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CHAPTER 5

Vibration and Acoustics

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The authors dedicate this chapter to the late Dr. Henning von Gierke

Aerospace systems generate some of the most severe vibration and noise environments encountered by humans. These dynamic environments, either singly or in combination, threaten the comfort, performance, and psychological well-being of persons associated with or exposed to aerospace operations. In more severe and/or prolonged periods of exposure, these environments become a health or occupational hazard, causing serious degradations in performance, modifications of physiological functions, and injury, including chronic back pain and hearing loss. Although relatively simple and straightforward methods are used to control moderate vibration and noise, the development of more complex control and mitigation methods and procedures requires a more in-depth understanding of the mechanisms involved in the generation of undesirable symptoms. Human vibration and bioacoustic research have directed attention to delineating the psychological, physiological, and performance effects of vibration and noise exposures on humans. The extensive knowledge and databases gathered from these studies serve as the basis for exposure guidelines and standards and for the development of predictive tools for estimating the environmental effects. Technological advances in vehicle design and human-integrated equipment continue to challenge researchers, designers, and health experts in ensuring effective aircrew performance, communication, and occupant safety during vibration and noise exposures. A significant portion of this chapter is reflective of the basic tools and knowledge associated with human response to vibration and noise presented in previous editions that have not dramatically changed over time. This edition expands on the issues and problems relevant to current and future aerospace systems.

WHOLE-BODY VIBRATION IN AEROSPACE ENVIRONMENTS

General Vibration Terminology

Vibration

Vibration is oscillatory motion in dynamic systems. A dynamic system possesses mass and the capability for relative motion between parts of the system, having the property of elasticity. Oscillatory motion can include periodic motion, in which the motion repeats itself in a given time period, or aperiodic, in which the motion does not repeat itself. In its simplest form, periodic vibration can be described as sinusoidal motion. Aperiodic vibration includes shock or transient motions. Random vibration is a type of motion described by its statistical properties that never exactly repeats itself. Stationary random vibration is characterized by statistical properties that can be estimated to be time-invariant. Nonstationary random vibration changes with time and is unpredictable. Most vibration encountered in aerospace environments is aperiodic or random.

The dynamic system of concern is the human body. In aerospace operations, oscillatory motion in the human body can be generated through structure-borne vibration or airborne vibration. Structure-borne vibration results from contact of the body with a physical structure such as a vehicle floor, seating system, or other equipment. Airborne vibration results from contact of the body with sound pressure waves produced during the airborne transmission of acoustic energy (also referred to as *vibroacoustics*).

Frequency

For simple periodic or sinusoidal vibration, the frequency of the motion is defined as the number of complete cycles of motion occurring in a unit of time, usually 1 second. The reciprocal of the frequency is the period of the motion, or the time associated with completing one cycle. The international unit for frequency is the Hertz (Hz), which is one cycle per second. Random vibration is also described in terms of its frequency content or frequency spectra by using appropriate spectral analysis techniques.

Amplitude

Amplitude or intensity is the measure of the system oscillatory motion about a position of rest. The amplitude of vibration can be described as displacement, velocity, or acceleration. For translational vibration, displacement is expressed in the unit meter (m). Velocity is expressed in units of meters/second (m/s). Acceleration is expressed in units of meters per second squared (m/s^2). For rotational vibration, displacement is expressed in units of radians (or degrees). Velocity is expressed in terms of radians per second and acceleration is expressed in terms of radians per second squared. For simple sinusoidal motion, the relationships among displacement, velocity, and acceleration are:

$$\text{Acceleration magnitude} = -\omega^2 x(t) \text{ or } -(2\pi f)^2 x(t) \quad [1]$$

$$\text{Velocity magnitude} = \omega x(t) \text{ or } (2\pi f)x(t) \quad [2]$$

where ω is the angular frequency in radians per second, f is the frequency in Hz ($\omega = 2\pi f$), and $x(t)$ is the instantaneous displacement at time, t. The amplitude of a sinusoidal motion can be expressed as a peak or peak-to-peak value. However, with random vibration, a time-averaged or root-mean-square (rms) value is commonly used. The rms value is calculated as

$$X_{rms} = \sqrt{1/T \sum_{0}^{T} x^2(t)dt} \quad [3]$$

where x is the amplitude at time t, and T is the period of the vibration or length of time over which the rms value is being determined. The rms value of a sinusoidal motion is conveniently calculated as $1/\sqrt{2}$ or 0.707 times the peak value. Acceleration is the most common unit used to describe vibration or oscillatory motion, particularly with regard to human exposure, due to the widespread and convenient use of acceleration transducers for measuring the motion. Acceleration is sometimes expressed in terms of g or the acceleration resulting from gravity. One g is equal to 9.80665 m/s^2 depending upon the location on earth.

Resonance

When a sinusoidal excitation force is applied to a simple mass-spring-damper system (one degree-of-freedom), the system will initially vibrate at its natural frequency (free vibration), as well as at the frequency of excitation. When damping is present, the motion associated with the natural frequency will die out (transient motion) but motion at the excitation frequency will continue (steady state) as long as the force is present. If the excitation force is equal to the natural frequency of the system, resonance occurs. Without damping, the oscillations continue to build up, usually with catastrophic consequences. With damping, the oscillations will have finite amplitude. Resonance also occurs during exposure to random vibration that includes the natural or resonance frequency of the system. When the dynamic system is complex and described as a multi–degree-of-freedom system, each subsystem associated with a degree-of-freedom has the potential for excessive oscillations at its resonance frequency.

Direction

A body or system can move in translation, rotation, or a combination of both. Translational vibration occurs when a body or system oscillates along a straight line or in a linear direction (sometimes referred to as *rectilinear motion*.) The translational vibration of a body or system is defined along three perpendicular lines or orthogonal axes and include the fore-and-aft (X), lateral (Y), and vertical or longitudinal (Z) directions. Rotational vibration occurs when a body or system oscillates or rotates about a linear axis. Roll occurs when the body or system rotates about the X-axis, pitch occurs when the vibration is about the Y-axis, and yaw occurs when the rotation is about the Z-axis. The directions from which vibration enters the human body have been standardized by the International Standardization Organization [ISO 2631-1: 1997(E)] (1) and are illustrated in Figure 5-1. The human body is sensitive to the direction of vibration. Therefore, the perpendicular or orthogonal axes of vibration move with the body for movement from a seated or standing orientation to a recumbent orientation. The human body can translate and rotate either in or about a single axis or in a combination of up to six axes (X, Y, Z, roll, pitch, and yaw).

Spectrum

The spectrum of vibration represents the distribution of amplitude across frequency. This distribution is described in frequency bands that may be proportional or of constant bandwidth. The one-third octave bandwidth is the proportional bandwidth typically used when assessing human vibration exposure. Examples of constant bandwidths include spectra defined in increments of 0.1 Hz, 0.25 Hz, and

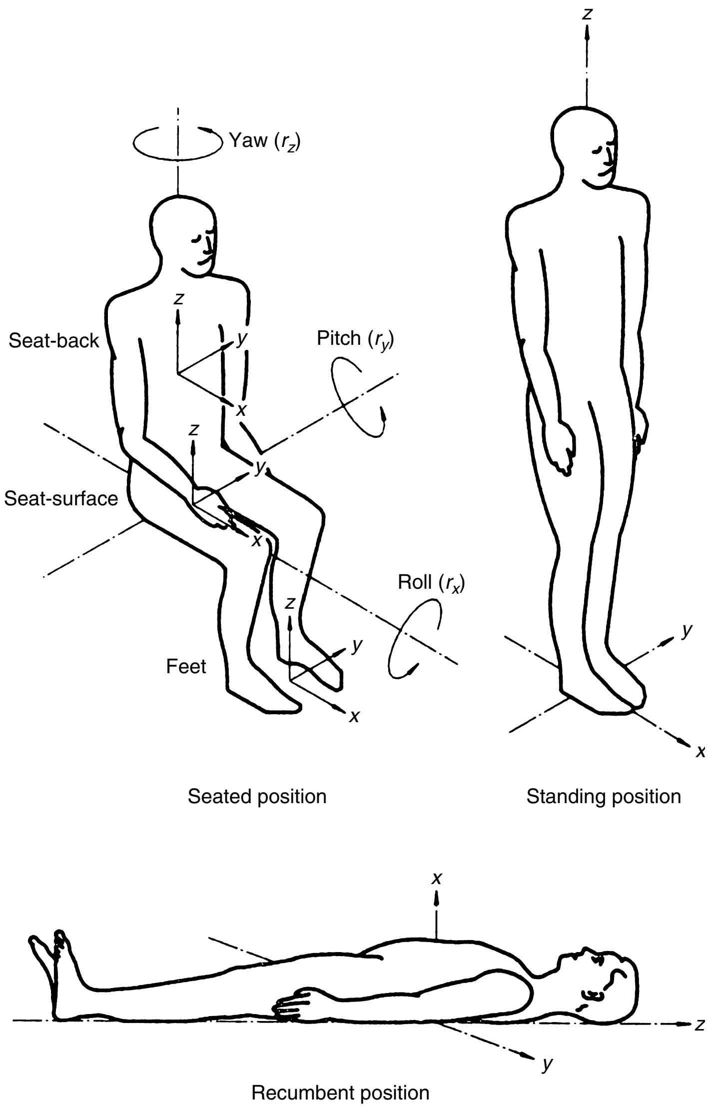

FIGURE 5-1 Basi-centric coordinate system of the human body. International Standards Organization (ISO). *Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements. ISO 2631-1:1997(E)*, 1997. [© ISO. This material is reproduced from ISO 2631-1 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization (ISO). No part of this material may be copied or reproduced in any form, electronic retrieval system or otherwise or made available on the Internet, a public network, by satellite or otherwise without the prior written consent of the ANSI. Copies of this standard may be purchased from the ANSI, 25 West 43rd Street, New York, NY 10036, (212) 642-4900, http://webstore.ansi.org.]

0.5 Hz. The most common unit used to describe the spectral components associated with human vibration exposure is the root-mean-square acceleration in m/s^2 rms.

Duration

In general, human tolerance to continuous vibration declines with increasing duration of exposure. Although the time-dependent effects of vibration are still not fully understood, it is generally accepted that long exposures at higher vibration levels may present a health risk, particularly when the exposures occur repeatedly over long periods. The time-dependent effects form the basis for exposure criteria and standards as described later in this chapter.

Aerospace Sources of Whole-Body Vibration

Air Vehicle Propulsion System

The primary internal source of vibration in aerospace vehicles is the propulsion system. In conventional propeller-driven aircraft, vibration between 10 and 1,000 Hz is generated through the unbalanced forces associated with the engine speed and the propeller blade passage frequency. Blade passage frequency is calculated as the product of the propeller rotation speed (or propeller rotation frequency) and number of blades. In rotary-wing aircraft (rotorcraft) such as helicopters, propeller rotation speeds (or rotor speeds) range primarily between 200 and 400 revolutions per minute (rpm) or approximately 3 to 7 Hz. The numbers of blades typically range from two to four, producing blade passage frequencies mainly between 6 and 28 Hz, although higher blade numbers do exist. Blade imbalances can cause vibration at frequencies that are multiples of the propeller rotation speed, that is, 2 per revolution (2P), 3 per revolution (3P), and so on. Vibration can also be generated as multiples or harmonics of the blade passage frequency. Other propeller-driven aircraft have higher propeller rotation speeds and higher blade passage frequencies. For example, the six-bladed C-130J aircraft has a propeller rotation speed (or frequency) of 17 Hz. The blade-passage frequency is 102 Hz (6 × 17). Figure 5-2 illustrates the frequency spectra measured beneath the seat of a crewmember onboard a two-engine, four-bladed military propeller aircraft. The data were analyzed in 0.5 Hz increments. In this case, the propeller rotation speed (or

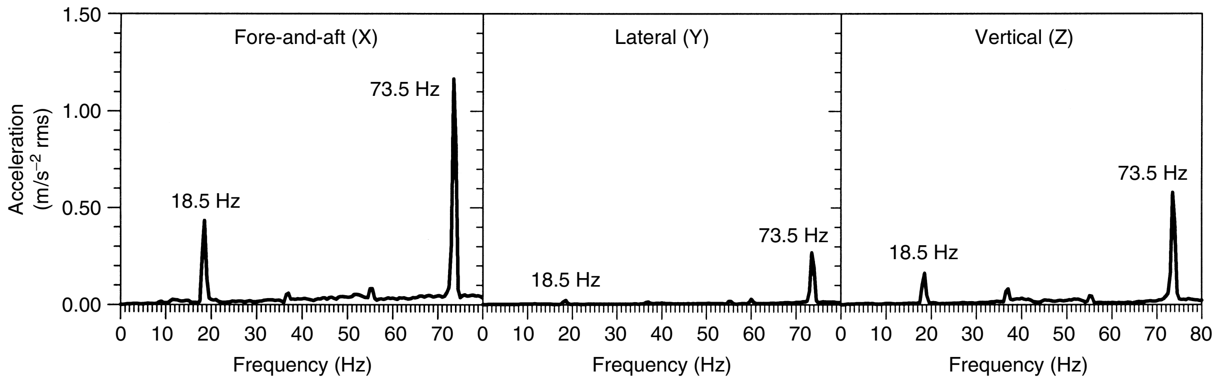

FIGURE 5-2 Example frequency spectra from a military propeller aircraft showing peak accelerations associated with the rotor speed propeller rotation frequency (~18.5 Hz) and blade passage frequency (~73.5–74 Hz).

frequency) was approximately 18.5 Hz, and the blade passage frequency was approximately 73.5 to 74 Hz. The structure-borne vibration generated at these frequencies is transmitted to the occupants through a seating system or other surface in contact with the body, can be felt by the occupant, and persists to varying degrees throughout the flight. Jet engines operate at higher speeds, minimizing the potential for generating low frequency, structure-borne vibration. In space vehicles, the primary internal source of vibration is combustion in the large, multistage rockets used to launch the vehicle.

