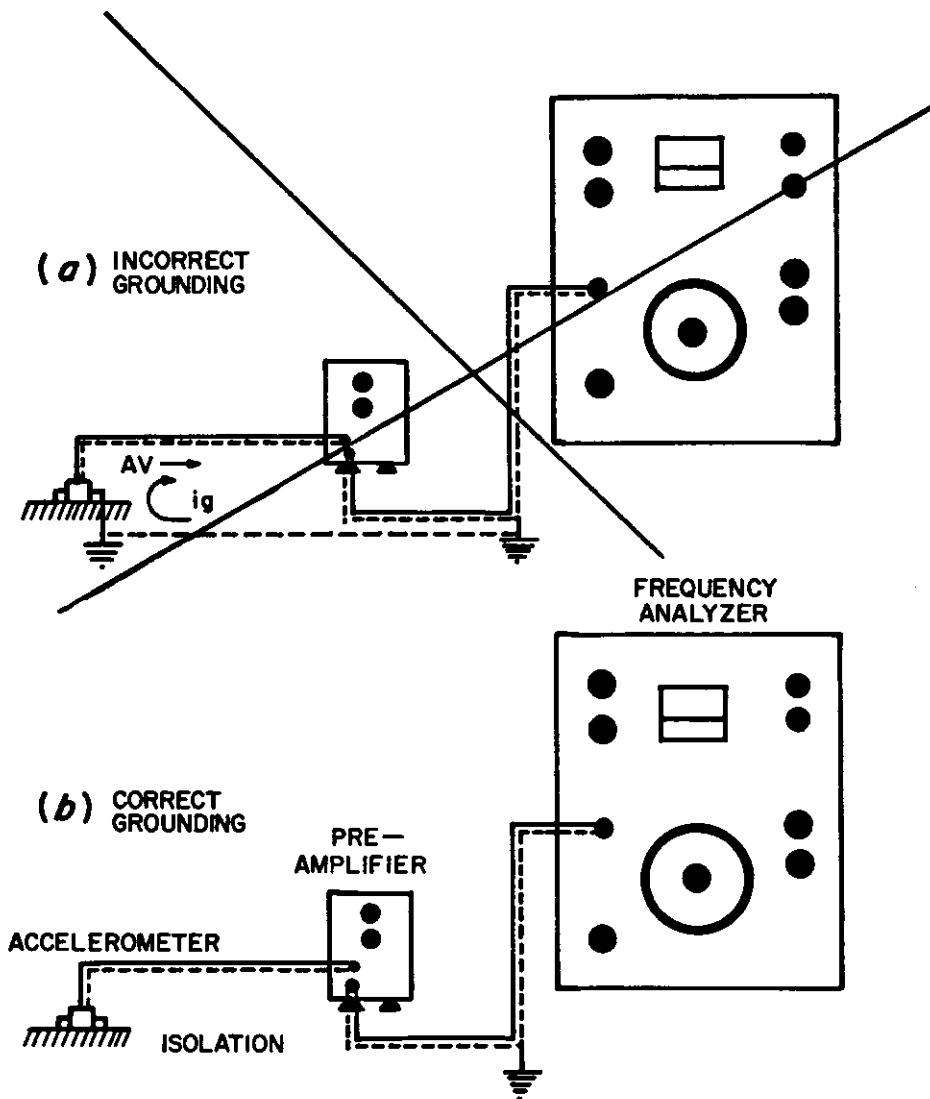


Figure 26-13. Illustration of Ground-Loop Phenomena.

- a) This method of connection forms ground loop and should be avoided.
- b) No ground-loop is formed. Recommended method of connection.

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respective frequency components. Experience is the best guide in pinpointing vibration sources in familiar machinery. Since machine vibrations produce noise, reduction of vibration often reduces noise problems as well.

CONTROL OF VIBRATION

Vibrations may be reduced by:

1. Isolating the disturbance from the radiating surface;
2. Reducing the response of the radiating surface; and
3. Reducing the mechanical disturbance causing the vibration.

Isolation

Vibration isolators effectively reduce vibration transmission when properly installed. The vibration of a machine on isolators is complex, since the machine can move along or rotate about its one vertical and two horizontal axes. The machine will have a resonant frequency for each of the six modes of vibration; thus, it is important that none of the six possible resonances occur at the frequency of the disturbance. To insure adequate isolation, the resonant frequency of the isolator should be less than half the disturbing frequency.

For the vertical mode, which is usually the most important, the resonant frequency of the iso-

lator is related to its static deflection under the weight of the machine by the following formula:

$$f = \frac{3.13}{\sqrt{d}}$$

where d is the static deflection, inches

f is the frequency, Hertz

To find the stiffness required from the isolation mount (spring) when the desired frequency has been determined, the formula:

$$K \approx 0.04 \times MS \times F_o^2 \quad \text{kg/cm}$$

can be used.

K = Spring constant

MS = Machine weight

F_o = Resonant frequency of the machine and isolation mount system.

Since the degree of isolation increases as the resonant frequency is lowered, the equation indicates that isolation is improved as the static deflection is increased.

Transmission of vibration to an adjacent structure may also be reduced by making electrical connections less rigid. For piping, electrical connections, and ductwork flexible connectors may be used. When using enclosures, the housing should be anchored to the floor rather than the machine to eliminate transmission of the vibration to the enclosures.

Another important consideration is that the vibration isolators be placed correctly with respect to the motion of the center of gravity of the machine, with the center of gravity located as low as possible. In cases of instability, i.e., "rocking", the effective center of gravity may be lowered by first mounting the machine on a heavy mass and isolating the mass from the machine.

