III. VIBRATION AS A HAZARD

A. THE PHYSICS OF VIBRATION

1. Components of a Vibrating System

Three components of a vibrating system are (1) mass, (2) elasticity, and (3) damping. The kinetic energy of the system is a function of the mass and motion of the system. The potential energy of the system is a function of the mass and elasticity of the system. When a system vibrates, the energy in the system alternately changes back and forth between kinetic and potential energy. In the absence of any mechanism to take energy out of the system, a system will theoretically vibrate forever once it begins to vibrate. Damping is the mechanism that transforms the kinetic and potential energy into heat and thereby takes energy out of a vibrating system. Thus if no energy is directed into a vibrating system to keep it in motion, the damping that is present will dissipate the initial energy in the system and all motion will stop. The human hand-arm system contains mass, elasticity, and damping and can be visualized as a series of masses connected by elastic and damping elements.

2. Parameters Associated with Vibration

Motion associated with vibration is oscillatory in nature. Such motion is called harmonic motion and is associated with motion around some equilibrium or reference position (Figure III-1). The displacement refers to the position of a vibrating object relative to its normal resting position [$X(t) = 0$ in Figure III-1]. The four primary vibration parameters—frequency, acceleration, velocity, and displacement—are interrelated. When the values for any two of the parameters are known for any single frequency, the values for the other two can be calculated. When the motion is harmonic, the displacement [$X(t)$] is

$$X(t) = X \sin(\omega t) \tag{1}$$

where

X is the peak displacement amplitude in meters,
ω is the angular frequency of oscillation in radians/sec, and
t is the time in seconds

The angular frequency can be expressed as

$$\omega = 2\pi f \quad or \quad f = \frac{\omega}{2\pi} \tag{2}$$

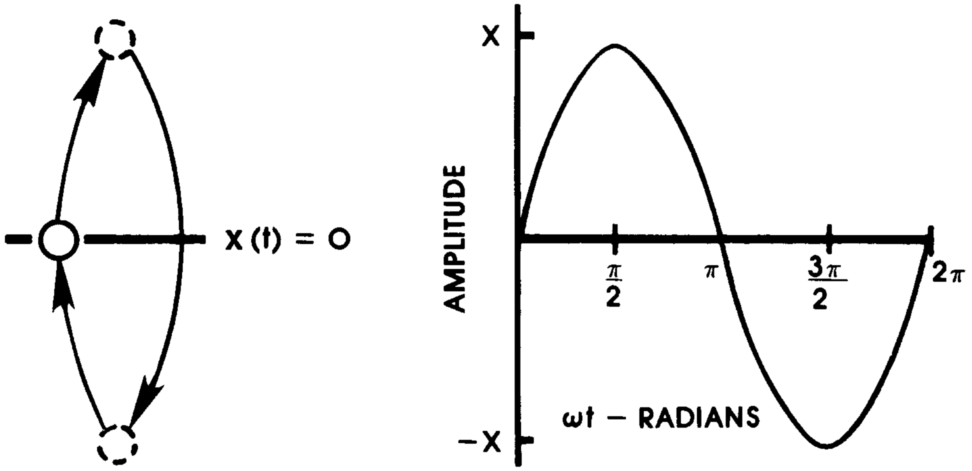

Figure III-1. Harmonic oscillation.

where

π is a constant equal to 3.1416, and
f is frequency (cycles/second, or hertz [Hz]).

The frequency (f) represents the number of complete cycles of oscillations an object makes in 1 sec. For example, if an object undergoes 10 complete cycles of oscillation in 1 sec, it has a frequency of 10 cycles/sec, or 10 Hz. The period of oscillation is

$$t = \frac{1}{f} \tag{3}$$

where t is seconds. The period of oscillation represents the time it takes an object to complete one cycle of oscillation.

The velocity of an object refers to the time rate of change of displacement and represents the first derivative of the displacement function given above (Equation 1). Velocity [$v(t)$] is expressed as

$$v(t) = \frac{dx(t)}{dt} = \omega X\, cos(\omega t) \tag{4}$$

where ωX is the peak velocity (m/sec). Velocity can be written as

$$v(t) = \omega X\, sin\, (\omega\, t + \frac{\pi}{2}) \tag{5}$$

indicating that velocity leads displacement by a phase of 90°.

The acceleration [$a(t)$] of an object refers to the time rate of change of velocity and represents the second derivative with respect to time of the displacement function, or

$$a(t) = \frac{d^2\, x\,(t)}{dt^2} = \frac{dv(t)}{dt} = -\omega^2 X\, sin(\omega t) \tag{6}$$

where $\omega^2 X$ is the peak acceleration amplitude (m/sec^2). Acceleration can be written

$$a(t) = \omega^2 X\, sin(\omega t + \pi) \tag{7}$$

indicating that acceleration leads velocity by a phase of 90° and displacement by a phase of 180°.

When a vibrating system acts in concert with externally applied vibration so that certain vibration frequencies impinging on the system are amplified, the frequencies at which maximum amplification occurs are referred to as resonances or natural frequencies. In the case of hand-arm vibration, a fundamental resonance is thought to occur between 100 and 200 Hz [Wasserman 1988].