During aircraft engine run-ups and ground-based maneuvering, ground operations and maintenance crews can be exposed to airborne vibration that is transmitted to the body through acoustic waves. The noise levels associated with airborne vibration can be substantial in military environments where ground crews are required to work close to powerful aircraft and in restrictive areas. Such a hostile vibration environment is also found on aircraft carriers.

Air Turbulence

Air turbulence is the major external source of structure-borne vibration in aerospace vehicles. Weather and thermal effects contribute to air turbulence during flights up to 10,000 m (32,808 ft). Wind shear occurring between moving air masses can cause clear-air turbulence at altitudes above 10,000 m. Ground turbulence, influenced by the local heating and cooling between the air and ground surface and by wind effects, is prevalent at altitudes below 500 m (1,640 ft). Ground turbulence is particularly important during tactical operations. Such operations can require the pilot to fly at low altitudes (below 500 m) at high speeds. Helicopters are affected by ground turbulence because they typically operate near the ground surface. In addition, vibration in these aircraft can also occur because of ground effects caused by the coupling between the downwash and rotating blades (2).

Air Vehicle Structural Resonance

Buffeting is the vibration of a vehicle as it interacts with the air in which it moves, generating aerodynamic forces on the structure. These forces can excite the various modes of vibration or resonances of the vehicle (including fuselage and wing bending). It is not uncommon to encounter buffeting during commercial jet aircraft flight because of bad weather, thermal disturbances, or clear air turbulence. Although occurring rarely, such vibration can be severe enough to affect control of the aircraft. Buffeting also occurs in military high performance jets during low-altitude, high-speed flight, and aerial combat maneuvers (ACMs). This low-frequency buffeting can be severe but short in duration. It can act as a control cue to the pilot during these maneuvers. However, the transmission of buffet vibration to the aircrew may cause involuntary motions in the body and affect the operation of critical equipment (3).

Space vehicles are affected by aerodynamic forces, particularly during the first few minutes of acceleration during launch. During launch, structural vibration can occur primarily between 2 and 15 Hz due to the excitation of lateral bending and longitudinal oscillatory motions (2). During reentry, the space vehicle is decelerated by atmospheric friction. Given modern day control systems, reentry into the earth's atmosphere is relatively smooth, although flight instabilities could cause relatively severe but short-term structural vibration (2).

Measurement and Analysis Techniques

Vibration Measurement Equipment

There are three components required to measure vibration: a transducer, signal conditioner or amplifier, and recording device. The transducer is an acceleration, velocity, or displacement detector that can measure the vibration in the various axes of translation and/or rotation. Accelerometers are the most commonly used transducers for measuring vibration because of their small size and light weight. Miniature accelerometers have been mounted onto major body anatomic structures such as the head. A semirigid disk with embedded accelerometers is commonly used to measure the vibration at the interface between the human body and contact surface, particularly in the seated position. The signal conditioner or amplifier is used to amplify the analog signal. Typically, the amplifier will produce an output in volts per unit of acceleration (when using an accelerometer). The signal conditioner may also be capable of filtering the analog signal to attenuate certain low frequencies (high pass filter) or high frequencies (low pass filter). Vibration signals are commonly converted to digital signals and stored on a digital tape recorder, computer, or other digital storage media.

A variety of vibration meters is available for evaluating human vibration exposure. The features of this equipment usually conform to vibration standards requirements for data collection, filtering, and processing. The vibration is typically collected at the interface between the human and contact surface as described in the preceding text.

Vibration Analysis

Spectral Analysis Techniques

Human vibration is typically evaluated as a function of frequency because the human body is very sensitive to the frequency of motion. Analog frequency or spectrum analyzers use calibrated narrow band, octave band, or fractional-octave band filters to estimate the spectral content of an analog time history signal. Digital spectral analysis uses the fast Fourier transform (FFT) to estimate the spectral content of a digital time history signal. The spectral density (also known as the *power spectral density* or *PSD*) is the mean square of the signal per unit frequency and is widely used to present and compare the frequency spectra of excited systems exposed to random vibration. When the measurement is acceleration, the units are $(m/s^2)^2/Hz$. The root-mean-square or rms value can be calculated by multiplying the mean square value by the width of the frequency band over which the measurement was integrated and taking the square root. Caution must be taken when applying the more common digital spectral analysis to estimate the spectral content. Digital signals are sampled at a defined sampling interval, Δ (seconds) or frequency, $1/\Delta$ (Hz). The Nyquist or folding frequency [$1/(2\Delta)$ Hz] is defined as one-half the sampling frequency ($1/\Delta$ Hz) and is the highest frequency that can be detected using the sampling interval, Δ (seconds). In order to avoid distortion or aliasing in the spectrum, the sampling interval should be small enough so that $1/2\Delta$ Hz is greater than the highest frequency component expected in the signal. When the highest frequency component in the measurement is unknown, antialiasing techniques are typically applied during processing of the data. There are several methods described in signal processing texts and computer software packages for estimating the power or autospectral density, as well as the cross-spectral density calculated between various measured responses of a system. It is cautioned that the application of analog or digital processing techniques assumes that the vibration can be approximated as stationary or time invariant.

Transfer Functions

The transfer function defines the vibration transmission characteristics of a physical system. The transfer function is used to characterize the input/output relations between the source of vibration and the excited system as well as the relationship between motions of coupled components composing the system. In this regard, it can be a useful tool for formulating and validating mathematical models of the system response and for developing mitigation techniques and processes. The simplest case for calculating any transfer function is with a single input and single output measured in the same direction. For random vibration, the transfer function can be calculated as the ratio between the cross spectral density of the output and input measurements and the auto spectral density of the input measurement. This method produces a transfer function that describes the linear relationship between the input and output. The coherence function is a calculated value between 0 and 1; the closer the value is to unity, the more linear the relationship between the input and output with less contributions from noise and other sources unrelated to the input vibration.

The single-input/single-output transfer function has also been used to estimate the transmission characteristics when there is vibration in more than one direction. Alternative analytic methods for estimating the multiaxis transfer matrix are described in textbooks on signal processing.

Two transfer function methods are typically used to describe the transmission characteristics and resonances of the human body. They are the driving-point mechanical impedance and transmissibility methods. Driving-point (mechanical) impedance is defined as the ratio between the measured transmitted force and the input velocity of a vibrating system occurring in the same direction and at the same location (usually at the interface where the vibration enters the body, i.e., seat or feet). The units for the driving-point impedance magnitude are Newton-seconds per meter (N-s/m). A related function, the apparent mass, is used by several investigators to reflect the biodynamic characteristics of the body. The apparent mass is the ratio between the transmitted force and the input acceleration.

Peaks in the driving-point impedance magnitude and the phase relations between the input and output provide information on the frequency range(s) in which maximum energy is transmitted to the human body (i.e., body resonances) and in which maximum physiological and psychological effects may occur. The driving-point impedance also provides quantitative information on the effects of certain conditions and equipment (posture, restraint, seats) and can be used as a first clue to the mechanical structure of the human body and how to describe that structure in mechanical and engineering terms. However, impedance is primarily affected by the response of major components of the system and those components located nearest to the driving point or measurement location. Transmissibility is the ratio between input and output measurements of the same units. The transmissibility method provides valuable information on the transmission pathways and has been historically calculated from the output acceleration measured at the head and the input acceleration measured at the point of contact with the vibrating surface (seat or feet). The transmission of vibration and impact through the body structure is of primary interest with respect to explaining undesirable effects such as trauma and performance degradation. Peaks in the magnitude of the transmissibility, like impedance, are associated with body resonances. Measurements at multiple locations can be used to estimate the resonance frequencies of system components and can, for the human body, provide coupling information between connected anatomic structures or regions. This information, as with impedance, is quite useful for developing and validating robust human vibration models (particularly mass-spring-damper or lumped-parameter models). For the human body, special consideration must be given to the weight, location, and method of attaching the transducer because these factors could affect the measurements.

Vibration Exposure Metrics

The transfer functions mentioned in the preceding text are used to describe the biodynamic responses of the human body. Characteristics of these responses are described in the section on **Vibration Effects on Humans**. There are human vibration standards that call for the use of specific metrics for assessing human exposure relative to health, safety, and comfort. The most common metric is the frequency-weighted rms acceleration. The acceleration is measured in all three orthogonal axes at the interfaces where the body contacts the vibrating structure. For the seated person, the interfaces include the surface between the buttocks and seat pan, the back and seatback, and the feet and supporting surface. For the standing person, the interface includes the feet and supporting surface. For the recumbent person, the interfaces include the pelvis and the supporting surface, and the head and supporting surface. A pliable disk with embedded accelerometers is typically used for these measurements. The measured acceleration is weighted in the time or frequency domain. In the time domain, the calculation is similar to Equation 3, where X_{rms} is now the weighted acceleration, a_w. Using the acceleration spectra (estimated using the spectral methods described previously), the weighted acceleration can be calculated as

$$a_w = \left[\sum_i (W_i a_i)^2 \right]^{\frac{1}{2}} \qquad [4]$$

where W_i is the frequency weighting associated with the *ith* frequency band, and a_i is the rms acceleration associated with the *ith* frequency band. The frequency weighting depends on the frequency, direction, and, in some cases, the location of the measurement. Historically, the frequency weighting curves were derived from equivalent comfort contours; the frequency weightings are high where the equivalent comfort contours are low (4). Researchers continue to evaluate human sensitivity to vibration. These efforts may result in a revision of the current frequency weightings. Additional manipulations of the weighted acceleration levels include the application of multiplying factors that reflect the relative effects of vibration direction, the use of the fourth-power instead of the second-power acceleration, and the vectorial summation of weighted acceleration levels for assessing vibration effects. Several of these metrics are described in the section on **Exposure Guidelines and Regulations**.

Vibration Effects on Humans

Human Body Biodynamics

The transfer function methods described earlier have been applied for characterizing human body biodynamics in vibration environments. Historically, most human whole-body vibration research and exposure assessments focused on measuring human responses during exposure to seated vertical vibration occurring along the vertical or longitudinal axis of the body (Z in Figure 5-1). The human body is most sensitive to vibration in the vertical direction. Some aerospace vehicles, such as propeller-driven aircraft and spacecraft, generate significant vibration in the horizontal directions. As mentioned in the previous section on vibration analysis, the two most common techniques used to evaluate the dynamic characteristics of the human body are the driving-point impedance (or apparent mass) and transmissibility.

Driving-Point Impedance/Apparent Mass

Figure 5-3 illustrates the driving-point impedance of one subject exposed to vertical vibration with several postures (5). At the low frequencies (below ~3 Hz), the body acts like a pure mass corresponding to the body weight (represented theoretically by the line $Z = m\omega$). Depending on the distribution of body mass and the associated composition, muscle tension, and posture, there is a major peak in the impedance that usually occurs between 4 and 8 Hz. This peak is known as the *primary whole-body resonance*. It is specifically associated with relative motions in the upper torso and shoulder girdle, including the soft tissue and organs in the upper thoracoabdominal region. These relative motions cause the transmission of higher forces back to the measurement site at the seat–occupant (or floor–occupant) interface as compared with the response of a rigid mass (Figure 5-3). At higher frequencies above the primary resonance frequency, more energy is absorbed by the elasticities and damping inherent in the soft tissues. At the higher frequencies, the impedance tends to decrease, although other smaller regions of resonance can be identified, particularly around 10 Hz and 15 Hz as shown in Figure 5-3. These peaks have been, in general, associated with resonances of the spine but may be influenced by the response of other anatomic structures, including the legs. Figure 5-3 shows that the sitting erect posture results in the upward shift of the resonance frequency by approximately 1 Hz. Using this simple representation, it can be shown that the erect posture results in stiffening of the body. The impedance of the human body is linear only to a first approximation. For simultaneous exposures to both vibration and sustained acceleration (inertial preload) at +2 G_z and above, the primary body resonance shifts to higher frequencies between 8 and 10 Hz with a corresponding increase in the magnitude of the impedance peak (6). The changes observed in body biodynamics and resonance behavior may also affect human tolerance (see section on **Physiology and Health**). However, any strong vibration occurring in the 8 to 10 Hz range could have more serious consequences during G-preload because of the shift in body sensitivity under these conditions. In contrast to the effects

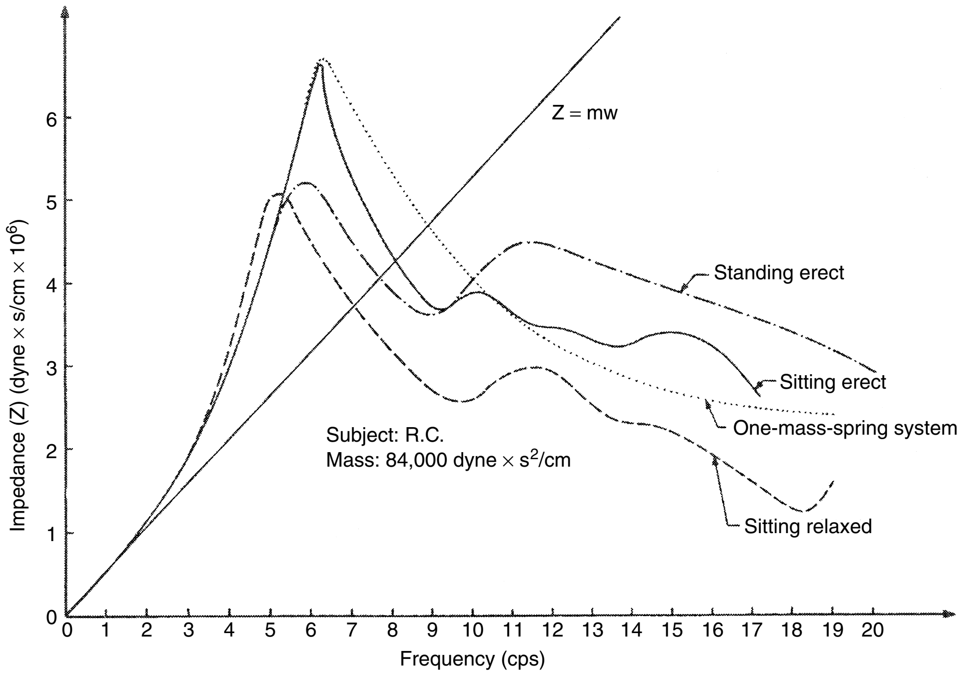

FIGURE 5-3 The modulus of the impedance of a subject at varied body postures compared with the impedance of a pure mass ($m\omega$) and a one-mass-spring system with damping. (From Coermann RR. *The mechanical impedance of the human body in sitting and standing position at low frequencies.* ASD technical report 61–492. Wright-Patterson Air Force Base, Ohio: Aeronautical Systems Division, Air Force Systems Command, United States Air Force, 1961.)

of sustained acceleration, studies have also shown that, under normal gravity, the primary resonance peak observed in the impedance shifts downward by 1 to 2 Hz with increases in the vibratory acceleration. The associated decrease in stiffness with higher vibratory acceleration is not as dramatic as the increase in stiffness associated with G-preload.