Reduction of Surface Response (Damping)

In cases where isolation of the vibrations is not suitable, or is difficult to arrange, the principle of vibration absorbers may be used. By attaching a resonance system to the vibrating structure (which counteracts the original vibrations), the structure vibrations can be eliminated. Through mathematical differential equations it can be shown that by tuning the absorber system resonant frequency, it is theoretically possible to eliminate the vibration of the machine.

Structural elements like beams and plates exhibit an infinite number of resonances. When subjected to vibrations of variable frequency, the application of separate dynamic absorbers to structural elements becomes impractical. Since there is usually little inherent damping of resonant vibrations in the structural elements themselves, external arrangements must be made to reduce vibrations.

External damping can be applied in several ways:

1. By means of interface damping (friction)
2. By application of a layer of material with high internal losses over the surface of the vibrating element
3. By designing the critical elements as "sandwich" structures.

Interface damping is obtained by letting two

surfaces slide on each other under pressure. With no lubricating material the "dry" friction produces the damping effect, although this commonly causes fretting of the two surfaces. When an adhesive separator is used, a sandwich structure results, a concept which will be discussed later.

Mastic "deadeners" made of an asphalt base are commonly sprayed onto a structural element in layers, to provide external dampening. These deadeners are commonly made from high-polymer materials with high internal energy losses over certain frequency and temperature regions. To obtain optimum damping of the combination structural element and damping material, not only must the internal loss factor of the damping material be high, but so must its modulus of elasticity (the ratio of stress to strain).

An approximate formula (see Figure 26-14) governing the damping properties of a treated panel is given by:

$$N \approx 14 \left(\frac{N_2 E_2}{E_1} \right) \left(\frac{d_2}{d_1} \right)^2$$

N = Loss factor of the combination structure element + damping material

N_2 = Loss factor of the damping material

E_1 = Modulus of elasticity of the structural element

E_2 = Modulus of elasticity of the damping material

d_1 = Thickness of the structural element

d_2 = Thickness of the damping material layer.

The ratio $\left(\frac{d_2}{d_1} \right)^2$ is the most important factor,

usually around 3:1 for best results.

The third method of damping is the use of sandwich structures; a thick or thin layer of viscoelastic material is placed between two equally thick plates, or a thin metal sheet is placed over the viscoelastic material which is covering the panel. The damping treatment will be more effective if applied to the area where vibration is greatest, but the actual amount of treatment and the area of coverage are best determined by experiment. As a rule of thumb, the amount (density \times thickness) of material applied should equal that of the surface to which it is applied. Since this can lead to using large amounts of damping material, the method of covering the damping material with a sheet metal overlay is often used. Studies²¹ show that to a certain extent, the thickness of a layer is not the most important factor; but in cases of sandwich layers, symmetry is most significant. Sandwich layers often are preferred due to a greater dampening factor (Figure 26-14) than with single layer coatings.

Reduction of Mechanical Disturbance

Mechanical disturbances that produce vibration can be reduced by reducing impacts, sliding or rolling friction, or unbalance.

In all cases, either mechanical energy is coupled into mechanical-vibratory energy, or energy in some other form is transformed into mechanical-vibratory energy. These other forms of energy include: varying electrical fields, varying hy-

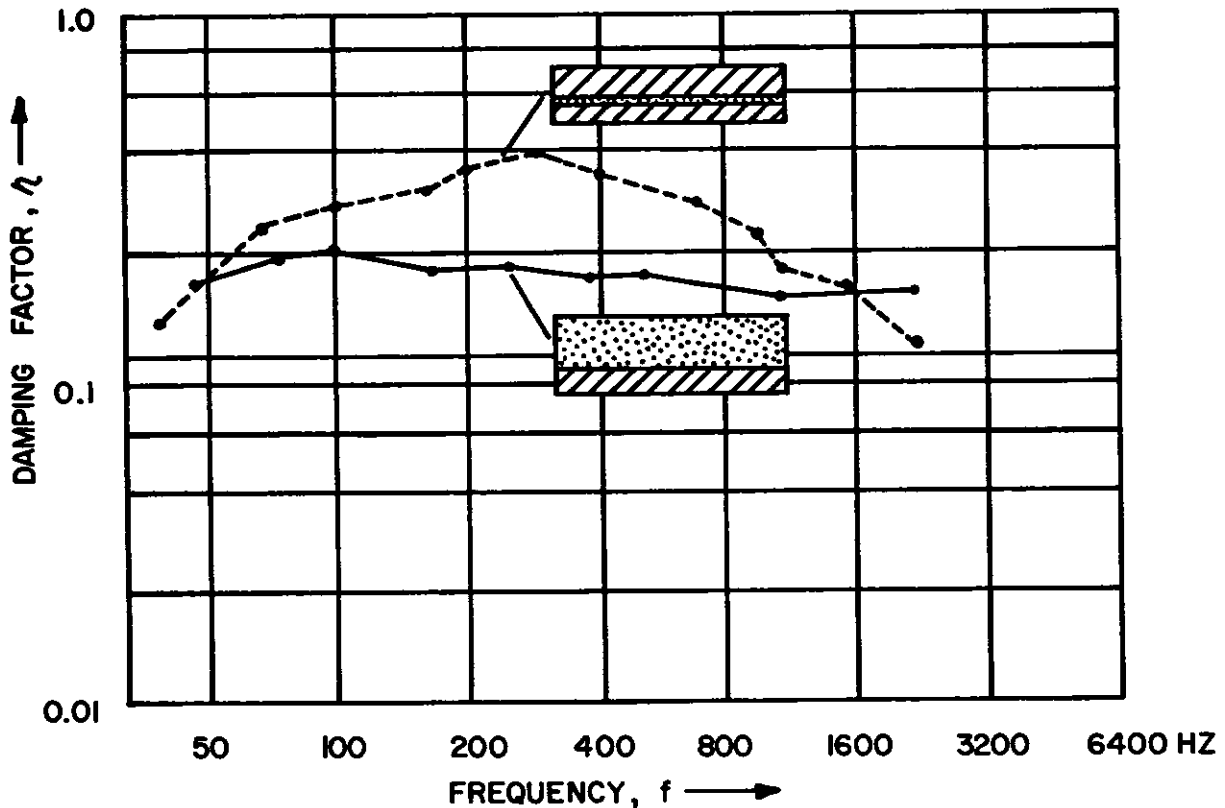


Figure 26-14. Results of Loss Factor Measurements on a Sandwich Structure with a Thin Visco-Elastic Layer, and on a Plate Supplied with One Layer Mastic Deadening ($d_2/d_1 \approx 2.5$). After Cremer and Heckl.²¹