3. Mechanical Impedance

When a vibrating stimulus is applied to a human, a mechanical structure, or another system, a motion results at the same frequency as the stimulus at the point of application and at other points in the system. The mechanical impedance of the system to which the stimulus is applied can be used to describe the dynamic characteristics and the motion of the vibrating system. Mechanical impedance [$Z(\omega)$] is defined as the ratio of the applied vibrating force [$F(\omega)$] divided by the resulting velocity [$v(\omega)$], or

$$Z(\omega) = \frac{F(\omega)}{v(\omega)} \tag{8}$$

Mechanical impedance is measured as a function of the frequency of the applied force. When both the applied force and resulting velocity are measured at the point of contact between the applied force and the vibrating system, the impedance is referred to as the "driving point mechanical impedance." When the resulting velocity is measured at a point on the system other than the point where the force is applied, the impedance is referred to as the "transfer mechanical impedance." Mechanical impedance measurements have been extensively used in human vibration to determine resonance, stiffness, damping, and other dynamic characteristics of the human body. Impedance is a measure of the total dynamic opposition the human body offers to the movement imparted by the vibration stimulus and can reflect body resonances without interfering with normal body function. Mechanical impedance measurements are noninvasive measurements that can be used to determine the dynamic properties of the body or different parts of the body such as the hand and arm.

Instead of velocity system dynamics in opposition (mechanical impedance) to movement, vibration can be viewed as a form of movement or dynamic compliance. The dynamic compliance [$D(\omega)$] is defined as the ratio of the displacement [$X(\omega)$] divided by the driving force [$F(\omega)$], or

$$D(\omega) = \frac{X(\omega)}{F(\omega)} \tag{9}$$

4. Vibration Related to the Hand-Arm System

Human response to vibration depends on several factors:

- Frequency of vibration
- Amplitude of vibration
- Time history of vibration exposure
- Direction of vibration
- Point of application of vibration
- Interaction between body and vibration input
- Effect of clothing and equipment
- Body size (height, weight)
- Body posture
- Body tension
- Body composition

Vibration is a vector quantity (i.e., it has a magnitude and direction). Thus nearly all of the variables above must be extended to multiple axes, depending on the nature of the vibration that is being examined.

As specified by the International Organization for Standardization (ISO) [ISO 1986], the vibration produced by the tool or the vibration transmitted to the hand should be measured in the three orthogonal basicentric or biodynamic directions specified in Figure III-2. The

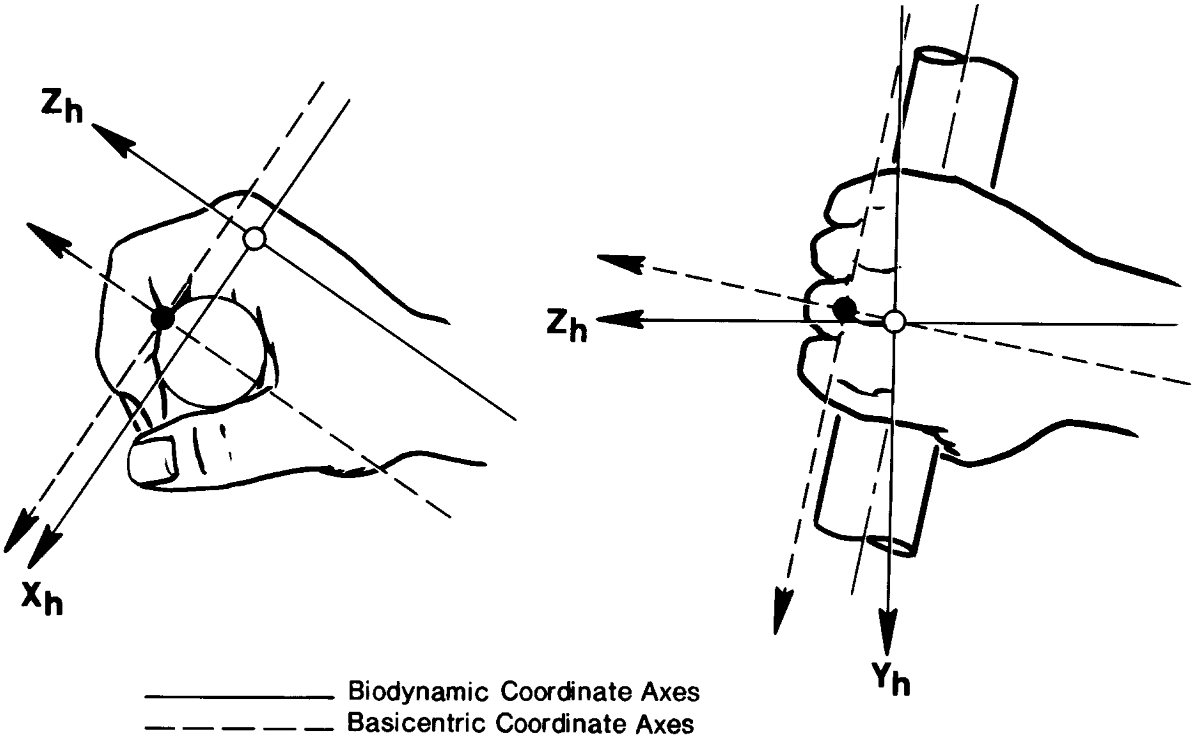

Figure III-2. Basicentric axes (x,y,z) for the hand (h).