Transmissibility

The primary peak observed in the vertical seat-to-head transmissibility coincides closely with the primary resonance peak observed in the impedance data. The vertical head transmissibility decreases to relatively low values at higher frequencies above the whole-body resonance (when there is no direct contact with a vibrating surface). The transmissibility has also been calculated between the input at the seat and other body locations including the chest, spine, and legs (7). Caution should be taken in interpreting these results because the attachment of the transducer to the body surface may be affected by the response of the underlying muscle or skin. Accelerometers have become very lightweight and can minimize some of these effects. These data, along with the driving-point impedance data, provide valuable information on the coupling behavior occurring between anatomic regions. For example, the resonance peak observed in the impedance between 8 and 10 Hz for some subjects coincided with a peak transmissibility response in the unsupported legs (7). Peaks in the spine transmissibility have been observed around 6 Hz, 10 to 12 Hz, and 12 to 20 Hz, coinciding with peak regions observed in the impedance for some subjects and suggesting significant coupling effects between anatomic structures or regions.

Exposure to vertical axis vibration can result in other motions in the body depending on posture and head orientation. Head pitching in the forward-facing position is quite prevalent and is also observed during exposure to fore-and-aft vibration. Off-axis head orientations (other than the forward-facing position) can increase the transmission of vibration to the head. Head vibration can have significant effects on visual performance as discussed later in this chapter. In addition, resonance of the eye has been reported to occur between 20 and 70 Hz (4) and can contribute to visual degradation.

There have been an increasing number of women entering the predominantly male aerospace workforce (see Chapter 22). Because most subjects participating in research have been men, there is the need to understand similarities and differences in female/male responses to aerospace vibration for insuring optimum performance and safety of qualified individuals. Recent research has suggested that some differences may exist in the vibration response characteristics between women and men, but these differences have so far not resulted in definitive effects on performance, health, and safety relative to aerospace operations. The limited data have suggested that, in general, the distribution of the mass, stiffness, and damping characteristics of the major dynamic anatomic regions differs between women and men, but not to the extent of dramatically affecting the primary resonance frequency associated with upper torso motion (7).

Multiaxis Vibration

Although vertical vibration has been the major concern in aerospace operations, the presence of vibration in more than one direction can contribute to even greater and more complicated motions of the body. Research efforts to determine the effects of multiaxis or combined-axis vibration in aerospace operations are becoming more common with the availability of safe but sophisticated multiaxis vibration platforms and improved methods for quantifying occupant vibration during operations. As mentioned previously, there are analytic methods available for estimating the multiaxis transfer matrix when substantial vibration occurs in more than one axis.

Airborne Vibration

The mismatch between the acoustic impedance of air and the human body surfaces prevents significant amounts of acoustic energy from entering the body, particularly at higher frequencies (8). With decreasing frequencies below 1,000 Hz, more acoustic energy is absorbed in the form of transverse shear waves. With exposure to high-intensity noise levels (120 dB) between 100 and 1,000 Hz, tissue vibration occurs and the noise is felt through the stimulation of somatic mechanoreceptors (2). Below 100 Hz, intense noise can cause whole-body vibration that not only affects motion in the chest, abdominal wall, viscera, limbs, and head but can also generate motions in the body cavities and air-filled or gas-filled spaces (2). Von Gierke reported that resonance of the chest wall and air-filled lungs occurs around 60 Hz (8).

Previous studies investigating the effects of airborne vibration have directed attention to the association between noise level and the subjective assessment of the exposure (9). Lightweight accelerometers have been attached to the body surface for estimating body accelerations while standing near jet aircraft during engine run-ups (10). Figure 5-4 shows peak acceleration in the upper torso between 60 and 100 Hz, particularly in the fore-and-aft (X) direction of the chest for one subject. This peak coincides with the upper torso resonance reported by von Gierke and Nixon (8). It also appears that, under the conditions tested, the peak increases with increasing noise level. It should be cautioned that these preliminary data do not address the effects of airborne vibration on individuals of varying weight and stature.

Physiology and Health

The mechanical stresses imposed on the body during vibration exposure can potentially lead to interference with bodily functions and tissue damage in practically all parts of the body, depending on the frequency range and exposure conditions. Most aerospace vibration exposures remain below injury levels. Acute exposures to whole-body vibration, primarily in the range of 1 to 20 Hz (11), of intensities voluntarily tolerated by human subjects up to the limit of severe discomfort or pain, have not resulted in demonstrable harm or injury. Continued exposures at the limits of tolerance are considered to have a high potential for producing bodily damage. Figure 5-5 illustrates the short time, 1-minute, and 3-minute tolerance limits reported by healthy adult male subjects exposed to vertical sinusoidal vibration (11). The figure shows the decrease in tolerance with longer exposure periods. Minimal tolerance occurs between 4 and 8 Hz, the frequency range associated with whole-body resonance. Figure 5-6 depicts the frequencies at which the most severe symptoms have been reported. Headache is often associated with exposure to frequencies above 10 Hz. Particularly for exposures to sustained fore-and-aft acceleration (G_x) with g_x or g_y vibration (space couch positions), motions are transmitted to the head directly from the headrest, which can lead to extremely uncomfortable and disturbing impacts to the head. During launch and reentry of spacecraft, the crew is oriented in the semisupine posture. This minimizes the influence of sustained acceleration by directing the force through the fore-and-aft or X direction of the body (Figure 5-1). This does couple the body more closely to the seating system. The vibration tolerance associated with this seat orientation is discussed in the section **Human–Equipment Interfaces**.

Most physiological effects in the 2 to 12 Hz frequency range are associated with the resonance of the thoracoabdominal viscera. Movement of the thoracoabdominal viscera

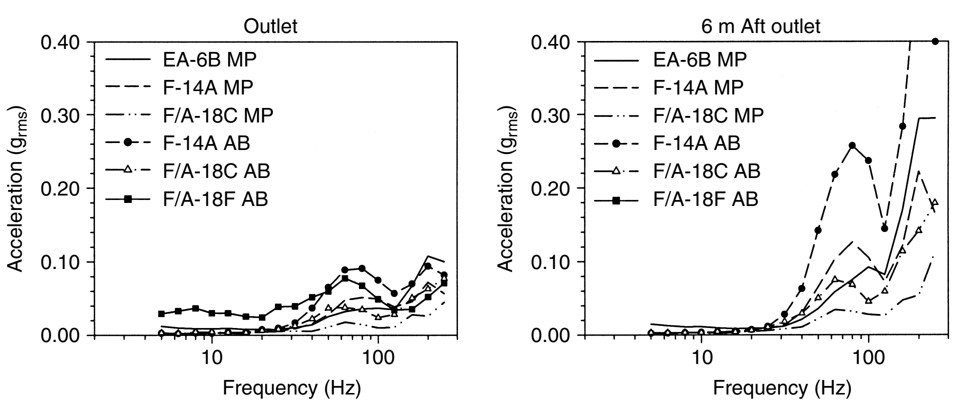

FIGURE 5-4 Acceleration peak observed between 60 and 100 Hz measured in the fore-and-aft direction of the chest during ground engine run-up tests in selected aircraft at military power (MP) and afterburner (AB). (Smith SD. The effects of airborne vibration on human body vibration response. *Aviat Space Environ Med* 2002;73(1):36–45.)

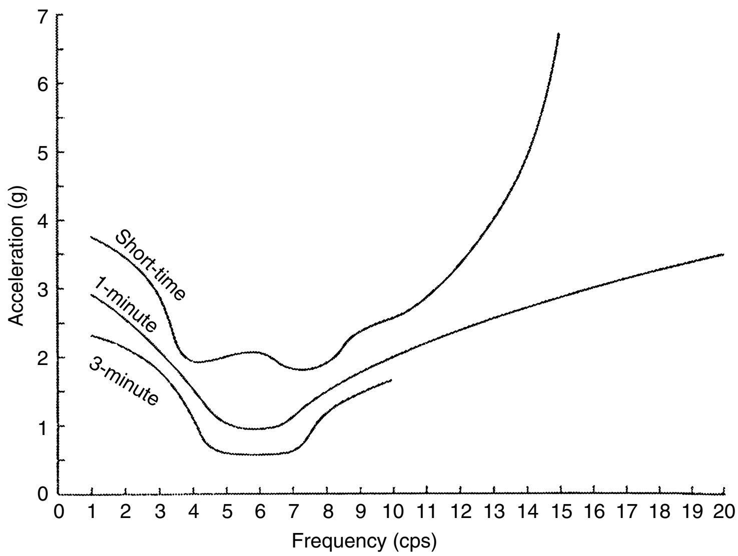

FIGURE 5-5 The short-time, 1-minute, and 3-minute tolerance limits reported during vertical sinusoidal vibration. cps, cycles per second or Hertz. (Magid EB, Coermann RR, Ziegenruecker GH. Human tolerance to whole body sinusoidal vibration. *Aerospace Med* 1960;31:915–924.)

in both X- and Z-axis excitation is responsible for the interference of vibration with respiration. It causes the involuntary oscillation of a significant volume of air in and out of the lungs, leading to an increase in minute volume, alveolar ventilation, and oxygen consumption. In experimental exposures to g_z vibrations, pCO2 decreased and clinical signs of hypocapnia were observed, suggesting hyperventilation (2). As shown in Figure 5-6, dyspnea results from short exposures to high-amplitude vibration. Changes in cardiovascular functions, including arterial blood pressure, cardiac index, heart rate, and oxygen consumption index, were shown to be dependent on the amplitude and the frequency of whole-body vibration. In general, the combined cardiopulmonary response to vibration in the 2 to 12 Hz range resembles the response to exercise. Although increased muscular effort of bracing against the vibration and psychological factors may account for some of the response, observance of the same general pattern in anesthetized animals speaks for the stimulation of various mechanoreceptors (12).

The most commonly reported chronic health symptoms in occupations that include prolonged whole-body vibration exposure are back pain and back disorders. However, these symptoms are also reported for other occupations as well. The spinal column is a major pathway for the transmission of vibration in the upper torso. Repeated exposures to vibration can affect the mechanical integrity of the musculoskeletal components, leading to injury. In aerospace operations, the highest incidence of back pain and back disorders is reported

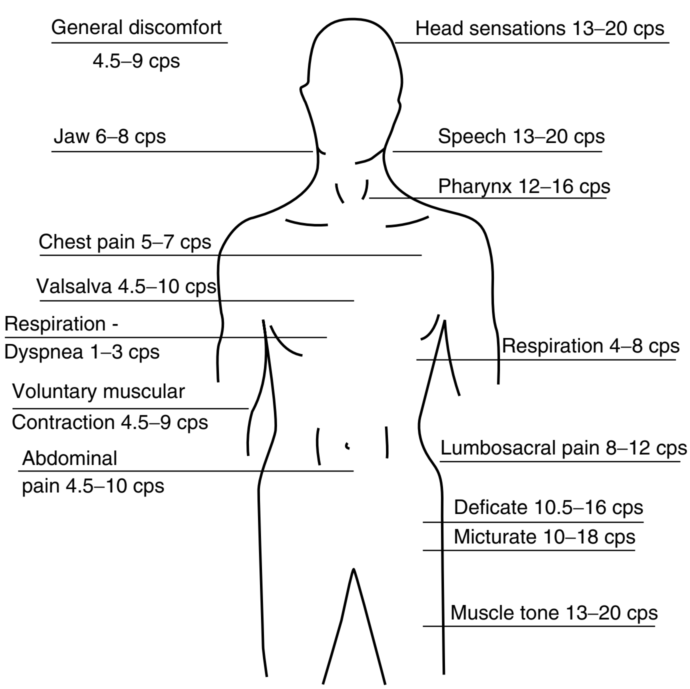

FIGURE 5-6 Symptoms experienced for frequencies between 2 and 20 Hz at tolerance levels. cps, cycles per second or Hertz. (Magid EB, Coermann RR, Ziegenruecker GH. Human tolerance to whole body sinusoidal vibration. *Aerospace Med* 1960;31:915–924.)

for helicopter pilots. Body posture is an important factor to consider in the generation of these symptoms. Helicopter pilots in particular may adopt poor sitting postures to operate the aircraft and to improve visibility (13,14).