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draulic forces, aerodynamic forces, acoustic excitation, and thermal changes.

Often mechanical vibration can be reduced by: (1) proper balancing of rotating machinery, (2) reducing response of equipment to a driving force, and (3) proper maintenance of machinery.

Limitations of Control Methods

In conjunction with the practical applications of isolators and dampers, certain limitations should be noted in the control of vibration:

1. Reduction in transmissibility can only take place by allowing the isolator to deflect by motion. Thus, certain space clearances must be provided for the isolated equipment.
2. If the resonant frequency of the isolation system is chosen incorrectly, the isolator may actually amplify the destructive characteristics. Select a spring mounting so that the natural frequency, F_0 , of the spring-mass system is considerably (at least one-half) lower than the lowest frequency component in the force system produced by the machine.
3. If the isolator produces unexpected non-

linear characteristics a great number of extra response effects may take place.

The reduction in shock severity which may be obtained by the use of isolators results from the storage of the shock energy within the isolators and its subsequent release in a "smoother" form. Unfortunately, since a shock pulse may contain frequency components ranging from nil to near infinity it is not possible to avoid excitation of the isolator-mass system.

Damping is a costly method of reducing the response of a radiating surface, and is therefore generally avoided. Mechanical disturbances, primarily dependent upon an effective maintenance program, are rarely eliminated completely.

In conclusion, all vibration problems should be approached by determining first if a quick, simple, and "common sense" solution is available. If a simple answer is not obvious, the quantitative results of measurements become essential in the analysis and solution of the problem. As various control procedures are tried, vibration measurements can be used to show the progress being made and predict the correct steps in reducing vibrations further.

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ILLUMINATION

John E. Kaufman

INTRODUCTION

Lighting of the industrial environment provides for the visibility of objects and awareness of space needed for man to perform in a productive and secure manner. Not only should the lighting be properly designed and coordinated with the thermal, spatial and sonic designs, but it should be maintained through planned servicing procedures. The only means for determining whether a particular environment has been properly designed and is correctly maintained is to perform periodic evaluations or surveys.

In evaluating the lighting in any environment it is important to know how to make an effective meaningful survey and this can only be done with a basic understanding of lighting terminology, established recommendations for quantity and quality of lighting, types of lighting equipment and design procedures, and finally survey methods and instruments to be used.

LIGHTING TERMINOLOGY

The lighting terms most often used in design and evaluation of illuminated spaces include: intensity, illumination level, luminance, reflectance, lamp and luminaire. Most often used units of measurement are: candela, lumen, footcandle and footlambert. For a more complete list of terms with their definitions see Section 1 of reference 1.

Intensity

Intensity, or more correctly luminous intensity, is an indication of how much light a source gives off in a given direction. The unit of luminous intensity is the *candela* (formerly "candle"). It is sometimes referred to as "candlepower."

Lumen

The lumen is the unit of light output from a light source. For example, a 100-watt incandescent lamp emits about 1700 lumens initially in all directions, whereas a 40-watt cool-white fluorescent lamp emits about 3200 lumens initially. By definition, a light source of one candela produces 4π lumens.

Illumination Level

Illumination level is the amount or quantity of light falling on a surface and is measured in *footcandles*. If, for example, 100 lumens from a light source falls on one square foot of a table top, the illumination level on the table would be 100 footcandles. Also, a surface one foot from a source with an intensity of 100 candelas would have an illumination level of 100 footcandles.

If the unit of surface area is in square meters rather than square feet, the illumination is measured in *lux*.

Luminance

Luminance, or photometric brightness, is a measure of the amount of light emitted or reflected from a certain area of a surface. Its unit is *foot-lamberts* when the area of surface is square feet. A surface emitting one lumen per square foot of surface has a luminance of one footlambert. A bare 40-watt fluorescent lamp has a luminance of about 2400 footlamberts, whereas the moon has a luminance of nearly 1170 footlamberts.

If the unit of surface area is in square meters rather than square feet luminance is measured in *candelas/square meter*.

Reflectance

Reflectance is a measure of how much light is reflected from a surface. Actually it is the ratio of the luminance of a surface to the illumination on the surface (i.e., $\text{reflectance} = \text{luminance} / \text{illumination}$). A completely black surface has a 0 percent reflectance. A perfectly white surface has a reflectance of nearly 1.0 or 100 percent. Most surface finishes have reflectances of between 5 to 95 percent.

Lamp

Lamp is the term used for man-made light sources. Incandescent lamps are also called "bulbs" and fluorescent lamps, "tubes." "Lamp" is also used for the name of a complete lighting device consisting of a lamp, shade, reflector, housing, etc.

Luminaire

A luminaire is a complete lighting device consisting of one or more lamps together with parts to distribute the light, to position and protect the lamps and to connect the lamps to the power supply.

PURPOSE OF LIGHTING

The purpose of lighting in industry is to provide efficient, comfortable seeing of industrial visual tasks and to help provide a safe working environment. Advantages derived from good lighting include: fewer mistakes, increased production, reduction in accidents, improved morale and improved housekeeping.