interaction between the hands and a vibrating tool is influenced by many factors, which should be reported in detail when assessing the magnitude of the hand-transmitted vibration [Brammer and Taylor 1982; Starck and Pyykko 1986; Wasserman et al. 1977; Taylor 1974; ANSI 1986; ISO 1986]. These factors include

- The type and condition of the tool being used
- The acceleration and the frequency spectrum produced by the tool under normal operating conditions
- The magnitude and direction of sustained forces applied through the hands to the tool or the workpiece (e.g., gripping force, axial thrust force, rotational moments)
- The orientation and posture of the hands, arms, and body during work (specifically, the angles of the wrists, elbows, and shoulder joints)
- The parts of the hands that are in direct contact with vibrating surfaces
- Types and sizes of the surfaces in contact with the hands
- The work practices used
- The total number of years the worker has used vibrating tools on any job
- Climatic conditions such as the ambient temperature and humidity and the temperatures of hand-held surfaces of the tool or workpiece

The following information should be reported when assessing the duration of hand-transmitted vibration exposure [ANSI 1986; ISO 1986]:

- The duration of vibration exposure per working day and the total exposure time in hours, months, and years
- The pattern of exposure within a period of time and its association with the working method (e.g., the length and frequency of scheduled and unscheduled work and rest periods, the intermittence of vibration during the work period, whether the vibrating tool is laid aside or held during rest breaks)

B. METHODS OF MEASURING HAND-TRANSMITTED VIBRATION

1. Measurement of Acceleration

The three parameters that describe the amplitude of vibration as a function of frequency are (1) displacement, (2) velocity, and (3) acceleration. However, vibration is generally specified in terms of acceleration for the following reasons:

a. The velocity and displacement can be obtained from the measurement of acceleration.

b. A large variety of accelerometers are commercially available.

c. The amplitude of acceleration at the higher frequencies is substantially higher than either displacement or velocity and, therefore, is easier to measure.

When acceleration is measured with an accelerometer, the velocity can be obtained by electronically integrating the acceleration signal over time. The displacement can be obtained by electronically integrating the acceleration signal a second time. Electronic integration tends to reduce or minimize noise introduced into the measurements.

2. Accelerometers

Piezoelectric accelerometers are usually used to measure the amplitude of vibration associated with hand-transmitted vibration. These accelerometers can be designed to measure vibration within the frequency range of 1 to 50,000 Hz. When vibration impinges on a piezoelectric accelerometer, it moves a small mass against the face of a crystal element. The crystal element produces an electrical voltage proportional to the compression of the mass against the crystal. This voltage is proportional to the acceleration. Because the voltage produced is often very small and loss in signal can easily occur over a long cable connecting an accelerometer to a corresponding instrument, a charge amplifier is used in conjunction with the accelerometer. This amplifier overcomes signal loss problems by measuring changes in the electrical charge (or capacitance) of the crystal caused by vibration. Because the crystal charge simultaneously varies with the voltage signal, a measure of acceleration is obtained. With some accelerometers, the charge amplifier is an external device (i.e., the charge signal from the accelerometer is directed to an external amplifier that converts the charge signal to a corresponding amplified voltage signal proportional to vibration amplitude). With other accelerometers, the circuitry for converting the charge signal to a voltage signal is an integral part of the accelerometer. For these, a voltage signal from the accelerometer is directed to a voltage amplifier that generates an amplified voltage signal proportional to vibration amplitude.

When vibration is measured, it is necessary to specify whether the vibration is being measured on an impact- or nonimpact-type tool. Impact tools include chipping hammers, scalers, pneumatic riveting hammers, pneumatic nailers, jack hammers, and any other tool that generates impulse vibration signals that dominate the vibration spectrum. Nonimpact tools include chain saws, nibblers, pneumatic wrenches, grinders, routers, circular saws, reciprocating saws, and other similar tools. To measure vibration amplitudes of impact tools, specially designed shock accelerometers or ordinary accelerometers with mechanical filters must be used. These accelerometers, which are commercially available, can withstand repeated high-level, high-crest-factor acceleration pulses. If regular accelerometers are used when impact vibration is present, serious errors can be introduced into the vibration measurements [Wasserman et al. 1977; Wasserman, et al. 1981]. These errors are associated with DC shifts within the accelerometer that seriously distort the low-frequency vibration amplitudes being measured. Shock accelerometers can be used to measure both impact and nonimpact vibration, but nonshock accelerometers can be used to measure nonimpact vibration only.

Although shock accelerometers can withstand exceptionally high impulse acceleration levels, they usually have very low voltage or charge sensitivities. In the case of impact vibration, the vibration amplitudes are sufficiently high that generally no signal-to-noise problem is associated with the recording or measuring instrumentation used to record and analyze the vibration signal. In the case of nonimpulse vibration, the vibration amplitudes can be so low that the acceleration signals are near the lower sensitivity of the recording or measuring instrumentation being used. For these cases, it is necessary to use accelerometers that have substantially higher voltage or charge sensitivities.