The symptoms of subjects exposed to airborne vibration were studied by the U.S. Air Force in the 1960s (9). In summary, for exposures below 150 dB, the most common symptom reported was mild-to-moderate chest vibration. From 50 to 100 Hz, pure tone exposures reached levels above 150 dB. Voluntary tolerance was reached at 50 Hz (153 dB), 60 Hz (154 dB), 73 Hz (150 dB), and 100 Hz (153 dB) based on the significance of symptoms reported by the subjects. Symptoms included headache (50 Hz); coughing, severe substernal pressure, choking respiration, salivation, pain on swallowing, hypopharyngeal discomfort, and giddiness (60 Hz and 73 Hz); and mild nausea, giddiness, subcostal discomfort, cutaneous flushing, and tingling (around 100 Hz) (9). In the more recent study (10), reports of increasing chest vibration coincided with the increase in the peak chest acceleration and the increase in the noise level. It has been suggested that prolonged exposures to high-pressure, low-frequency noise may have physiological and pathological consequences.

Performance

Manual Control and Head Tracking

Low-frequency aerospace vibration that occurs during turbulence or buffeting in jet aircraft, helicopter operations, and launch and reentry of space vehicles present a particular challenge to manual control and head tracking performance. The involuntary motions of the body and the extremities introduced by the vibration are imposed as disturbances on the required control of the human operator. The greater the vibration amplitude of the hand, foot, or head in comparison with the required control motion (through strong original excitation or through resonance reinforcement), the larger the undesirable interference.

Laboratory manual control experiments have shown that manual tracking errors increase in the 2 to 16 Hz frequency range at seat accelerations above approximately 0.05 g_z rms. The maximum decrement is usually in the range of 4 Hz, which is in the vicinity of the main body resonance (4 to 8 Hz). Above approximately 0.25 g_z rms, manual control can be seriously affected and worsen with time due to fatigue (2). For X-axis and Y-axis vibration, the largest decrements are at 1.5 to 2 Hz. Caution should be taken in generalizing the decrements because they depend too much on the specific details of the control task (e.g., position, velocity or force control, amplitude of required control motion) and the hand-arm or foot-leg support. Early studies suggested that high-intensity noise between 100 and 105 dBA combined with vibration produced less decrement in manual tracking performance than with vibration alone. However, when 110 dBA noise was combined with vibration, the tracking performance was more degraded than observed for either noise or vibration alone (15).

The advent of helmet-mounted equipment requires the head to track and target objects. Low-frequency vibration that causes oscillations of the head can increase tracking and targeting error. Off-axis head orientations can further increase head motions and have been associated with increased head tracking error below 10 Hz (16).

The severity of the vibration interference can be influenced to some extent by the operator's control strategy. For example, under turbulent flight conditions, pilots often postpone manual activity during short bursts of high-amplitude vibrations and introduce corrective action as soon as the burst is over. Under sustained turbulence, very low frequencies can excite "pilot-induced oscillations," which are caused by inappropriate control inputs. The pilot apparently has time to correct for the disturbance inputs but, owing to misinterpretations of kinesthetic cues or the response characteristics of the motor system, he or she does not compensate in an appropriate way at some frequencies and adds to aircraft instabilities.

Visual Performance

A complex relationship exists among all of the relevant parameters affecting visual performance including vibration frequency, amplitude and direction, viewing distance, illumination, contrast, the shape of the viewed object, and the occupant posture and restraint. Difficulties in reading instruments and performing visual searches occur when vibration introduce relative movement of the eye with respect to the observed object or target, even when the observed object (such as the instrument panel) is excited by the same structural vibration. The greatest decrement in visual performance occurs with vibration of the object or display alone, followed by vibration of the occupant alone. The least relative effect occurs with vibration of both the occupant and the object or display (4).

Compensatory eye movement is the physical response to vibration and affects visual performance. During head rotation, the vestibulo-ocular reflex causes the eye to move in the opposite direction of the motion, thereby stabilizing the line-of-sight (LOS) to a stationary object (compensatory eye movement). The compensatory eye movement has been shown to be effective up to 8 Hz with some studies showing effectiveness up to 20 Hz (4). Compensatory eye movement is the most effective during head rotations. Exposure to translational vibration at lower frequencies is expected to produce both translation and rotation of the head. At higher frequencies, the eye resonance described previously can result in blurred vision. Given the damping effect of the body at higher frequencies, this effect may occur only where high levels of vibration are present or when the head comes in direct contact with a vibrating surface.

The launch and reentry phase of spaceflight presents a unique problem for visual performance because the crew is oriented in the semisupine posture with both body and head closely coupled to the seat and restraint system. This special case is discussed further in the section **Human–Equipment Interfaces**.

Cognitive Performance

Early studies strongly suggested that the performance of simple cognitive tasks (pattern recognition and monitoring of dials and warning lights) were not affected by vibration. More demanding tasks have shown to be affected by vibration and combinations of vibration and noise. One study involved mental arithmetic and short-term memory during a 0.5 g_z (peak) vibration at selected frequencies between approximately 5 Hz and 16 Hz. The results showed significantly slower performance as compared to the static condition (17). Regardless of these findings, it has also been suggested that vibration can increase the level of arousal, similar to observations in noise, depending on the exposure intensity, exposure time pattern, and the subject activity.

As with manual tracking performance, studies have also been conducted on the combined effects of vibration and noise on cognitive performance. An early study suggested that either 100 or 110 dBA noise combined with vibration produced more adverse effects on the performance of a mental arithmetic task than either stressor alone. In another study using a complex counting task, it was found that the effect of noise was reversed with vibration. While 100 dBA noise as compared to 65 dBA noise produced greater performance degradation, the 100 dBA noise combined with vibration as compared to the 65 dBA noise combined with vibration produced less degradation (15). These results were similar to the results for manual tracking performance using similar noise levels.

Human-Equipment Interfaces

In aerospace operations, the human body becomes coupled with any interfacing equipment, including seating systems and helmet systems. Although this coupling could provide the mechanisms for minimizing vibration effects, current use of this equipment in aerospace environments has been associated with comfort, health, and performance degradation, exacerbating effects already described previously. For example, most conventional seat cushions tend to increase the transmission of vertical vibration from the seat to the upper torso and head in the vicinity of whole-body resonance (4 to 8 Hz), but dampen these motions at higher frequencies as compared to sitting in a rigid structure. Passive suspension systems have been used to attenuate vehicle vibration near human resonance but typically increase the transmission of vibration to the body at around 2 Hz and below, producing relatively large displacements at these frequencies. Active suspension systems use a feedback mechanism to stabilize the seat motion relative to the vehicle motion. In military aircraft that include ejection seats, the seat cushions are relatively thin and stiff, to minimize any rebound of the body during ejection or ground impact. Consequently, they provide little damping or isolation from any vehicle vibration. Current suspension or isolation systems may add unwanted weight and compromise crashworthiness in these types of aircraft. As mentioned previously, vibration transmitted directly from the headrest to the head can affect visual performance, causing visual blurring most likely related to eye resonance.

Helmet systems used in military flight environments can affect head motions. Increasing the mass of the helmet and increasing the distance between the center of gravity (CG) of the head/helmet system and the head have been shown to increase head pitch in the forward-facing direction (18). Sophisticated helmet-mounted visual systems including night vision goggles (NVG), helmet-mounted displays (HMDs), and helmet-mounted targeting and display (HMT/D) interfaces present unique issues in performance. For example, the compensatory eye movement is rendered ineffective in stabilizing the LOS to a viewed object when using an HMD because of the movement of the projected object with the head (19). It has been shown that reading error is greater with the use of an HMD as compared with a panel-mounted display (4). Relative head/helmet motion or slippage could further reduce the effectiveness of these systems. As mentioned previously, degradation in head tracking performance has also been associated with vibration (3,16). The low-frequency buffeting associated with maneuvering of certain fighter aircraft can cause substantial involuntary motions of the head and may compromise the performance of head tracking and targeting systems. The extreme head/helmet orientations that can occur during these operations exacerbate this issue.

The vibration encountered during launch and reentry of spacecraft presents a special case for human tolerance and visual performance in the semisupine posture, where coupling between the occupant and seating system is critical. Studies were conducted back in the 1960s to evaluate the effects of the seat or couch, body restraint, and head restraint on subjective tolerance and visual performance. Figure 5-7 illustrates the mean level of acceleration tolerance at the tested frequency for the seat or couch configurations (20). The exposure duration depended on the frequency; the higher the frequency, the less time to reach a given acceleration level. The longest tolerance exposure took 250 seconds or approximately 4 minutes. There was no helmet or head restraint used with the contoured couch. The subjects maintained their head in the headrest. If head buffeting became intolerable, they could lift their head and continue until voluntary tolerance was reached. A helmet system with restraint in the X and Y directions was used with the adjustable couch. The helmet restraint release was designed into the system. Once the subject released the helmet restraint, the exposure was discontinued and the associated acceleration level considered the voluntary tolerance. Figure 5-7 shows that the adjustable couch produced higher tolerance in the X-axis below approximately 10 Hz but flattened at higher accelerations, low tolerance in the Y-axis above approximately 8 Hz, and similar tolerance as compared to the contoured couch in the Z-axis. In the X-axis, the main focus of complaints was in the thoracic area, particularly with the contoured couch. The subjects reported difficulty breathing with both configurations. Repeated impact of the sacrum was reported for the adjustable couch, although, in general, the body was more coupled to this couch as compared to the contoured couch. These symptoms were

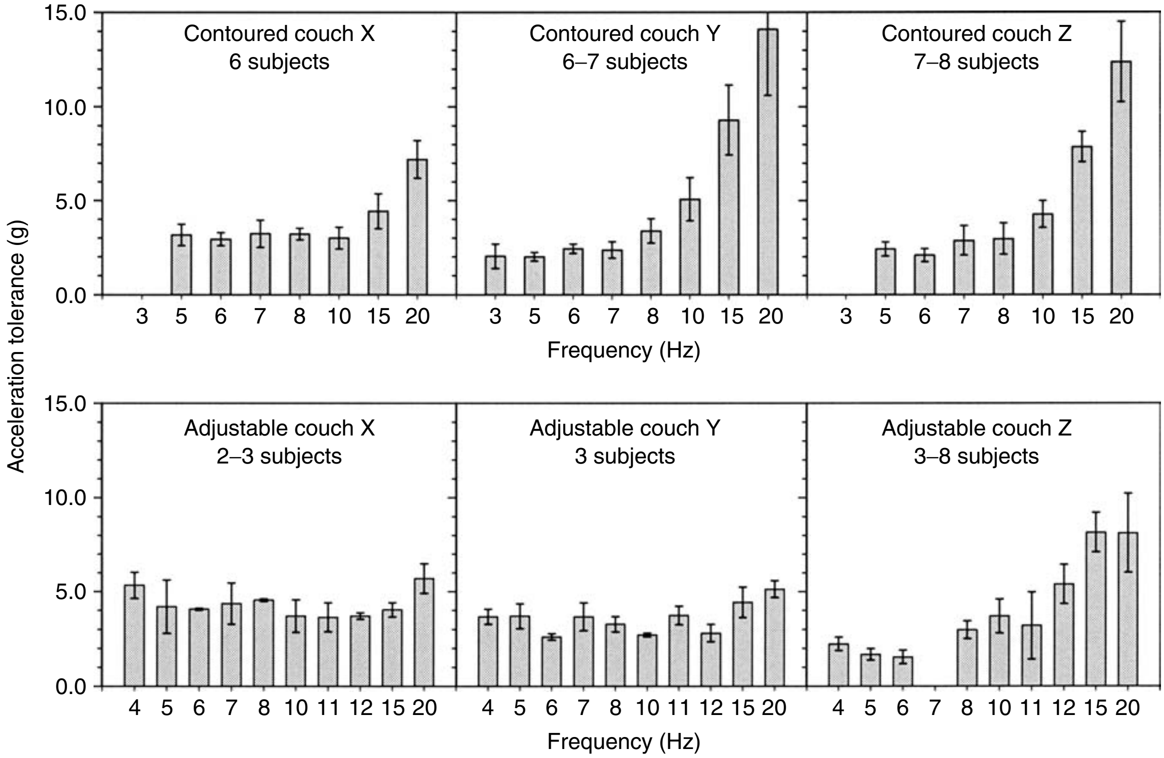

FIGURE 5-7 Mean level of human acceleration tolerance for two spacecraft couches. Tolerance is shown for the three orthogonal directions of the recumbent occupant (Figure 5-1) at selected frequencies. (Redrawn from data presented in Temple WE, Mandel MJ, Clarke NP, et al. *Man's short-time tolerance to sinusoidal vibration. AMRL-TR-65-96*, Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratories, 1965.)

also reported for the Y-axis, but not as frequently. Frictional rubbing and banging were reported for the contoured couch in the Y direction. In the Z-axis, there were more complaints about the head, including headache and sore neck muscles. Raising the head appeared to isolate the head from higher frequency vibration in the contoured couch, but may have contributed to fatigue. The helmeted head and good coupling to the adjustable seat limited complaints at low frequencies but reduced tolerance at higher frequencies, particularly in the horizontal directions (20).

Dial-reading performance was investigated at 6, 11, and 15 Hz using a Mercury helmet (21,22) and Apollo helmet (23) in the semisupine posture. The Mercury helmet was tested in the X ($+1\ G_x \pm 1.1\ g_x$) and Y ($+1\ G_x \pm 0.9\ g_y$) directions in the first study and only in the X direction in the second study. The Apollo helmet was tested in both the X and Y directions at levels coinciding with those used in (21). The first study (21) included the unrestrained and restrained helmeted head. The second study (22) included the restrained head and a piston-spring damper. The third study (23) tested the helmet with and without a liner. In general, all three studies showed that coupling the head to the seat reduced the reading error at frequencies below 10 Hz. This also coincided with the increase in tolerance when restraining the head (20). The results suggested that isolating the head at frequencies above 10 Hz might improve reading performance and improve tolerance (22). It is cautioned that the early tolerance and performance studies were conducted in well-controlled laboratory environments with physically qualified military members.