Lighting for Task Performance

Visual tasks in industry vary in degree of difficulty depending on their size, their contrast (between detail and surround), their luminance and the time available for seeing. The smaller a task size the more difficult it is to see — for equal illumination a very small letter identification on a printed circuit board is harder to see than the type on this page. Tasks of low contrast, such as a gray stain on gray cloth are more difficult to see

than higher contrast tasks such as a dark gray stain on white cloth. Also, it usually is easier to see an inspection task if more time is available for viewing.

The factors of size, contrast and in many cases time, are inherent in a visual task. On the other hand task luminance is variable and can easily affect task visibility — the higher the luminance (the greater the illumination) the more visible the task. This is due to an increase in eye sensitivity with increased luminance.

Lighting for Safety and Comfort

Lighting adequate for seeing production and inspection tasks usually will be more than needed for safety alone. If task lighting is not provided throughout the working space, adequate surrounding illumination is required to provide visibility of nearby objects which might be potential hazards or to see to operate emergency control equipment. In addition, lighting of ceiling and walls and the avoidance of glare will help provide a greater sense of well being and comfort.

ILLUMINATION REQUIREMENTS FOR INDUSTRY

Quantity of Illumination

The difficulty of seeing tasks, based on contrast, size and time for viewing as discussed above, is used as a basis for determining the levels of illumination for industrial areas. Research has shown that levels of illumination in the thousands of footcandles are required to see dark, low-contrast tasks as easily as light-colored tasks of high contrast under low levels. For light-colored, high-contrast tasks, the levels required for good visibility are very low. However, there are many factors in addition to visibility that affect the concept of easier seeing which suggest a minimum of 30 footcandles be used for all areas where seeing is done regularly, even for the simplest seeing tasks.²

The *American National Standard Practice for Industrial Lighting*³ contains a tabulation of recommended levels of illumination for specific visual tasks and areas based on task characteristics and the visual performance requirements of young adults with normal eyes. According to the *American National Standard Practice for Industrial Lighting*³ "These lighting recommendations are intended to provide guides for lighting levels desirable from an overall operational standpoint rather than from safety alone and, therefore should not be interpreted as recommendations for regulatory minimum lighting levels." Table 27-1 is a sample of the type of recommendations listed and is included here to show its form. Task areas are shown with corresponding footcandle levels recommended for the tasks in the area, these levels to be used as the minimum value on the task when the lighting system and room surface have depreciated to their lowest before maintenance procedures are effected (cleaning, relamping, painting, etc.). Also, in some cases, as denoted by a double asterisk, supplementary lighting can be used.

The levels recommended usually do not take

into account the wearing of safety goggles that materially reduce the light reaching the eyes. If they are worn, the level of illumination should be increased in accordance with the absorption of the goggles used.

Quality of Illumination

By definition, quality in lighting pertains to the distribution of luminances in a visual environment and is used in a positive sense to imply that all luminances contribute favorably to comfort, safety, esthetics as well as ease of seeing. Excessively high luminances may produce glare and veiling reflections and affect eye adaptation. Improper distribution of luminances also may affect adaptation and cause shadows. Installations of very poor quality are easily recognized but those of moderately poor quality are not, even though there may be a material loss in seeing.

TABLE 27-1.

Levels of Illumination Currently Recommended*

Area	Footcandles on Tasks*
Clothing manufacture (men's)	
Receiving, opening, storing, shipping	30
Examining (perching)	2000**
Sponging, decating, winding, measuring	30
Piling up and marking	100
Cutting	300**
Pattern making, preparation of trimming, piping, canvas and shoulder pads	50
Fitting, bundling, shading, stitching	30
Shops	100
Inspection	500**
Pressing	300**
Sewing	500**

*Minimum on the task at any time.

**Can be obtained with a combination of general lighting plus specialized supplementary lighting. Care should be taken to keep within the recommended luminance ratios. These seeing tasks generally involve the discrimination of fine detail for long periods of time and under conditions of poor contrast. The design and installation of the combination system must not only provide a sufficient amount of light, but also the proper direction of light, diffusion, color and eye protection. As far as possible it should eliminate direct and reflected glare as well as objectionable shadows.

Glare. There are two general forms of glare — *discomfort glare* and *disability glare* — and both may be caused by bright light sources (electric and daylight) and by bright reflections in room surfaces. Glare from light sources and luminaires is known as *direct glare*; that from surfaces, as *reflected glare*.

Discomfort glare, as its name implies, produces discomfort and may affect human performance, but does not necessarily interfere with visual performance or visibility. In some cases extremely bright sources (the sun) can even cause pain. Disability glare does not cause pain, but reduces the visibility of objects to be seen. An example is the reduced visibility of objects on a roadway at night caused by the glare of bright oncoming headlights.

An industrial environment, then, will be relatively comfortable visually, if there is no glare, and seeing will be unimpaired if there is no disability glare. The effects of glare can be avoided or minimized by mounting luminaires as far above or away from normal lines of sight as possible and by limiting their luminance and quantity of light emitted toward the eyes. In general, this can be done by shielding luminaires to at least 25 degrees down from the horizontal and preferably down to 45 degrees. In other words, the brightness of bare lamps preferably should not be seen when looking in the range from straight ahead to 45 degrees above the horizontal. For critical working areas such as offices and laboratories the quality criteria of the *American National Standard Practice for Office Lighting*⁴ should be followed. *Veiling Reflections.* When reflected glare is produced on or within the visual task itself it becomes a veiling reflection because in most cases it will veil the task (reducing its visibility) by reducing its contrast. In some cases these losses in contrast are quite apparent; in others the losses are unnoticed yet may produce a marked reduction in visibility. The effects of veiling reflections may be reduced by increased levels of illumination and or by using layouts and luminaires designed to limit the light directed toward the task that will be reflected into the eyes. See the *IES Lighting Handbook*.¹