The accelerometer should not affect the vibration amplitudes that are being measured. Large accelerometers can cause "mass-loading" on the surface to which they are mounted. That is, the mass of the accelerometer is sufficiently large compared with the mass of the object to which it is attached that the vibration signal being measured is significantly distorted. Many commercially available, light-weight accelerometers weigh 5 grams or less. The smallest accelerometer that can be used for a specific application should be chosen. The total weight of the accelerometer assembly (weight of multiple accelerometers, if more than one is used, plus accelerometer mounting block) should not exceed 20 grams in most cases. Accelerometers weighing less than 20 grams may be required for measuring vibration on small, lightweight tools.

Because vibration is a vector quantity, it is necessary to make vibration measurements in the three orthogonal axes. These axes should always be oriented in the manner specified in Figure III-2. The vibration measurements in the three axes should always be made at or as near as feasible to the surfaces of the vibrating hand-held tool or workpiece where the maximum vibration energy enters the hands. Figures III-3 through III-6 show suggested accelerometer mounting locations for chain saws, chipping hammers, and horizontal and vertical grinders [Wasserman et al. 1981]. The vibration in the three basicentric orthogonal axes may be measured with a specially designed triaxial accelerometer (a commercially

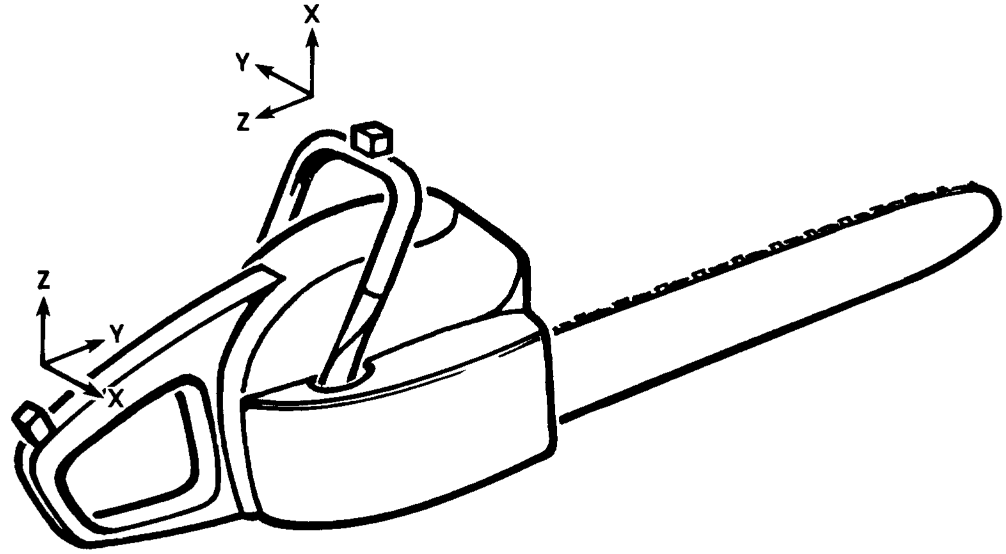

Figure III-3. Accelerometer locations and axis (x, y, z) orientations for chain saws.

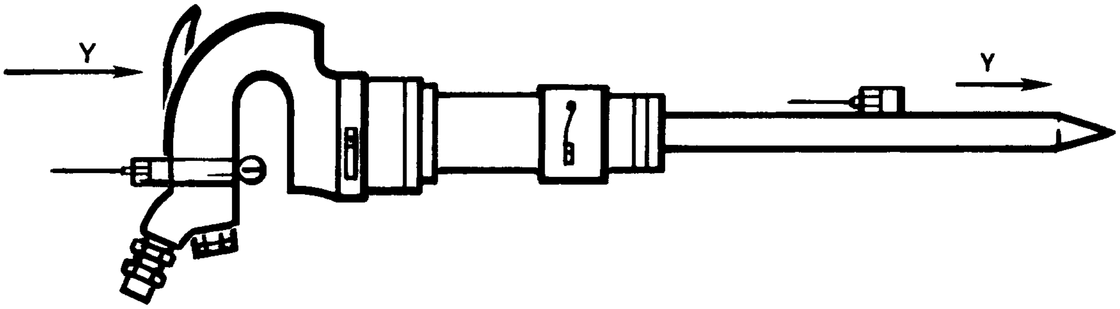

Figure III-4. Accelerometer locations and axis (x, y, z) orientations for chipping hammers.

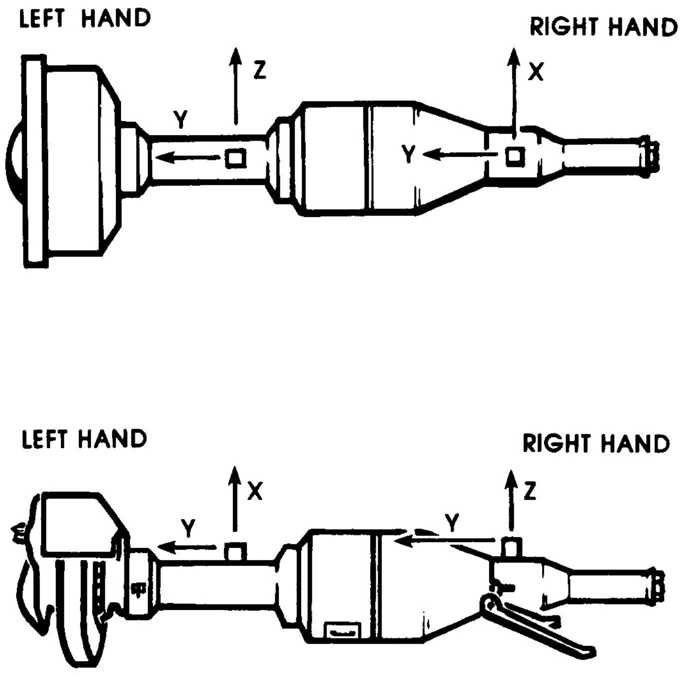

Figure III-5. Accelerometer locations and axis (x, y, z) orientations for horizontal grinders.