Vibration Protection and Mitigation

Exposure Guidelines and Regulations

National and International Standards

Given the physiological and psychological effects of vibration described previously, it is clear that there are no simple assessment procedures and exposure limits that are applicable to all environmental, human posture and restraint, and task performance conditions. However, based on laboratory and field experiences, whole-body vibration standards have been developed that provide boundaries and guidelines for assessing the effects of vibration. The primary national standard for structure-borne vibration is the American National Standards Institute (ANSI) *Guide for the Evaluation of Human Exposure to Whole Body Vibration* (ANSI S3.18–2001) (24). The primary international standard is the International Standards Organization's (ISO) *Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole Body Vibration, Part 1: General Requirements* (ISO 2631-1: 1997) (1). The 2001 ANSI standard is identical to the ISO 2631-1: 1997.

The ISO 2631-1: 1997 uses the frequency-weighted accelerations and multiplying factors described in the section

Vibration Analysis for assessing the effects of vibration. For assessing the effects of vibration on health, the ISO 2631-1: 1997 provides health guidance caution zones as shown in Figure 5-8 (based on Equation B.1). Below the lower boundary zone, health effects have not been clearly documented or observed. Within the upper and lower boundary zones, caution is indicated for potential health risks. Above the higher boundary zone, health risks are likely. The highest rms value of the frequency-weighted acceleration determined in any axis at the seat pan is compared to these zones. In addition to a caution zone based on the weighted rms acceleration (second power), a caution zone is also provided on the basis of weighted fourth power vibration dose method. The vibration dose value (VDV) represents a cumulative exposure and is more sensitive to peaks in the exposure. It is noted that the emphasis of these standards is on the health risk to the lumbar spine.

The ISO 2631-1: 1997 also provides likely comfort reactions to vibration occurring in public transport. For assessing comfort, the acceleration is measured in each translational axis at the main supporting surfaces (seat pan, seatback, and feet). For vibration occurring in more than one direction, the point vibration total value is calculated at each surface or location using the root-sum-of-squares of the weighted accelerations. If the comfort is affected by vibration at several locations (i.e., seat pan, seatback, or feet), the overall vibration total value is calculated from the root-sum-of-squares of the respective point vibration total values. In addition, the ISO 2631-1: 1997 includes guidelines for the effects of vibration on the incidence of motion sickness in the frequency range from 0.1 to 0.5 Hz. The ISO 2631-1: 1997 has been recently applied to assess and compare the vibration occurring in selected military propeller aircraft (25).

Part 5 of the ISO 2631 titled "Method for the Evaluation of Vibration Containing Multiple Shocks (ISO 2631-5: 2004)" was developed to assess the effects of repeated shocks on the health of the lumbar spine. Exposures to multiple shocks may occur in the operation of aircraft in rough air, vehicles driving over rough terrain, or boats traveling in rough seas. An acceleration dose is calculated using a

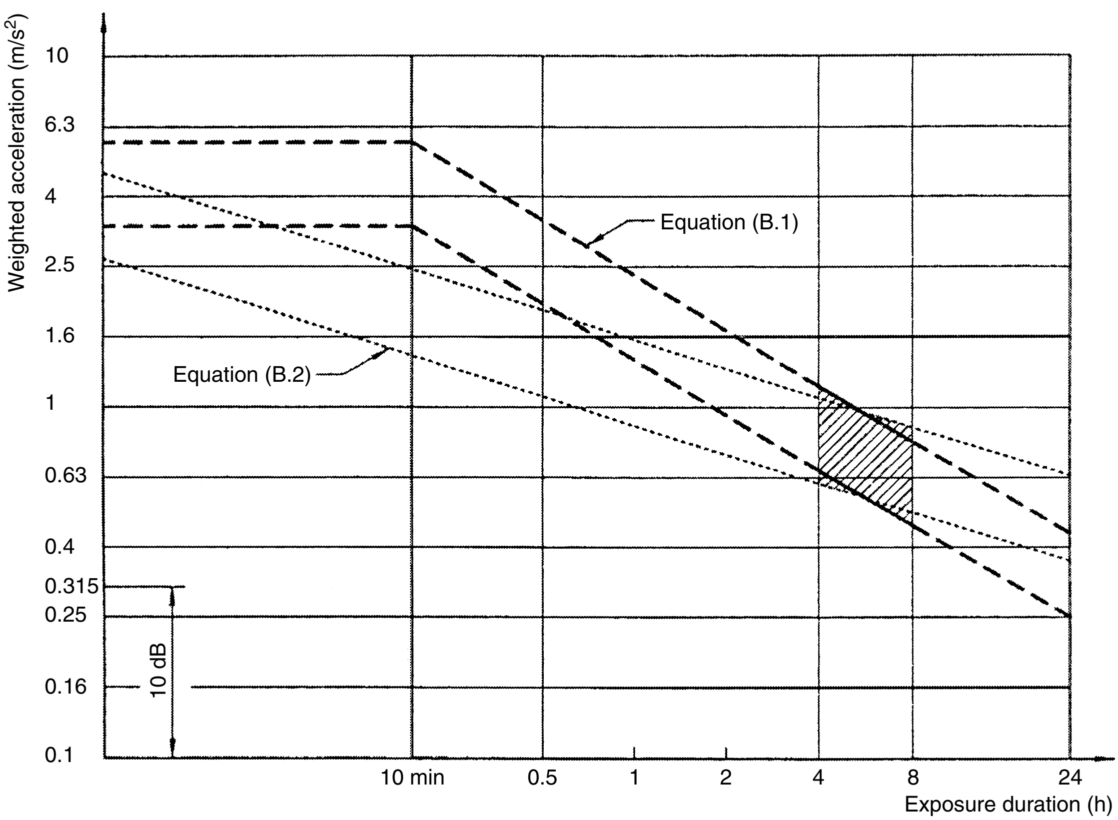

FIGURE 5-8 ISO 2631-1: 1997(E) Health Guidance Caution Zones. Equation (B.1) is defined by the following relationship: $a_{w1} \cdot T_1^{1/2} = a_{w2} \cdot T_2^{1/2}$. Equation (B.2) is defined by the following relationship: $a_{w1} \cdot T_1^{1/4} = a_{w2} \cdot T_2^{1/4}$. International Standards Organization (ISO). *Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements*. ISO 2631-1:1997(E), 1997. [© ISO. This material is reproduced from ISO 2631-1 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization (ISO). No part of this material may be copied or reproduced in any form, electronic retrieval system or otherwise or made available on the Internet, a public network, by satellite or otherwise without the prior written consent of the ANSI. Copies of this standard may be purchased from the ANSI, 25 West 43rd Street, New York, NY 10036, (212) 642-4900, http://webstore.ansi.org.]

biomechanical model and the measurements defined in ISO 2631-1: 1997 for the seat pan. The model predicts the response of the lumbar spine to a given input. The standard provides guidelines on the probability of an adverse health effect based on the acceleration dose, the ultimate strength of the lumbar spine, the person's age, and number of years of exposures.

European Union Directive

The European Union established its human vibration directive in 2002 (Directive 2002/44/EC) (26). The directive uses the ISO guidelines for measuring the vibration exposure in each translational axis. The directive defines an exposure action value (EAV) and exposure limit value (ELV) based on either the 8-hour energy-equivalent frequency-weighted acceleration level (A8 in ISO 2631-1: 1997) or the VDV (ISO 2631-1: 1997). If the EAV is exceeded, the employer must take appropriate action to try and reduce the daily exposure. If the ELV is exceeded, the health risk is considered to be high enough to prohibit further exposure.

United States Government Standards

There are specifications and guidelines given for vibration exposure in military operations including the Department of Defense Design Criteria Standard, Human Engineering, MIL-STD-1472E (27). Other government standards include the Man-Systems Integration Standards, NASA-STD-3000 (28) and the American Conference of Governmental Industrial Hygienist (ACGIH), Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs) (29). Only the MIL-STD-1472E refers to the 1997 ISO 2631-1 guidelines. As of 2006, the NASA-STD-3000 is based on previous editions of the ISO 2631-1. The ACGIH provides TLVs based on the weighted rms acceleration curves given in ISO 2631/1-1985 that are both time and frequency dependent. These values refer to that limit under which most workers may be repeatedly exposed with minimum risk to health (particularly with reference to back problems) with an emphasis on ground vehicles and heavy equipment.

Current airborne vibration exposure criteria (as of 2006) are given with respect to the noise level. The Air Force Occupational Safety, and Health Standard, AFOSHSTD 48-20 (30) recommends that, for minimizing whole body vibration effects, no octave or one-third octave band noise level exceeds 145 dB for frequencies in the range of 1 to 40,000 Hz, and that the overall sound pressure level (OASPL) be below 150 dB (unweighted). There are no time limits for exposures below these levels.

Vibration Mitigation Strategies

One obvious solution for reducing aerospace vibration is to eliminate the vibration at the source. The other approach is to isolate the occupant and equipment from the source of vibration. Eliminating the source of vibration may be quite difficult (as well as costly), particularly if the source may be an unavoidable consequence of the vehicle interaction with the operational environment (turbulence and vehicle resonance). In the case of propeller-driven or rotary-winged vehicles, vibration may be mitigated to acceptable levels by insuring proper propeller balance and synchronization (25). As mentioned at the beginning of the chapter, the rotor speed and number of blades also play an important role in defining the vibration characteristics of an aircraft. For the propeller-driven aircraft, it may be possible to isolate the occupant and equipment by relocating them to areas where the vibration is expected to be lower depending on the aircraft (away from the propeller plane). Currently available vibration damping and isolation techniques may be used to minimize vibration at higher frequencies, but designing such processes and mechanisms to reduce low-frequency vibration for which humans are the most sensitive is still a challenge. However, developing seat cushions that distribute seated pressure may help reduce the discomfort in localized regions of high loading. The discomfort, fatigue, and potential visual effects of higher frequency vibration should not be neglected. Damping and isolation of controls, displays, and seating systems may mitigate some of these effects. In the case of HMDs and targeting systems, physically minimizing the involuntary head motion associated with low-frequency vibration is also a challenge. Computer software and active feedback mechanisms may be used to reduce the adverse effects on performance. In some cases, rigid coupling between the body and contact surfaces may minimize unstable motion at very low frequencies that could cause repeated impact and injury. It may be more advantageous, with increasing frequency, to remove any coupling between the body and the vibration surface, such as removing the head from contact with the headrest. The development of successful mitigation processes and mechanisms for minimizing aerospace vibration requires the active participation of vehicle developers, users, equipment designers, structures experts, and human vibration experts. In addition, controlled laboratory testing and robust models can serve as tools for investigating specific vibration effects and causal factors necessary for reducing the adverse effects of aerospace vibration.

ACOUSTICS IN AEROSPACE ENVIRONMENTS

General Acoustics Terminology

Acoustics

Acoustics is the scientific study of sound including the generation, propagation, and the effects of sound waves.

Sound

Sound is the auditory sensation evoked by an oscillation in pressure, stress, particle displacement, particle velocity, and so on, in a medium with internal forces, or the superposition of such propagated oscillations.

Noise

Noise is any undesired sound. Therefore, the labeling of a particular sound is subjective, as noise has to do with an individual's perception. What is music to some listeners is noise to others. Further, a person's response to sound also has to do with their perception of the sound.

Sound Pressure Level

The sound perceived by the human ear is commonly measured as a sound pressure. The technical definition of sound pressure is the total pressure at a point minus the static pressure at that point. The unit of sound pressure is Pascal (Pa). The sound pressure level (SPL) is defined as 20 times the logarithm to the base ten of the ratio between the rms sound pressure, p, in a stated frequency band, and the reference sound pressure, p_0, of 20 μPa (31). The unit of SPL is the decibel (dB) and the symbol is L_p.

$$L_p = 20 \log_{10}(p/p_0) \qquad [5]$$

SPLs can be logarithmically added across frequency bands to calculate an OASPL. Sound levels are the SPLs adjusted by a weighting to better represent the varying sensitivity of the human ear to different frequencies and sound pressure ranges. The A-weighting was introduced for levels below approximately 55 dB, B-weighting was for levels between 55 dB and 85 dB, and C-weighting was designed for levels above 85 dB (32). A-weighting is almost exclusively used for measurements relating to the human response to noise for both hearing damage and annoyance. The difference between A-weighted and C-weighted sound levels is an indication of the low-frequency energy content in a sound spectrum. The A-weighted sound level is denoted by L_A and expressed in dBA units.

Sound Power Level

The definition of sound power is the sound energy radiated by a source per unit time. The unit of sound power is watt (W). The human ear does not perceive sound power, only sound pressure. The sound power level (PWL) is ten times the logarithm to the base ten of the ratio of a given sound power, W, in a stated frequency band to the reference power, W_0, of 1 picowatt (1 pW) (31). The unit of PWL is the dB and the symbol is L_W.

$$L_W = 10 \log_{10}(W/W_0) \qquad [6]$$

PWLs can be logarithmically added across audio frequency bands to calculate an overall PWL. Summation of all the PWL for all noise sources inside is a key factor in a number of analyses. Although PWLs and SPLs are both reported in dB, the two levels are not interchangeable. Sound power is the total acoustic energy being radiated by a source in all directions. If the sound power of a source is known and the acoustic characteristics of a room or other enclosure are known, the SPL can be calculated for a crewmember's location.