Luminance Distribution. The eyes function more efficiently and comfortably when the luminances within the visual environment are not too different from that of the seeing task. While performing a task the eyes become adapted to the luminance of the task. If however, the eyes shift to view a window or floor of higher or lower luminance and then back to the task, the visibility of the seeing task will be reduced until the eyes readapt to the task luminance. To reduce this effect, maximum luminance ratios are recommended as shown in Table 27-2. As an aid in achieving these reduced luminance ratios, the reflectance of room surfaces and equipment should be as listed in Table 27-3. *Distribution, Diffusion and Shadows.* In industrial areas where the locations of equipment and operations are not known, it is desirable to provide uniform illumination such that the highest and lowest levels are no more than one-sixth above or below the average. This also will help maintain desirable luminance distributions as recommended above.

Depending on the type of visual task and the operation, some tasks require directional lighting and others diffuse, but in both cases shading of the task should be avoided. Most tasks can be

TABLE 27-2
Recommended Maximum Luminance Ratios³

	Environmental Classification		
	A	B	C
1. Between tasks and adjacent darker surroundings	3 to 1	3 to 1	5 to 1
2. Between tasks and adjacent lighter surroundings	1 to 3	1 to 3	1 to 5
3. Between tasks and more remote darker surfaces	10 to 1	20 to 1	*
4. Between tasks and more remote lighter surfaces	1 to 10	1 to 20	*
5. Between luminaires (or windows, skylights, etc.) and surfaces adjacent to them	20 to 1	*	*
6. Anywhere within normal field of view	40 to 1	*	*

*Luminance ratio control not practical.

A—Interior areas where reflectances of entire space can be controlled in line with recommendations for optimum seeing conditions.

B—Areas where reflectances of immediate work area can be controlled, but control of remote surround is limited.

C—Areas (indoor and outdoor) where it is completely impractical to control reflectances and difficult to alter environmental conditions.

TABLE 27-3
Recommended Reflectance Values²
Applying to Environmental Classifications
A and B

	Reflectance* (percent)
Ceiling	80 to 90
Walls	40 to 60
Desk and bench tops, machines and equipment	25 to 45
Floors	not less than 20

*Reflectance should be maintained as near as practical to recommended values.

satisfactorily illuminated by diffuse illumination, but tasks of inherently low contrast and of a three-dimensional nature often can be seen best using directional light to produce shadows and reflections to improve contrast. Examples of such tasks are glossy black thread on matte black cloth and

scratches on sheet metal. In the latter case it is especially important that the lighting be designed so that it will not produce reflected glare in the sheet metal.

Color. For equal levels of illumination variations in the color quality of currently used "white" light sources have little or no effect upon clearness or speed of seeing. However, when contrast is low and color discrimination is important, source and surrounding surface colors should be selected carefully.