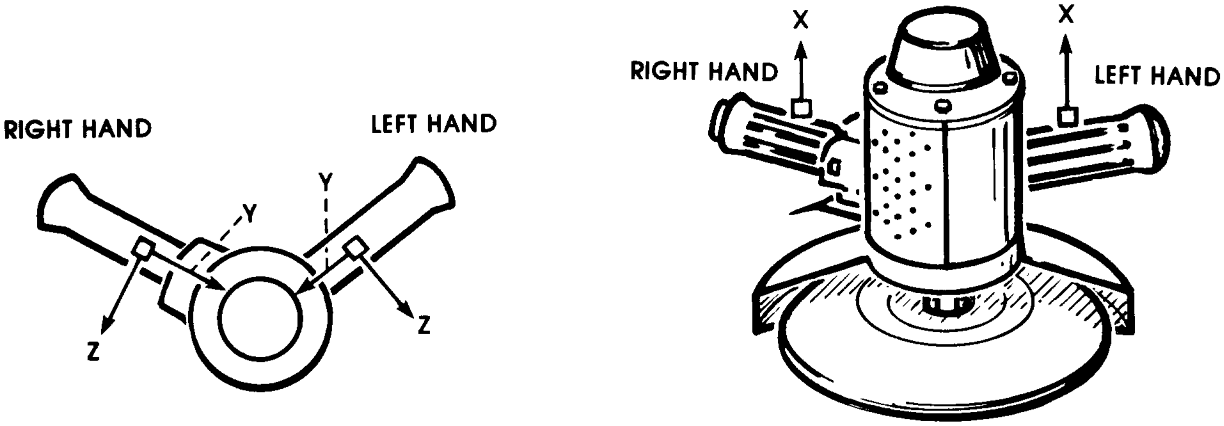

Figure III-6. Accelerometer locations and axis (x, y, z) orientations for vertical grinders.

available multiple accelerometer block that measures vibration in three axes) or by three regular accelerometers that are oriented along the three orthogonal basicentric axes (Figure III-3) that are attached to a small metal cubic block. The accelerometers should be attached directly to the vibrating surface, and the accelerometer and accelerometer-mounting configuration should be selected so that they do not distort the vibration measurements. More detailed information on procedures associated with the mounting of accelerometers can be found in Hempstock and O'Connor [1977], Reynolds et al. [1984], Wasserman et al. [1981], and Wasserman [1987].

3. Vibration Frequencies

Many vibration frequencies found in the workplace and other environments contribute to the total vibration measured. In the case of hand-transmitted vibration, the frequency range of importance designated by the International Organization for Standardization (ISO) is 5.6 to about 1,400 Hz [ISO 1986]. However, many types of tools produce vibration up to 5,000 to 10,000 Hz. Measured vibration data can be separated into its constituent parts by using a Fourier spectrum analysis. Mathematically, this can be expressed as

$$\begin{aligned} f(t) = {} & a_o + a_1 \, sin(\omega t) + a_2 \, sin(2\omega t) + \ldots + a_n \, sin(n_{\omega} t) \\ & + b_1 \, cos(\omega_1 t) + b_2 \, cos(\omega_2 t) + \ldots + b_n \, cos(\omega_n t) \end{aligned} \qquad (10)$$

where a_1 through a_n and b_1 through b_n define the amplitude of each of the corresponding vibration frequencies ω_1 through ω_n present in a given frequency spectrum. The combined sine and cosine terms give the actual vibration frequency components comprising the spectrum in the frequency range of interest and in their corresponding phases. The vibration spectrum is the frequency "finger print" of the vibration present in a given situation. Spectra are usually derived by means of computer analysis and graphically displayed as follows:

a. The horizontal axis represents frequency (Hz).

b. The vertical axis represents one of the following: acceleration (m/sec^2), velocity (m/sec), displacement (m or cm), or energy (joules).

c. The total number of vertical lines in the spectrum indicates all of the vibration frequencies present in the frequency range measured.

d. The height of each of the vertical lines indicates the amplitude of a parameter given in item b above. Each respective frequency element contributes to the total spectrum.

The Fourier spectra give the specific frequencies at which the vibration energy exists. Often when a vibration analysis is made, only the general vibration amplitudes are sought and it is not necessary to determine specific vibration frequencies at which these amplitudes exist. When this is the case, vibration amplitudes are measured using 1/3-octave-band filters.