Spectrum

The spectrum of sound represents the sound pressure or power distributed across frequency. It is commonly described in terms of levels in successive pass bands of octave, half-octave, and third-octave bandwidths but can be in a successive bandwidth of any size. Noises of concern to aerospace medicine are frequency dependent in terms of their effects on humans. The spectrum of acoustic energy important to human perception ranges from less than 1 Hz to more than 20 kHz. The young, normal human ear is sensitive to acoustic energy of approximately 15 Hz to 20 kHz, which is termed the *audio frequency range*. Infrasound, energy below approximately 20 Hz, can be perceived at high-intensity levels but not as pure tones. Ultrasound is classically defined as acoustic energy above 20 kHz; however, the term is applied to energy as low as 8 to 10 kHz, and subharmonics of ultrasonic levels above 20 kHz can affect SPLs in the hearing range.

Time History

Pressure time histories describe variations in the sound pressure of an acoustic event as a function of time. The frequency content is not quantified in pressure time histories of signals. However, high-speed spectrum analyzers will give a three-dimensional (3-D) depiction of sound pressure versus frequency band as a function of time. Steady state sounds are those with a time course or duration greater than 1 second. Measurements in aerospace vehicles are usually taken over a time period of 15 seconds. Impulse sounds, individual pressure pulses of sudden onset and brief duration, are those with a time interval of less than 1 second and a peak-to-rms ratio greater than 10 dB. Impulse sounds are typically described by the rise time, peak level, duration, and number of events or repetitions. The frequency content of impulse sounds is determined by spectral-energy-density analysis.

Sound Propagation in Free Field

Theoretically, sound waves in a free field (i.e., an acoustic space with no reflections) spread spherically in all directions from an idealized point source. As a result of the spherical dispersion, the sound pressure is reduced to half of its original value as the distance is doubled, which is a 6-dB reduction in SPL. The speed of sound in air is density dependent and is therefore a function of air temperature, barometric pressure, and relative humidity. However, temperature is the largest factor in the speed of sound in air, which is approximately 344 m/s (1,129 ft/s) at a temperature of $21^{\circ}C$. Practically, aerospace noises do not radiate uniformly in all directions, but follow forms or patterns characteristic of the source and obstructions in the pathways. This directivity of sound radiation must be included in the evaluation of noise to ensure the appropriate placement of personnel.

Sound in Enclosed Spaces

Interior aerospace environments are enclosed spaces in which sound is reflected multiple times from the boundaries. A receiver within the enclosure is exposed to sound coming directly from the source (direct field) and sound arriving after having been reflected off one or more boundaries (reverberant sound field). The direct field is only source and distance dependent and is not affected by the size of the enclosure or the reflective characteristics of the boundaries. The reverberant field is strongly dependent on the dimensions of the enclosure and the sound-absorbing properties of the bordering walls. Owing to multiple wall reflections, the magnitude of the reverberant field builds up to a level determined by the acoustic absorption of the enclosure and the surface area of the enclosure. Sound energy density in an enclosure, of which the largest dimension is not more than three times any other dimension and much larger than the acoustic wavelength (high frequencies), will approach uniformity throughout the enclosure away from the sound source and the enclosure walls. As the distance from the sound source increases, the relative contribution of the reverberant field to the OASPL will increase until it dominates the direct sound field (32). The reverberant acoustic field is characterized by the reverberation time which is the time required for the energy density to be reduced to 60 dB below its steady-state value after a sound source has been stopped. The reverberation time is an important parameter to determine adequate speech communication characteristics in an interior aerospace environment. In enclosures with parallel walls, some of the acoustic waves emanating from the source will propagate along certain paths where they repeat upon themselves and form normal modes of acoustic vibration or standing waves. In the presence of lower-order standing waves, the response of the interior space is a function of frequency and location, and the spatial SPL distribution will be irregular and may vary substantially. Aerospace vehicles can produce high acoustic levels in relatively small, enclosed volumes. Acoustic environments in these vehicles need to be maintained at manageable levels so that the crew and passengers are afforded a safe, functional, effective, and comfortable environment.

Multiple Sound Sources

Two coherent (fixed relative phase) tonal sounds at the same frequency add vectorially and their relative phase will determine their sum to be somewhere between 3 dB and 6 dB. Practically, most sounds emanating from two sources are incoherent and are summed (in an acoustic free field) on a pressure squared, or linear energy basis, resulting in a 3 dB increase in SPL. In settings where a reflector, such as the ground or a wall, is near the source, the summation would be more than 3 dB as a result of the reflected energy. Many sources such as jet engines have both constructive and destructive frequency-dependent interference and in those cases, the addition of a second source may result in an increase of SPL from 2 to 5 dB in practice.

Aerospace Noise Environments

Atmospheric Flight

Aerodynamic noise generated by a vehicle moving through the atmosphere is a significant source during atmospheric flight. For powered aircraft, the propulsion system required to power the aerospace vehicle through the earth atmosphere is usually the most intense source. The specific noise environments for several vehicles are discussed in the subsequent text.

Gliders

The noise associated with gliders such as sailplanes, hang gliders, and paragliders is the aerodynamic noise generated from the object and pilot moving through the air. The noise is mainly dependent on the aerodynamic design of the glider, including the pilot, the speed relative to the air medium and the turbulence in the air. Helmets are mandatory for hang glider and paraglider pilots and help reduce the aerodynamic noise arriving at the pilot's ears. When flying in tandem, shouting (or the use of an electronic communication system) is needed to achieve effective communication.

Ultralights

Lightweight and slow-flying aircraft, including powered hang gliders (trikes), powered paragliders, and rotary wing craft, are often referred to as *ultralights* or *recreational aircraft*. The vehicles are often an open-air design with the pilot (and passenger) located very close to the engine and propeller or rotor. The engines are typically two-stroke or four-stroke piston engines driving high-rotational-speed propellers. The proximity of the propeller and engine sound sources to the pilot and passenger(s) presents a real concern for the well-being of their hearing. Studies have shown that pusher propeller–driven ultralight planes were 5 to 15 dB noisier than those equipped with tractor propellers (33). Acoustically well-designed helmets (possibly with active noise control), muffled engines, and low blade tip speed propellers help minimize the noise hazard.

Propeller Aircraft

Loud tonal noise from piston or turbo propeller engines in the cabins of some general aviation, commercial and military aircraft may pose a threat to the hearing and comfort of the occupants and the effectiveness of voice communications. Beating noise occurs when the tonal noises from two propellers are at similar levels but differ slightly in frequency. Synchronization of the propellers may cease this modulation. Consistent use of appropriate personal noise-excluding equipment can greatly reduce or eliminate the threat of potential noise-induced hearing loss (NIHL) and deteriorated audio communications.

Rotorcraft

Significant rotorcraft cabin noise sources include the impulsive, periodic, and broadband noises from the rotors and the structure-borne noises from, especially, the gearbox. Present communication equipment in helicopters may become marginal or inadequate for some phases of flight. Aircrew members may be vulnerable when required to work in maximum level noise areas inside open or closed helicopters. Medical rescue and other personnel immediately outside the helicopter in the direct downwash of the rotating blades may find both the transmission and reception of voice communication marginal to unacceptable. Helicopter noise spectra contain high-level, low-frequency noise for which sound attenuating properties of flight helmets and headsets are least effective. Substantial progress has been made in the development of special noise-excluding headwear, and some helicopter noise situations will benefit from these developments.

Jet-Powered Aircraft

Aerodynamically induced energy is at a maximum for aircraft during liftoff, climb out, dives, supersonic dashes, and maneuvers. This category of acoustic energy is of relatively high frequency, which is more easily controlled than the low-frequency content. Airborne and structure-borne noise from the engines, the turbulent boundary layer over the fuselage and airframe noise all contribute to the interior acoustic environment. The character and the level of the noise vary with aircraft type, flight operation, and flight condition. Interior noise levels may be considerably higher for full-power engine operation during takeoff and the reverse thrust operation during landing. However, these conditions are experienced for only short durations compared to the duration of the cruise flight. High interior noise levels on long flights may cause discomfort, fatigue, annoyance, sleeplessness, and irritation. Under those circumstances, occupants may want to use earplugs or noise-canceling headphones to alleviate detrimental effects. The flight crew compartments of most commercial passenger aircraft are sufficiently sound treated to minimize or eliminate noise as a voice communication problem. It is desirable that ambient noise levels in commercial aircraft passenger compartments are high enough to provide acoustic privacy for the conversations of passengers seated close to one another. Conversations from nearby passengers, not masked by the background noise, may cause speech interference and feelings of discontent with the acoustic environment.

Fighter Aircraft

In most fighter aircraft now flown, acoustic levels are typically approximately 105 dB, but levels can go down to 95 dB during descent or other flight operations, and at the worst, can reach levels between 115 and 118 dB (Teleconference between Goodman JR, McKinley RM. Wright-Patterson AFB, Ohio: February, 2007;16.). High performance aircraft require voice communication equipment to be integrated with the flight helmet–oxygen mask system. Typically, this consists of high-quality, altitude-compensated earphones inside the helmet and a noise-canceling microphone in the oxygen mask. Both the helmet and oxygen mask act as noise shields. Crewmembers of other types of military aircraft may use the flight helmet with a noise-canceling microphone mounted on a boom or simply a headset that also includes a noise-canceling boom microphone, or in some cases, dual hearing protection is required. These terminal equipment items are designed specifically for the noise environments in which they are used and their performance is reliable.

Launch Vehicles During Liftoff

The intense combustion and powerful thrust required to propel a space vehicle during liftoff generates noise that is transmitted throughout the vehicle structure and internally to the crew stations. These high-level noises are typically of short duration. The OASPL for the Space Shuttle during launch measured approximately 149 dB externally and 118 dB internally. Adequate hearing protection is required during this portion of the flight to prevent damaging effects to the hearing of the crew.

Space Flight

Noises during space flight originate in the space vehicle itself. The acoustic environment is characterized by the type of the noise sources, the kind of operations, the number, layout, and levels of the noise sources, the design of the source enclosures, the geometry and acoustic properties of the crew habitable volume, and environmental factors.

Space Shuttle Orbiter

The Space Shuttle Orbiter (Orbiter) was originally designed to be operated for 10 to 14 days, but was later modified for extended-duration operations of up to 16 days plus 2 contingency days. The predominant noise sources in the Orbiter are the cabin fans and other noise sources include avionics, cooling fans, water pumps, and water separator. Payloads manifested onboard introduce additional continuous or intermittent noise sources. Levels normally range from 65 dBA to 68 dBA when payloads are flown and used. During the STS-40 mission, noise levels exceeded the specification levels in both the Orbiter and Spacelab. The Spacelab levels went up to a time-weighted average (TWA) as high as approximately 76 dBA due to experiments and exercise noise, and created significant concerns: inadequate communications, annoyance, poor habitability, and hearing threshold shifts. This situation was created by inadequately controlling the mix of payloads and their operations.

International Space Station

The International Space Station (ISS) is an on-orbit laboratory workshop and a home with long-term crew occupation. Mission duration for the crews in ISS may range from 3 months to 7 or more months at present. ISS modules have equipment such as fans, pumps, compressors, avionics, and other noise-producing hardware and systems to serve their functional, life-support, and thermal control needs. Payload racks with scientific operating equipment create continuous or intermittent noises or combinations of both. The crew exercises on a treadmill and uses other conditioning devices, which all generate noise. In the ISS, payload racks can be added or changed during a mission. Communications between the crew and the ground are at raised levels to communicate over the background environment, adding to the overall crew noise exposure. Acoustic levels at most locations in the ISS are close to 60 dBA (34). The Service Module (SM) which is the activity center due to eating, hygiene, and communication activities, has elevated noise levels. This module has required the use of hearing protection devices over long periods of time. SM upgrades that were implemented since 2003 have lowered the sound levels and more improvements in the acoustic environment are planned.

Exploration Mission Vehicles
Initial exploration missions to the moon are planned for up to 14 days. Acoustic management challenges are significantly increased as the travel time for future spacecraft to destinations beyond the moon is measured in years rather than months and the available physical living and working environments are smaller than the ISS interior space. Manned outposts planned for the moon and Mars will also be an acoustics challenge. Acoustic requirements for such missions will have to be adjusted to better consider the effects of long-term exposures, communications, and habitability. These missions will be more autonomous and crews will not have normal responses from mission control nor the relief offered by a relatively quick return home from orbit.

Noise and Speech Analysis

Noise Exposure Metrics

Noise exposure metrics have been established to quantify the human exposure to sound. Following are the definitions of some noise exposure metrics applicable to the aerospace noise environments.

Time-Weighted Average
An individual's noise exposure typically varies by level and duration during a work period. These variations in noise exposure are combined to define the person's time-weighted average (TWA). The TWA is expressed in dBA and is calculated using the noise exposure criterion specified in an adopted hearing conservation program. Acoustic energy is doubled if it is increased by 3 dB, and halved when decreased by 3 dB. Variations in the exposure time correspond to this pattern. The following equation defines the TWA as follows:

$$TWA = 10\log\left[\frac{1}{480}\sum_{i=1}^{n}\left(2^{(L_{Ai}-85)/3}t_i\right)\right] + 85 \qquad [7]$$

where i is the individual exposure interval, n is the total number of exposure intervals in the day, t is the exposure time in minutes for exposure interval i, and L_{Ai} is the A-weighted SPL (dBA) at the ears for the exposure interval. The TWA can be calculated for any number of exposure intervals, each having its own exposure level.

Equivalent Sound Level (L_{eq})
The equivalent sound level (L_{eq}) is the A-weighted SPL of a fluctuating sound averaged over a given time interval. The time interval over which the levels are averaged is typically defined as 1 minute, 1 hour, 8 hours, or 24 hours depending upon the importance of the time interval and application. The L_{eq} is defined by the following equation and has units of dBA

$$L_{eq} = 10\log\left[1/T\sum_{i=1}^{n}10^{L_{Ai}/10}t_i\right] \qquad [8]$$

where i is the individual exposure interval, n is the total number of exposure intervals, t_i is the duration in minutes for interval i, T is the total time in minutes for the L_{eq} (such as 1, 60, 480, or 1,440), and L_{Ai} is the A-weighted SPL (dBA) for interval i. Time-varying sound can also be expressed by a sound level indicating the percentage of time a level is exceeded. As an example, the sound level L_{10} indicates that the level is exceeded 10% of the time and identifies the high level components of a sound. L_{90} is a measure of the ambient or residual level.