INDUSTRIAL LIGHTING EQUIPMENT

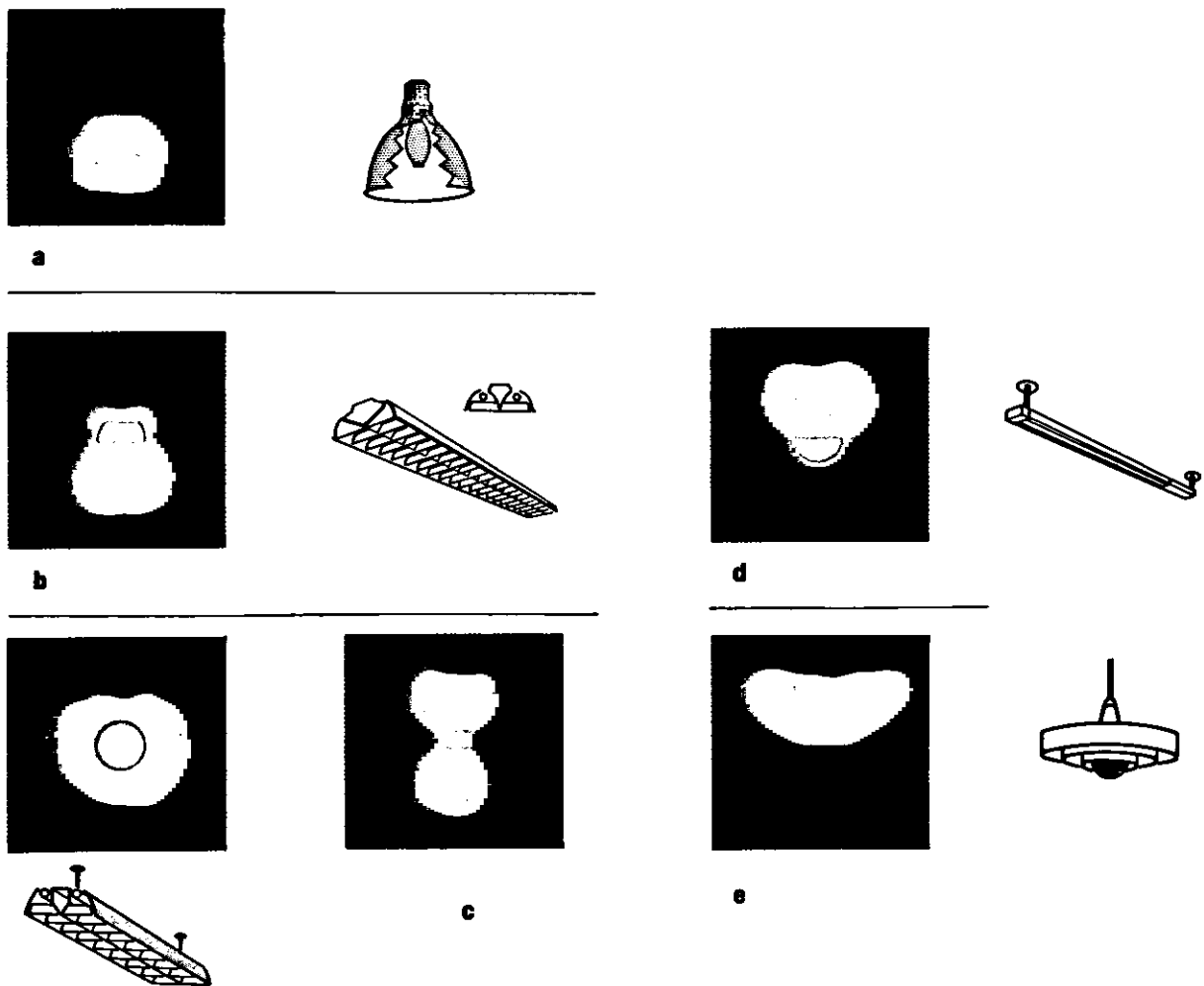
Light Sources

Daylight and electric light are the two main sources of light for industrial areas. The use of daylight depends on building design orientation and site conditions as well as the availability of daylight at the location;² however, because daylight is not always available electric lighting is provided.

Electric light sources used for industrial application fall into three categories: incandescent (including tungsten-halogen), fluorescent and high-intensity discharge (including mercury, metal halide and high pressure sodium). Although all types can be used, there are certain applications for which some are better suited than others. For detailed information on their physical and operating characteristics as well as industry averaged photometric data (lumen values) consult the *IES Lighting Handbook*.¹

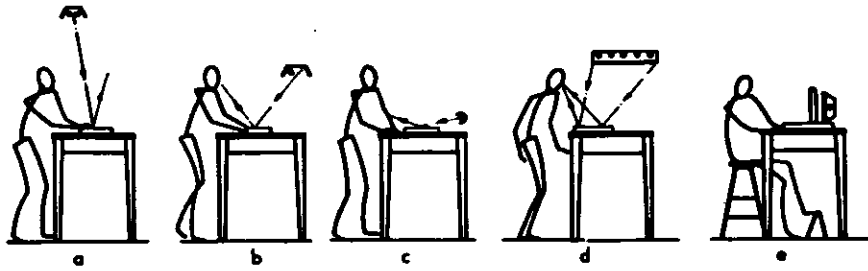
Luminaires

There are two categories of luminaires for industrial lighting — general and supplementary. *General Luminaires* are classified into five types according to their light distribution, as shown in Figure 27-1, and are used to provide general lighting throughout an area or localized general lighting, where the luminaries are located to provide higher levels at specific task locations yet provide some degree of general lighting. Each type of dis-



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Figure 27-1. Luminaire Classifications by Light Distribution: (a) Direct Lighting, (b) Semi-Direct Lighting, (c) General-Diffuse and Direct-Indirect Lighting, (d) Semi-Indirect Lighting and (e) Indirect Lighting.



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Figure 27-2. Examples of Placement of Supplementary Luminaires: (a) Luminaire Located to Prevent Reflected Glare — Reflected Light Does Not Coincide with Angle of View. (b) Reflected Light coincides with Angle of View. (c) Low-Angle Lighting to Emphasize Surface Irregularities. (d) Large-Area Surface Source and Pattern are Reflected toward the Eye. (e) Transillumination from Diffuse Sources.

tribution has an application in industrial lighting, for example: *direct* types are the most efficient (but may produce disturbing shadows and glare unless units are of large size, mounted close together and have some upward light), whereas at the other extreme *indirect* types are least efficient but produce more comfortable lighting. No one system can be recommended over all the others. Each should be evaluated based on the quantity and quality requirements of the space.

Supplementary luminaires are luminaires used along with a general lighting system but are located near the seeing task to provide the higher levels or quality of lighting not readily obtainable from the general lighting system. They are divided into five major types from Type S-I to S-V, based on their light distribution and luminance characteristics. Each has a specific group of applications and locations, as shown in Figure 27-2, to best illuminate the seeing task involved.

LIGHTING DESIGN

In industrial areas where the primary function of the lighting installation is to provide illumination for quick, accurate performance of visual tasks, the task itself is the starting point in the lighting design. Factors to be considered in the design process are listed below, but it should be recognized that the success of the design also depends on the accuracy of the information available to the designer.

1. Visual Task.

- a. What commonly found visual tasks are to be lighted?
- b. How should the tasks be portrayed by the lighting? Should the lighting be diffuse or directional? Are shadows important for a three dimensional effect? Will the tasks be susceptible to veiling reflections? Is color important?
- c. What level of illumination should be provided in accordance with the *American National Standard Practice for Industrial Lighting*?⁸

2. Area in Which Task Is Performed.

- a. What are the dimensions of the area and reflectances of surfaces?
- b. What should the surface luminances be to minimize eye adaptation effects without creating a bland environment?
- c. Might the surfaces produce reflected glare?
- d. Is illumination uniformity desirable (general illumination or task illumination)?