In many cases when measurements are made to determine whether a particular level of vibration is within acceptable limits specified by a standard or regulation, using a single number to express the vibration stress is desirable. With respect to hand-transmitted vibration, the frequency-weighted acceleration level in m/sec^2 is the single-number variable used by the American National Standards Institute (ANSI) [ANSI 1986], the ISO [ISO 1986], the American Conference of Governmental Industrial Hygienists (ACGIH) [ACGIH 1988], and the British Standards Institution (BSI) [BSI 1987]. The frequency-weighted acceleration may be obtained by passing the signal through a frequency-weighting filter.

4. General Considerations Associated with Vibration Measurements

The duration of vibration signals associated with many vibrating hand-held tools or workpieces is relatively short. Thus to measure the vibration spectra or the 1/3-octave-band center frequency vibration acceleration associated with these signals, real-time analyzers must be used. These analyzers measure or compute the vibration amplitudes at all frequencies simultaneously. The dynamic range of these analyzers should be as large as possible over the frequency range of 5 to 5,000 Hz.

To analyze vibration signals, the signals must first be recorded and then played back through the recording device to an analyzer. This procedure is usually necessary when multiaxis acceleration measurements are being made relative to both hands at the same time. The recording device is usually a multichannel FM tape recorder or a multichannel analog-to-digital board that directs the recorded signals into a computer.

When high-peak acceleration signals associated with percussive tools are being analyzed, precautions must be taken to ensure that no part of the measuring, recording, or analyzing system is overloaded. To avoid overload, one of the following may be used:

- A commercially available shock accelerometer with a low voltage or charge sensitivity

- An electronic low-pass filter with an upper cut-off frequency above 5,000 Hz placed between the accelerometer voltage or charge amplifier and the recording device or analyzer

- A mechanical low-pass filter with a linear transfer function between 5 and 5,000 Hz placed between the accelerometer and the tool or workpiece

The acceleration signals associated with hand-transmitted vibration vary with time. Thus when measuring acceleration, it is always necessary to obtain values that are averaged over time. The acceleration is measured and reported as the root mean square (*rms*) value of acceleration [$a_{(rms)}$] in m/sec^2. The rms value of acceleration is

$$a_{(rms)} = \left[\frac{1}{T}\int_0^T a^2(t)\ dt\right]^{1/2} \tag{11}$$

where

$a(t)$ is the instantaneous amplitude of acceleration, and

T is the period of time over which a(t) is averaged.

The value of T in Equation 11 must be long enough to be representative of the task associated with the use of the tool being investigated. Also, T should be sufficiently long to ensure reasonable statistical accuracy of the data [Hempstock and O'Connor 1977; ANSI 1986; ISO 1986].

During a vibration measurement, the tool or workpiece should be operated in a manner that is representative of its everyday use. The measured vibration signals in each of the three basicentric orthogonal axes of vibration should be reported as rms acceleration in each of the 1/3-octave-band center frequencies.

C. GUIDELINES FOR ASSESSING VIBRATION AMPLITUDES

Most assessments of vibration amplitudes are based on vibration measurements of the dominant, single-axis vibration directed into the hand [ISO 1986; ANSI 1986; BSI 1987]. That is, the largest of the rms acceleration amplitudes along the three orthogonal basicentric axes shown in Figure III-2 may be used for assessing exposure to hand-transmitted vibration. Recommendations of the ISO, ANSI, and BSI are derived from studies associated with such tools as chain saws, pneumatic chipping hammers, and hand-held grinders. The level of vibration exposure associated with these tools is characterized not only by the vibration of the tool, but also by the type of coupling that exists between the tool and the hands of the tool operator (e.g., tight grip or axial thrust force), and the length of time the tool is used without interruption. Most studies assume good coupling exists between the tool and hands. Many of the assessment guidelines are based on time-averaged, frequency-weighted rms acceleration levels. Most of the studies indicate that regular daily vibration exposures do not exceed 4 hr per regular 8-hr workday [Brammer and Taylor 1982; Starck and Pyykko 1986; ANSI 1986; ISO 1986].

The overall time-averaged intensity of exposure to hand-transmitted vibration varies with such factors as the tool operator's work assignments, work practices, intermittence of exposure to vibration, and length of rest periods between vibration exposures. Thus when measuring vibration to assess the effects of exposure to hand-transmitted vibration, the estimates of total daily exposure should be based on representative vibration measurements for all of the different operating conditions (e.g., using more than one type of tool) associated with the operator's total work assignments over an 8-hr workday. This approach will usually result in several different sets of 1/3-octave-band center frequencies with different rms acceleration amplitudes for each of the different operating conditions. The total daily time-averaged rms acceleration [$a_{t(rms)}$] for each 1/3-octave-band can be obtained from

$$a_{t(rms)} = \left[\frac{1}{T_t} \sum_{i=1}^{n} \left[a^2_{(rms)\,i} \times T_i \right] \right]^{1/2} \tag{12}$$

where

$a_{(rms)i}$ is the component of rms acceleration with a time duration of T_i for the i_{th} operating condition

$$T_t = \sum_{i=1}^{n} T_i$$

Many of the assessments and recommendations are based on an actual tool use of 4 hr over an 8-hr workday. If the value of T_t in Equation 12 is other than 4 hr, the total daily rms acceleration amplitude can be converted to an equivalent 4-hr acceleration amplitude [$a_{t(rms)}(4\ h)$] by Equation 13 [ANSI 1986; ISO 1986; Wasserman 1987]:

$$a_{t(rms)}\ (4\ hrs) = \left[\frac{T_t}{4} \right]^{1/2} \times a_{(rms)}\ (T_t\ hrs) \tag{13}$$

where

$a_{t(rms)}\ (T_t h)$is the rms value of acceleration given by Equation 12, and
T_t is the total daily exposure time.