Speech Intelligibility Descriptors

The most pervasive operational threat to voice communications is noise. Speech communication assessment techniques use physical measurements that compare the noise signal to the speech signal to evaluate the masking effect on the speech. These techniques range from the simplest (A-weighted sound level) to the most complex method (speech intelligibility index or SII) for determining the intelligibility of speech under a variety of situations. The most accurate procedure measures the intelligibility response with operators using the communications equipment of interest in the actual or accurately emulated acoustic environment of interest.

A-Weighted Sound Level
A-weighted sound level values are used to display the quality of various types of communication as a function of the sound level of the noise. Examples for face-to-face, intercom, and public address system communications in a range of A-weighted sound level background noises are shown in

TABLE 5-1

Speech Communication Capabilities versus A-Weighted Sound Pressure Level (dBA) Background Noise

Communication	*Below 50 dBA*	*50–70 dBA*	*70–90 dBA*	*90–100 dBA*	*110–130 dBA*
Face-to-face (unamplified speech)	Normal voice at distances up to 6 m	Raised voice at distances up to 2 m	Very loud or shouted voice level at distances up to 50 cm	Maximum voice level at distances up to 25 cm	Very difficult; impossible even at a distance of 1 cm
Intercom system	Good	Satisfactory to difficult	Unsatisfactory using loudspeaker	Impossible using loudspeaker	Impossible using loudspeaker
Public address system	Good	Satisfactory	Satisfactory to difficult	Difficult	Very difficult

Table 5-1. The A-weighted sound level procedure is suitable for prediction of intelligibility for purposes such as surveying and monitoring. It is less practical for noise control and engineering purposes because noise spectral information is lacking.

Speech Interference Level

Speech interference level (SIL) is an indicator used to evaluate the effect of steady background levels on the quality of face-to-face speech communication. The SIL is the arithmetic average of the SPL of the interfering noise in the four octave bands centered at 500, 1,000, 2,000, and 4,000 Hz. The U.S. Federal Aviation Administration (FAA) uses the more recent Preferred Speech Interference Level (PSIL) that only includes the 500, 1,000, and 2,000 Hz octave bands. The quality of communications expected for PSIL and dBA values at several separation distances and voice levels are shown in Figure 5-9. The accuracy of the PSIL decreases in reverberant spaces.

Noise Criteria

Noise criteria (NC) ratings are used to determine quality of speech communication based on the octave band levels of the noise in the environment of interest. To evaluate a space, the measured octave band levels of the noise are converted to an NC rating. Descriptions are provided of the living conditions that correspond to the derived NC values. The curves associated with the NC ratings are presented in Reference (32). NC curves have been used for initial requirements in the Orbiter, are implemented as requirements in ISS, and planned to be used in the Constellation Program for exploration missions. These NC curves as the continuous noise limits for space vehicles are discussed in more detail in the section **Noise Regulations, Measurements, and Control**.

Balanced Noise Criteria

Balanced noise criteria (NCB), an expansion of NC criteria, provide guidance for the specification or the assessment and control of noise environments. It is used to enable satisfactory speech communication and habitation in indoor spaces by considering disturbances and annoyance resulting from sound and vibration. SIL is used by NCB to determine the acceptability of speech communication in an environment of interest. NCB curves and NCB values for various types of workspaces and comprehensive guidance on their use can be found in Reference (35). Procedures for determination of the presence of rumble and hiss in an environment are also included in the NCB (35).

Speech Intelligibility Index

The calculation of the articulation index (AI) has been used for several decades as a measure of the intelligibility of voice signals, expressed as a percentage of speech units that are understood by the listener when heard out of context (36). The SII (37) is a major revision of the AI standard and defines computational methods that produce results highly correlated with the intelligibility of speech under a variety of adverse listening conditions, such as noise masking, filtering, and reverberation. The SII is computed from acoustic measurements or estimates of the speech spectrum level, the noise spectrum level, and from physical psychoacoustical measurements of the hearing threshold

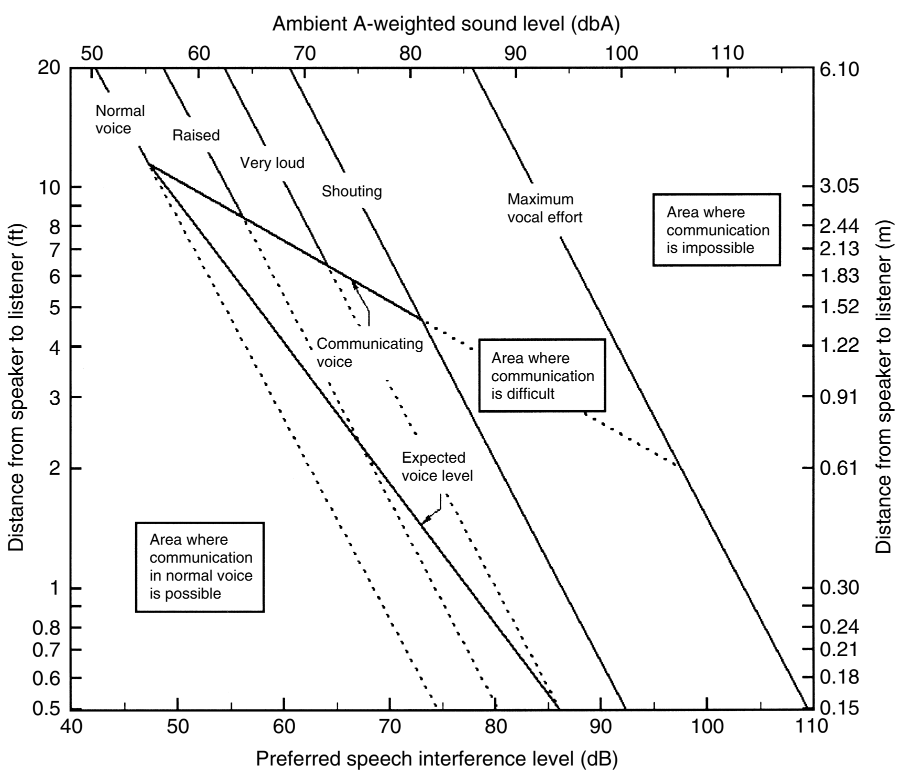

FIGURE 5-9 Effectiveness of voice communications as a function of preferred speech interference level (PSIL) and distance from speaker to listener.

level. Various audio frequencies contribute different amounts to speech intelligibility, and, within a certain range, a higher speech-to-noise ratio means higher intelligibility. The intelligibility of a speech communication system is predicted by measuring the speech-to-noise ratio in each contributing band and adding the results. The computed SII is converted to speech intelligibility scores.

Speech Transmission Index

The Speech Transmission Index (STI), like SII, is based on the AI. Speech intelligibility based on measurements of the communication system or on calculations is objectively predicted by the STI, provided all necessary information is available. It yields a single-number index of 0 to 1 that correlates well with other psychophysical measures of speech intelligibility. An STI value of 0.6 is required for a communication with a minimal rating of "good." A value of 0.35 corresponds with approximately 50% intelligibility of redundant sentences. The STI can also be used with digital communication systems (38,39).

Speech Intelligibility Tests

Standardized methodologies are used to measure the performance of occupied habitable volumes, total voice communication systems, and the individual components of the communication chain with or without the person-in-the-loop. These methods are based on the subjective assessment of speech intelligibility. The basic unit is the percentage of a given sample of speech correctly perceived by an observer. These samples comprise groups of syllables, words, phrases, and/or sentences that are directly related to everyday speech. Most of these materials, or intelligibility tests, were standardized with human operators-in-the-loop and they provide reliable measurements that can be generalized to other populations. Three procedures used in speech intelligibility testing have been standardized and are described in ANSI S3.2–1989 (40). They include the Phonetically Balanced (PB) Monosyllabic Word Intelligibility Test, Modified Rhyme Test (MRT), and the Diagnostic Rhyme Test (DRT).

Effects of Noise on Crew and Crew Communications

The effects of aerospace noises on humans have been divided into physiological and psychological responses. Physiological responses, both auditory and nonauditory, involve changes in physiological mechanisms or functions attributed to the noise. Auditory effects are confined to direct influences on the peripheral auditory system and the hearing function. Acoustic energy exposures can also affect the vestibular system, the autonomic nervous system, sleep, produce startle, and can induce fatigue; however, with few exceptions, these nonauditory effects are also mediated through the auditory system. Psychological response behavior to noise is influenced by the human's perceptions, judgments, attitudes, and opinions, which may be either related or unrelated to the noise itself. Most noise exposures stimulate elements of both types of responses, which clearly interact with one another.

Audio communications in an aerospace environment are also affected by noise, possibly endangering the safety, performance, and well-being of the participants, diminishing the effectiveness and efficiency of the communications and perhaps preventing messages or (alarm) signals from being heard correctly, or received altogether.

Auditory Physiological Effects

Human Hearing Function

The human auditory system is an extremely sensitive and highly specialized mechanism that is quite adaptable and quite resistant to the adverse effects of acoustic energy unless abused (Figure 5-10) (41). The audible frequency range in the healthy, young human ear extends from approximately 15 Hz to 20 kHz. The most sensitive region of hearing is from approximately 500 Hz to 4 kHz and is most important for understanding speech. Hearing sensitivity is expressed in decibels relative to the normal threshold of hearing or standard hearing reference zero. The human usually does not notice acoustic intensity increases less than 3 dB above the initial level (at twice the energy as the original source) and psychophysically judges a sound to be about "twice as loud" when the intensity is increased by 10 dB. Signal

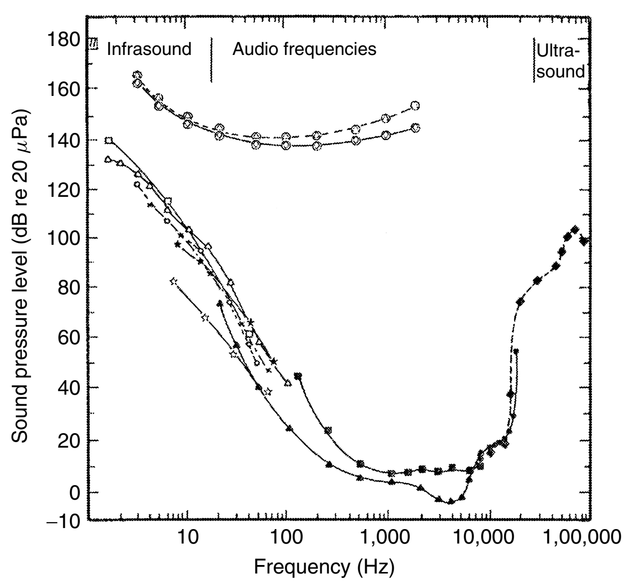

FIGURE 5-10 Human auditory sensitivity and pain threshold levels. □ = Von Bekesy (1960) Data-Minimum Audible Pressure (MAP); ◯ = Yeowart, Bryan, and Tempest (1969) Data-MAP; △= Whittle, Collins, and Robinson (1972) Data-MAP; × = Yeowart, Bryan, and Tempest (1969) Data-MAO for bands of noise; | = Standard reference threshold values-MAP (American National Standard on Specifications for Audiometers, 1969); ▲ = ISO R226-Minimum Audible Field (1961); • = Northern, et al. (1972) Data; ♦ = Corso (1963) Data-Bone conduction minus 40 dB; ◇ = Von Bekesy (1960) Data = Tickle, pain; △ = Benox; □ = Static Pressure-Pain; ⋆ = Yamada et al. (1986) Average hearing threshold; ★ = Yamada et al. (1986) Minimum hearing threshold. (Adapted from Nixon CW. Excessive noise exposure. In: Singh S, ed. Measurement procedures in speech, hearing, and language. Baltimore: University Park Press, 1975.)

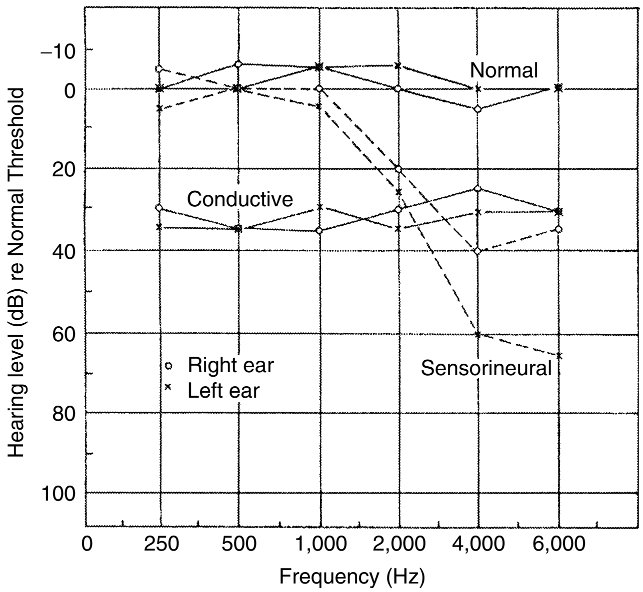

FIGURE 5-11 Typical audiograms showing normal hearing, a conductive-type hearing loss that is relatively flat, and a sensorineural or perceptive hearing loss with the characteristic loss of sensitivity with increasing frequency.

detection by the human ear requires higher SPLs in the infrasound region (below 20 Hz), and tonal quality is lost below approximately 15 Hz. Ultrasound acoustic energy (above 20 kHz) is not ordinarily perceived by the human ear. The harmonics of infrasound and subharmonics of ultrasound may be significant and perceived outside of their respective frequency regions.