3. Luminaire Selection.

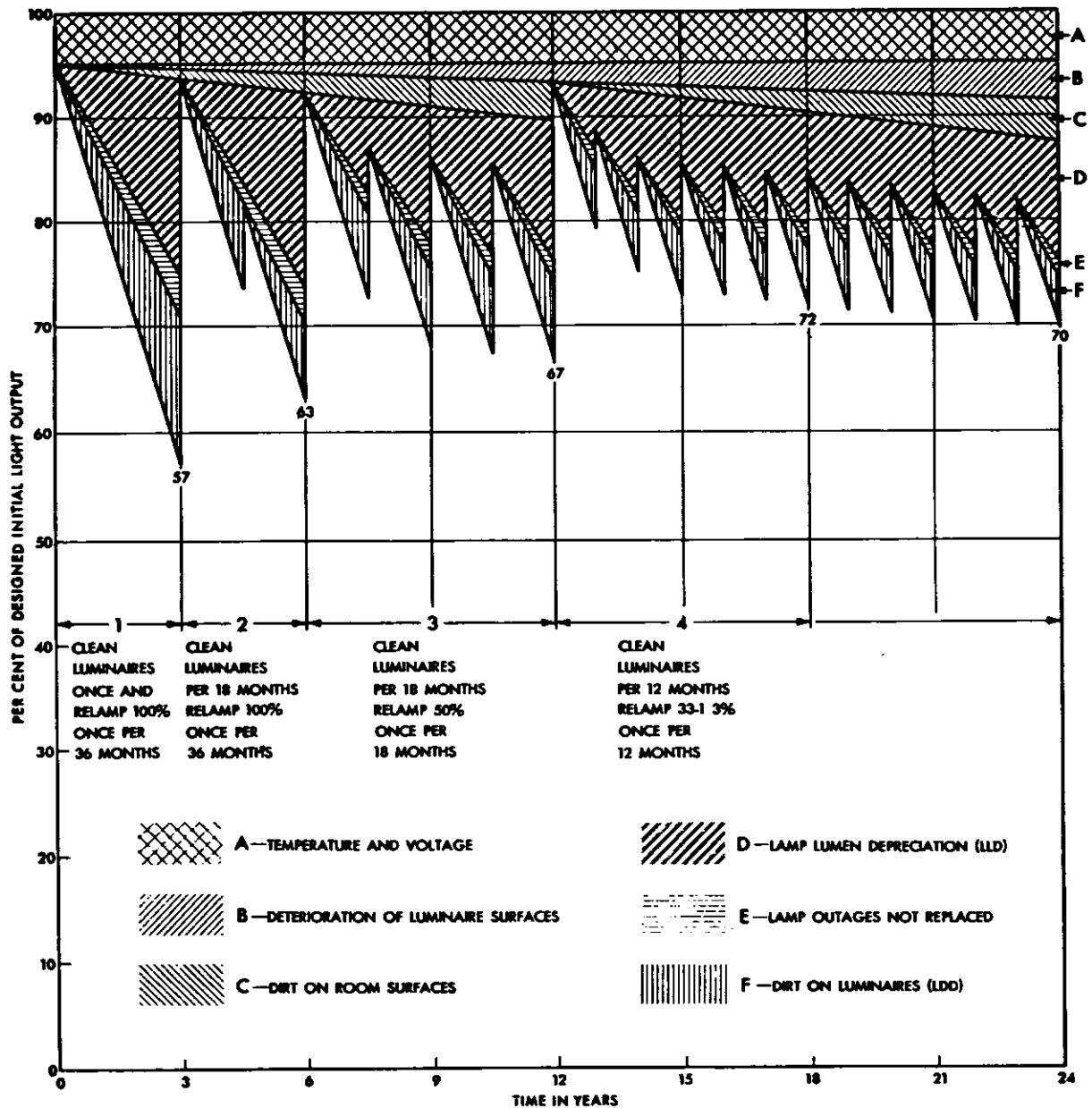
- a. What type of distribution and lamp color quality is needed to properly portray the task (for diffusion, shadows or avoiding veiling reflections) and provide a comfortable environment (visually, thermally and sonically)?
- b. What type is needed to illuminate the area surfaces (for eye adaptation, for avoiding reflected glare)?
- c. What is the area atmosphere and therefore the type of maintenance characteristics needed?
- d. What are the economics of the lighting system?

4. Calculation, Layout and Evaluation.

- a. What layout of luminaires will portray the task best (illumination level, direction of illumination, veiling reflections, disability glare)?
- b. What layout will be most comfortable (visually — direct and reflected glare, thermally)?
- c. What layout will be most pleasing esthetically?

General Illumination

When task locations are not known or a flexible arrangement of operations is desirable, lighting is usually designed to provide general illumination of the required amount throughout the area. This is also true where supplementary luminaires are used for task illumination alone. The calculation procedure for designing general illumination



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Figure 27-3. Six Causes of Light Loss. Example above uses 40-watt T-12 cool white rapid start lamps in enclosed surface mounted units, operated 10 hours per day, 5 days per week, 2600 hours per year. All four maintenance systems are shown on the same graph for convenience. For a relative comparison of the four systems, each should begin at the same time and cover the same period of time.

is the *Lumen Method*, where, with a uniform layout of luminaires, a relatively uniform level of illumination will be provided on a horizontal work-plane at a given distance above the floor. A detailed outline of this method can be found in *General Procedure for Calculating Maintained Illumination*.⁶

Task Illumination

When task locations are known, *Point Method* procedures are used for design. Methods are

available⁷ for calculating illumination levels at specific locations on horizontal, vertical and inclined surfaces, from all types of general or supplementary lighting systems. Use of these methods is the most accurate means of checking illumination levels on tasks during the design stage.

Maintenance

As mentioned above, the success of the lighting design is dependent on the accuracy of the information available to the designer, including

the lighting servicing plan for maintaining the lighting from installation to end of life. Figure 27-3 illustrates the sizeable effects of various elements of light loss (temperature, voltage, dirt on luminaires and room surfaces, lamp depreciation and burnouts and deterioration of luminaire parts) on the level of illumination from initial operation (100 hours use) through various stages of servicing procedures. It is important to know or correctly assume these losses. It is equally as important to know the type of servicing plan so that minimum maintained levels can be designed for; so that during a lighting survey the surveyor will know if initial or lowest expected values are being measured, or whether the survey is somewhere between.