The acceleration $a_{xyz(rms)}$ associated with vibration in the three basicentric orthogonal directions in Figure III-2 can be obtained from the following equation:

$$a_{xyz\,(rms)} = \left[a^2_{x(rms)} + a^2_{y(rms)} + a^2_{z(rms)}\right]^{1/2} \qquad (14)$$

where

$a_{x(rms)}$ is the *rms* value of acceleration in the x direction,
$a_{y(rms)}$ is the *rms* value of acceleration in the y direction, and
$a_{z(rms)}$ is the *rms* value of acceleration in the z direction.

When comparing measured tool vibration acceleration levels with recommended limits, the comparison should be made using the acceleration level measured in the dominant basicentric axis.

D. FACTORS THAT INFLUENCE VIBRATION AMPLITUDES

1. Effects of Tool Type

Several factors influence the vibration levels produced by vibrating tools. The first is whether or not it is an impact tool. Vibration acceleration levels related to impact tools are generally higher than vibration levels associated with nonimpact tools. When appropriate elastomer or similar materials isolate the vibration-generating parts of tools from contact with the hands, the vibration acceleration levels are usually reduced.

2. Effects of Tool Operation

Other factors that affect the vibration acceleration levels of tools are associated with the ergonomics of operating the tool and related tool design. For example, a chipping hammer works by means of a reciprocating piston actuated by fluctuating pressure pulses. The vibration is generated by the repeated impact of the piston on the end of the chisel inserted into the hammer and the subsequent impact of the chisel on the workpiece. The fundamental vibration frequency is associated with the repetition rate at which the piston strikes the chisel. There is a vibration frequency at multiple harmonics of the primary repetition rate of the tool. The weight of the hammer also influences the vibration acceleration amplitudes directed into the hand. For similar operations, the heavier hammers appear to direct lower vibration levels into the hand at the tool handle. More of the vibration energy generated by the heavier tools goes into moving the tool mass, leaving less energy directed into the hand at the handle. However, increasing the tool weight may increase the grip force required to use the tool and thus increase vibration transmission to the hand. Increased tool weight could also increase stress on the wrist, elbow, and/or shoulder, which in turn could result in musculoskeletal disorders such as carpal tunnel syndrome (CTS).

Imbalance and repetitive impulses are the primary causes of vibration in chain saws and other tools using gasoline engines as the driving mechanism. Imbalance is associated with the rotating and reciprocating masses of the engine. The primary vibration frequency is directly related to the operating speed of the engine. Repetitive impulses are associated with the motion of the chain on the guide bar and the explosions of the gas-air mixture in the engine. The hand-transmitted vibration associated with these vibration mechanisms can be significantly reduced by properly designing and placing elastomer vibration-isolation pads between the engine and the chain saw handles.

The vibration associated with grinders and similar tools is related to the unbalanced rotating mass of the grinder and to the interaction between the grinder wheel, cup or pad, and the workpiece. If the grinder is well maintained, the vibration associated with the unbalanced rotating mass of the grinder is usually not a problem. The condition of the grinder wheel or cup, however, has a very significant effect on the vibration amplitudes produced. If the wheel or cup is well dressed and kept "in round," the vibration associated with the interaction of the wheel or cup with the workpiece will be at a minimum. If the wheel or cup is not periodically "dressed" during use, it can become "out-of-round" and very rough. This substantially increases the vibration acceleration of a poorly maintained grinder compared with a new grinder [NIOSH 1984].

3. Effects of Tool Maintenance

Poor maintenance of vibrating tools significantly influences the vibration acceleration amplitudes that are generated. For example, the vibration acceleration of poorly maintained grinders may be many times higher than the corresponding vibration acceleration of new grinders. Part of the difference can be associated with poorly dressed grinding wheels. As was mentioned above, the use of elastomer vibration-isolation pads in chain saws can be very effective in reducing chain saw vibration directed into the hand. However, these pads must be inspected and replaced periodically.

4. Effects of Work Cycle and Work Conditions

The work cycles, work conditions, and work incentives significantly affect the time-averaged vibration acceleration level associated with many tools. For example, a major use of chipping hammers is for cleaning castings in foundries. In some foundries, the workers clean castings on a piecework basis—the more castings cleaned, the more wages earned. For these situations, the chipping hammers are generally operated at full throttle for periods of up to 4 hr or more in an 8-hr workday [Brammer and Taylor 1982].

Another use of chipping hammers is to form propeller blades. For this situation, the chipping hammers are operated at 1/2 to 3/4 throttle for periods of up to 3 hr over an 8-hr workday [Brammer and Taylor 1982]. Typically, grinders are used for an additional 2.5 to 3 hr during the workday. The time-averaged vibration acceleration at the handle of the chipping hammer was 10 to 14 m/sec^2 for the hammer operated at 1/2 to 3/4 throttle versus 50 to 190 m/sec^2 for the hammer operated at full throttle [NIOSH 1981]. The total time-averaged rms acceleration amplitudes depend on the duration of use and corresponding acceleration associated with the chipping hammer and the grinder.