Guidance for the use of light loss factors in design and information on lighting maintenance can be found in the *IES Lighting Handbook*.¹

LIGHTING SURVEYS

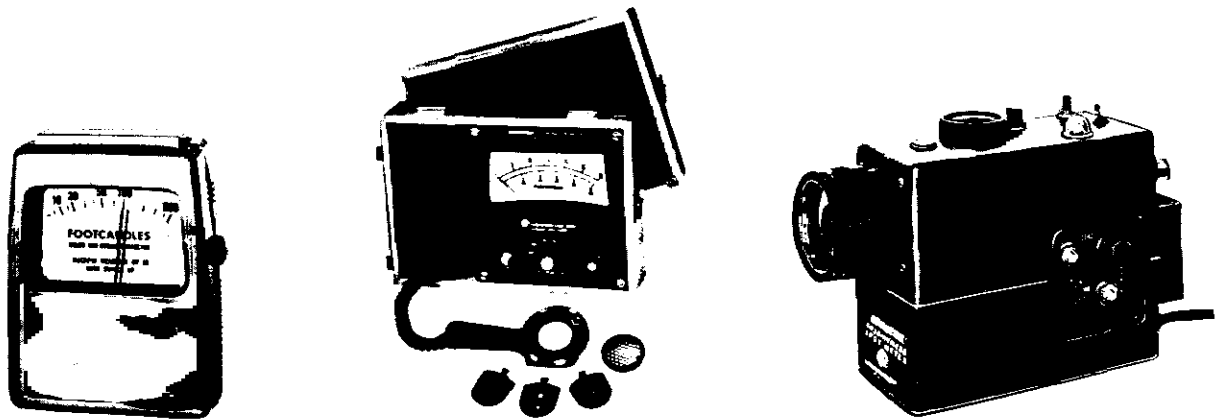
Evaluation of the lighting in an industrial environment depends on the amount and type of information obtained during survey procedures

and on the evaluator's knowledge and understanding of industrial operations and their associated lighting recommendations. The material presented so far in this chapter deals with lighting recommendations. The following deals with the survey and evaluation.

Measurable Quantities

A lighting survey can be as simple or as comprehensive as desired, but in any case three essential quantities are measured or determined: illumination (footcandles), luminance (footlamberts) and reflectance (percent). For the more comprehensive surveys, temperature and voltage are also measured.

Illumination readings are made at task locations for task lighting, at various locations on the horizontal work-plane for general lighting, and in some cases on various room surfaces to determine luminances and reflectances. *Luminance* readings are made of luminaires and room and task surfaces. *Reflectance* determinations are made of room surfaces. *Temperature* is measured in the air near luminaires. *Voltage* is measured at the luminaire input.



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Figure 27-4. Typical Photoelectric Meters Used in Lighting Surveys: (a) Pocket-Size Illumination Meter, (b) Paddle-Type Illumination Meter with Operational Amplifier, and (c) Luminance Meter.

Instruments

Illumination (Light) Meters. Figure 27-4a and b shows two typical illumination meters — a pocket-type and a more accurate paddle-type. The degree of accuracy required dictates the type of meter to be used, but in any case, instruments should be color corrected (to account for the response of the eye to light), cosine corrected (to compensate for light reflected from the light-detecting cell surface), calibrated for accuracy and with scale ranges so that no measurements are made below one-quarter full scale. A luminance meter (see below) can be used to measure illumination if a

target of known reflectance is measured (illumination = luminance ÷ reflectance).

Luminance (Brightness) Meters. Figure 27-4c shows a typical direct reading portable luminance meter. Again the degree of accuracy required dictates the type of meter to be used and its corrections, sensitivity and calibration. Luminance of surfaces also can be measured using an illumination meter if the reflectance of the surface is known (luminance = illumination × reflectance).

Reflectance can be measured directly using a Baumgartner reflectometer,¹ however in field surveys, reflectance is usually determined by visual

comparison of the unknown surface with color chips of known reflectance (Munsell Value Scales¹) or by calculation using measurements (reflectance = luminance ÷ illumination).

Survey Procedures

The publication *How to Make a Lighting Survey*,⁷ developed by the Illuminating Engineering Society in cooperation with the U. S. Public Health Service, provides a uniform detailed lighting survey form along with instructions for use. The survey involves recording the following information:

1. Description of the illuminated area — room dimensions; colors, reflectances and condition of room surfaces; and temperature surrounding luminaires.

2. Description of the general lighting system — quantities, condition, wattages, lamps, distribution, spacing and mounting.

3. Description of any supplementary lighting equipment used — as in 2, above.

4. Description of instruments used — manufacturer, model and date of last calibration.

5. Illumination measurements — at specific locations, depending on type of lighting system used.

6. Luminance measurements — from specific work locations in normal viewing directions.

7. Answers to a series of questions concerning the lighting servicing procedure and a subjective evaluation of the lighting.

Evaluation of Results

The measurements and other data recorded are used to determine: (a) illumination levels (for compliance with footcandle recommendations), (b) luminance values (for compliance with luminance ratio limits for visibility and safety) and (c) an indication of the degree of comfort and pleasantness in the area (from answers to related questions). In addition, these data are useful in de-

termining if adequate maintenance or lighting servicing procedures are in effect. Also, they can indicate if deficiencies exist and what changes can be made for improvement; (e.g., application of higher or lower surface reflectances, better use of color, different luminaire locations for uniformity and to avoid shadows and glare, more light on the ceiling and better control of the daylighting).

It should be realized, of course, that the conditions existing during the survey may not be the same as those assumed by the designer in his design procedure, and the surveyor and evaluators should be aware of this.

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Preferred Reading

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