5. Effects of Coupling between Hand and Tool

Another factor that can influence the transmission of vibration energy produced by vibrating tools is the coupling that exists between the tool and the hands of the operator. Even though the degree of coupling between the hand and a vibrating tool affects the amount of vibration energy transmitted to the hand from the tool, it will not have much effect on the measured vibration acceleration amplitudes produced by the tool. The reason is that the vibrating mass of the tool in contact with the hand is usually much greater than the total effective mass of the hand that is coupled to the tool. In some situations (e.g., electrically driven engraving tools, small riveting guns, and the light-weight handles of small, antivibration hobby chain saws), the mass of the hand may be of the same order of magnitude as the mass of the vibrating tool. For these situations, the degree of coupling between the hand and the tool will have an effect on the vibration acceleration amplitudes measured on the tool.

E. VIBRATION RESPONSE CHARACTERISTICS OF THE HAND

1. Factors Influencing the Vibration Response Characteristics of the Hand

Several factors influence the vibration response characteristics of the hand. These include the following:

- Grip force exerted by the hand around the tool handle
- Axial or static force exerted by the hand on the tool
- Size of vibrating surface in contact with the hand
- Body position associated with using the hand tool
- Clothing and gloves worn

Of these factors, the effects of grip and axial force are the most important, followed by body position and gloves [Griffin et al. 1982; Goel and Rim 1987].

Although it has been demonstrated that the presence of vibration-related disorders affect an individual's subjective response to and perception of vibration directed into the hand, these disorders do not have a measurable effect on the vibration-response characteristics of the hand [Wasserman et al. 1981]. Radwin et al. [1987] reported that vibration can affect the way operators hold and use tools, which is then reflected in altered work performance and injury risk. With increased vibration, grip force on the tool handle is increased, and tactile sensitivity is decreased.

2. Energy Directed Into the Hands

Many vibration assessment guidelines are based on 1/3-octave-band, center-frequency-weighted rms acceleration levels. However, acceleration levels alone do not necessarily represent a true measure of the energy that is directed into the hand. To obtain this information, the coupling between the tool handle must be considered along with the acceleration levels. This can be accomplished by attaching a specially designed fixture to the handle of a vibration tool to measure grip force (coupling) as well as acceleration. A second method is to use the results of acceleration measurements on a tool handle in conjunction with dynamic compliance [Brammer and Taylor 1982; Reynolds et al. 1984; Wasserman et al. 1981].

If the vibration directed into the hand is harmonic in nature or can be broken down into harmonic components, it can be shown that the amplitude of the energy dissipated (E_D) in the hand and arm as a result of damping or other dissipative mechanisms is

$$E_D = \frac{\ddot{X}^2 \, sin(\Phi)}{2\omega^4 \, X/F} \tag{15}$$

where

ω is the frequency in units of radians/second,
X is the measured amplitude of acceleration (m/sec^2) at ω,
X/F is the dynamic compliance (m/N), and
Φ is the radians.

Similarly, the energy (E_S) that is stored in the hand as kinetic and potential energy, and is consequently transferred back and forth between the hand and vibrating tool handle, is presented by Brammer and Taylor [1982], Reynolds et al. [1984], and Wasserman et al. [1981] as follows:

$$E_S = \frac{\ddot{X}^2 \cos(\Phi)}{2\omega^4 \, X/F} \tag{16}$$

Also of interest is the time rate of change of energy or power transmitted to the hand. The power (W) is

$$W = \frac{\ddot{X}^2 \sin(\Phi)}{2\omega^3 \, X/F} \quad \text{or} \quad W = \omega E_D \tag{17}$$

The power transmitted to the hand and arm is related to the energy that is dissipated in the hand and arm.

3. Mathematical Models of the Hand and Arm

The hand-arm system is a very complicated, continuous, nonhomogeneous system that consists of skin, muscle, bone, etc. An accurate model must take all of these components into account. Many investigators have developed models of the hand and arm [Brammer and Taylor 1982; Meltzer et al. 1980; Mishoe and Suggs 1977; Miwa 1968a; Reynolds and Keith 1977; Wasserman et al. 1977; Reynolds and Falkenberg 1984; Starck and Pyykko 1986]. Mechanical impedance or dynamic compliance data or both were used as the basis for developing many of these vibration models. The parameters of many of the models can be related to the physiology of the hand and arm. However, there is no general agreement about which parts of the hand and arm should be described by a model. For example, work reported by Suggs and Mishoe [1977] and Wood and Suggs [1977] supports the idea that the mass elements of a model should represent the respective masses of the fingers, hand, arm, etc. However, the work reported by Reynolds and Keith [1977], Reynolds and Falkenburg [1984], and Wasserman et al. [1977] supports the idea that the mass elements of a model should represent the components of dermis and epidermis of the skin, subcutaneous tissue, and muscle tissue in the area of the hand that is in direct contact with a vibrating surface. Most models imply that (1) vibration energy directed into the hand at frequencies below 80 Hz is transmitted to and can be perceived in the arm, and (2) vibration energy directed into the hand at frequencies above 100 Hz is generally local to the area of the hand in contact with a vibrating surface. These implications are confirmed by vibration transmissibility tests in the hand and arm.