An individual's hearing sensitivity for standard audiometric test frequencies is expressed in decibels hearing level (dB HL), or dBs relative to reference values of normal hearing. The range of normal hearing sensitivity for pure-tones (as measured in air-conduction audiometry) is from −10 to 25 dB HL, as shown in Figure 5-11. Hearing levels greater than 25 dB HL are considered abnormal and constitute hearing loss. Conductive type hearing losses, caused by impairment of outer and middle ear functions, usually reduce hearing sensitivity for low-frequency stimuli, or when more severe may show a flat audiogram.

Sensorineural hearing loss, usually attributed to inner ear impairment, characteristically displays a loss of sensitivity in the high frequencies. Noise-related hearing losses often appear as an audiometric "notch" pattern, in the 4 kHz or 6 kHz region, that advances (with more noise damage) into lower frequencies. The progression of noise-induced sensorineural loss correlated with the number of years of exposure has been widely documented (42). The term *mixed hearing loss* is used to define a loss with both conductive and sensorineural components.

Persons with hearing losses greater than 35 to 40 dB in the speech-frequency range (500 Hz to 4 kHz) experience communication problems and are potential candidates for hearing aid amplification, if medical remediation is not possible. Although many conductive hearing losses are often amenable to medical or surgical treatment, sensorineural hearing losses usually do not respond to such means. Consequently, prevention of such sensorineural disorders, through hearing loss prevention programs, is critically important.

A number of protective actions operate in the region of the middle ear to reduce the amount of acoustic energy transmitted to the inner ear. At high sound intensities, the motion of the stapes changes from a piston-like to a rocking action in the oval window resulting from temporary dislocation of the ossicular joints, reducing the efficiency of transmission. In addition, extremely loud sounds can trigger the acoustic reflex, which causes the stapedial and tensor tympanic muscles to contract, increasing the stiffness of the ossicular chain, and dampening the transmission of low-frequency acoustic energy. This mechanism provides no protection, however, for brief impulses (like rifle shots) shorter than 20 milliseconds owing to the slow response latency of this reflex (from 25 to 100 milliseconds).

A National Aeronautics and Space Administration (NASA) summary of physiological effects of noise is provided in Table 5-2 (43), listing various conditions of exposure in terms of SPL, frequency band, and duration for a number of reported disturbances. Other observed nonauditory physiological effects due to noise exposure are presented in Reference (43) and include the following:

- Increases in the concentration of corticosteroids in the blood and brain and change in the size of the adrenal cortex
- Electrolytic imbalances and changes in blood glucose level
- The possibility of effects on sex-hormone secretion and thyroid activity
- Reports of vasoconstriction, fluctuations in blood pressure, and cardiac muscle changes
- Abnormal heart rhythms

Static Air Pressure

Differential pressures may occur across the tympanic membrane with variations in pressure associated with changing atmospheric (flight) conditions and a Eustachian tube that remains closed. Although a high-pressure differential may cause noticeable discomfort or pain, lower pressure differences could cause an undetected decrease in hearing sensitivity of 8 dB to 10 dB for frequencies below 1,500 Hz and above 2,300 Hz. These effects are usually transitory and may be relieved by the Valsalva maneuver or other means of equalizing ambient and middle ear pressures.

Hearing Threshold Shift

NIHL may be either temporary or permanent and either type of NIHL may have significant impact on operational success. Temporary threshold shift (TTS) is a short-term loss of hearing sensitivity after exposure to noise, subject to the intensity, spectral content, and duration of the noise exposure. Although the fastest recovery of hearing typically occurs within the first 12 to 14 hours of a noise exposure,

TABLE 5-2

Physiological Effects of Noise

	Condition of Exposure		
Reported Disturbances	*Sound Pressure Level (dB) Re: 20 μPa*	*Spectrum*	*Duration*
Reduced visual acuity, chest wall vibrations, gag sensations, respiratory rhythm changes	150	1–100 Hz	2 min
Reflex response of tensing, grimacing, covering the ears, and urge to avoid or escape	100	—	Sudden onset
Pain in the ears	135	20–2,000 Hz	—
Pain in the ears	160	3 Hz	—
Discomfort in the ear	120	300–9,600 Hz	2 s
Hearing temporary threshold shift of 10 dB	94	4,000 Hz	15 min
Hearing temporary threshold shift of 10 dB	100	4,000 Hz	7 min
Hearing temporary threshold shift of 10 dB	106	4,000 Hz	4 min
Tympanic membrane rupture	155	2,000 Hz low frequency	Continuous blast
Tympanic membrane rupture	175	—	—
Mechanical vibrations of body felt, during sensations	120–150	OASPL	—
Vertigo and, occasionally, disorientation, nausea, and vomiting	120–150	1.6 To 4.4 Hz	Continuous
Irritability and fatigue	120	OASPL	—
Temporary threshold shift occurs	65	Broadband	60 d
Human lethality	167	2,000 Hz	—
Human lethality	161	2,000 Hz	—
Temporary threshold shift occurs	75	8 to 16 kHz	5 min
Temporary threshold shift occurs	110	20 to 31.5 kHz	45 min

OASPL, overall sound pressure level.

additional (although slower) recovery can continue over the next 24 to 48 hours. Intense noise exposures (e.g., from high-level impulses) or long-duration exposures to continuous noise can result in larger amounts of TTS. Individual ears vary greatly in their susceptibility to the adverse effects of noise (44). There is no evidence that hearing loss related to a given noise exposure will develop several months or years after the cessation of that noise exposure. Although the ability to determine the noise susceptibility of an ear would be most valuable before a work assignment in noise, no satisfactory method for quantifying susceptibility has been developed. Exposure standards and criteria do not include a susceptibility factor because of this wide variance and the inability to predict TTS for a specific ear. TTS can also be caused by other means such as the excessive use of aspirin or other drugs. TTS during flight is a concern because of hearing loss and operational considerations.

Permanent threshold shift (PTS) is a loss of hearing that persists, with no recovery of sensitivity, regardless of the time away from the noise. Both the TTS and the PTS types of hearing loss are measured and reported in decibels. Relationships have been established between recent TTS and noise exposure and between PTS and noise exposure experienced in daily activities performed over many years. Noise-induced TTS is considered an essential precursor to noise-induced PTS. It is further assumed that noise exposures that do not produce TTS will not produce PTS. PTS develops similarly to TTS but on a slower time scale and different noise exposures that produce equal amounts of TTS are also considered equally noxious with regard to PTS. If a residual hearing loss from TTS remains, 30 days or more postexposure, the NIHL may be considered a PTS. These assumptions, based on TTS data from the laboratory and TTS/PTS data from actual field noise exposures, have provided a basis for formulating noise exposure standards and hearing damage risk criteria (DRC) that relate noise exposure with hearing loss (45,46). Noise exposures equal to or greater than a TWA of 85 dBA for an 8-hour period are considered hazardous and can cause PTS. The development and statistical distribution of NIHL in a population as a function of daily noise exposure for exposure times from 10 years to 40 years (as well as aging) can be estimated by standardized procedures (46). However, these estimates still show wide variability in hearing threshold shifts among individuals, suggesting that other endogenous factors (e.g., gender, race, exposure to ototoxic drugs and chemicals) can influence one's own personal susceptibility to hearing loss.

The most common metric used to identify early signs of NIHL among noise-exposed personnel in hearing conservation programs is the standard (or significant) threshold shift (STS). Federal hearing standards (used by Occupational Health and Safety Administration (OSHA), the U.S. Department of Defense and NASA) define STS as an average change in hearing threshold in either ear of 10 dB or more from baseline at 2,000, 3,000, and 4,000 Hz (30,47–49), where NIHL is first evidenced. Although the STS may be computed using age corrections, described in OSHA 29 Code of Federal Regulations (CFR) 1910.95, Appendix F (47), such corrections may be eliminated to provide an earlier alert of developing NIHL.

Presbycusis

Noise-induced sensorineural hearing loss may be confounded by presbycusis (42), which is the gradual loss of high-frequency auditory sensitivity that accompanies advancing age in much of the population. Such high-frequency hearing loss due to aging often occurs, ironically, at several of the same frequencies for which NIHL occurs. Although not a standard procedure, some evaluations of NIHL attempt to estimate what portion of the loss, if any, is contributed by presbycusis. This may be accomplished statistically by subtracting the average presbycusis value for a non–noise-exposed population from the hearing loss values at each frequency. Present data suggest less presbycusis loss for women than for men, whereas there appears to be no gender differences with respect to NIHL (45). The remaining loss of hearing may be attributed to the noise exposure history of the individual, other factors considered.

Auditory Pain

Auditory pain resulting from intense noise is associated with excessive mechanical displacement of the middle ear system and is believed to occur in the threshold region at which damage begins. Noise-induced auditory pain occurs almost independent of frequency at levels of 130 dB to 140 dB SPL and above. No pain is associated with overexposure of the inner ear. However, tinnitus (ringing or similar sounds in the ear) is often a more obvious alert that noise exposures have been excessive.

NASA's standards for broadband limits in space state that crewmembers shall not be exposed to continuous noise levels that exceed 120 dB in any octave band or 135 dB OASPL under any circumstances (43). Other limits are discussed in the section **Noise Regulations**.

Nonauditory Physiological Effects

Generally, humans adapt quite well to stimuli such as noise; however, adaptation has not been demonstrated by the responses of a variety of nonauditory systems. Changes in physiological responses to noise have been measured under laboratory conditions and in real-life situations; however, the magnitudes of these changes are often no greater than those experienced under typical daily living conditions. Although some physiological reactions to certain noises occur at levels as low as 70 dBA, the state of understanding is still unclear about relationships between potential adverse physiological effects and general noise exposure, as well as to the significance to general health and well-being of the changes that do occur (42).

General Physiological Responses

Most nonauditory effects mediated through the auditory system may be avoided with the use of appropriate hearing protection. Unfortunately, use of hearing protectors may have a negative effect on communication (e.g., where the wearer has a preexisting hearing loss). Such devices may also become uncomfortable for long-term wear. Even with maximum hearing protection, exposure to SPLs in excess of 150 dB should be prohibited because of mechanical stimulation of receptors other than the ear. Noise spectra containing intense low-frequency and infrasonic energy may excite body parts such as the chest, abdomen, eyes, and sinus cavities, causing concern, annoyance, and fatigue. The response of the vestibular system to extremely high levels of noise apparently mediated through the auditory system can manifest itself by disorientation, motion sickness, and interference with postural equilibrium.

General and specific physiological responses to sound include effects on peripheral blood flow, respiration, galvanic skin response, skeletal muscle tension, gastrointestinal motility, cardiac response, pupillary dilation, headaches, and renal and glandular function. The contribution of conditions such as temperature extremes, poor ventilation, threat of accidental injury or death, special task demands, and other non–noise elements that tend to grow as noise intensity grows cannot be ascertained with current data.

Subjective reports of disorientation, vertigo, nausea, and interference with postural equilibrium during high-intensity noise exposure suggest stimulation of the vestibular system. Empirical efforts to demonstrate the vestibular response to acoustic energy have been inconclusive; however, evidence does suggest that the vestibular system is the most probable site responding to the acoustic stimulation. Other than the vestibular system, mechanoreceptors and proprioceptors may be the primary mediators of physiological responses at SPLs above 140 dB.

Sleep Interference

Sleep is a physiological necessity. Interruption and acute lack of sleep can adversely affect rest, relaxation, performance, and health. Sensitivity to noise varies among individuals in the population and with factors such as aging. Young people are the least sensitive, and older adults are the most sensitive to awakening by sounds. Familiar sounds or words may waken a person at levels much lower than those required for less familiar sounds. Sleep interference resulting from noise may arouse or waken a person. It can also induce changes in the stages of sleep of a person who does not waken. People are more susceptible to behavioral wakening during sleep stage 2 compared to other stages and are most resistant to awakening in deep sleep stage 4 and during rapid eye movements (REMs) with dreaming. People not awakened by noise stimuli have displayed changes in electroencephalographic recordings, as well as in peripheral vasoconstriction and heart rate during the sleep. People who experience these biologic changes are unaware of the acoustic exposure and the sleep stage changes. After a period of sleep deprivation almost all time is spent in sleep stages 3, 4, and REM and the sensitivity to wakening is decreased. The primary impact of sleep deprivation is fatigue. Effects of aircraft noise exposure on sleep have been studied extensively in the laboratory and the community. Noises that are adequate stimuli do cause sleep disturbances and associated annoyances. However, it is still not known if or how awakenings or sleep stage changes relate to health effects (50).

NASA's space program has encountered sleep interference concerns since the Apollo Program. Space Shuttle Orbiter missions had problems due to high noise levels from payload operations, as well as during dual shift operations on the Orbiter mid-deck, where both work and sleep were required within the same relatively small cabin volume. Sleeping bunks were added and extensive noise control measures were implemented to provide quiet rest and sleeping areas in the Orbiter and ISS.

Startle

Startle may be evoked by a wide variety of stimuli but is a particularly common response to sudden, unexpected noises. The physiological aspects of the startle response are usually independent of the stimulus and include increased pulse rate, increased blood pressure, and diversion of blood flow to the peripheral limbs and gross musculature. The universality and uniformity of this reaction from one person to another suggests that startle is an inborn reaction that is modified little by learning and experience.

Several studies point out that nonauditory physiological responses to acoustic energy have been observed and measured among selected populations. At the same time, it should be emphasized that these findings are not sufficiently clear or consistent to demonstrate relationships reliable enough to generalize about any typical populations. The aerospace physician must evaluate potential adverse effects of aerospace noise environments on an individual basis, especially when they fall outside the conditions specified in existing standards and criteria for allowable noise exposures. In ISS, noise levels from an intermittent noise source in the U.S. Laboratory were significantly high enough to create a startle concern, so design changes were made to lower the levels of the source.

Psychological Effects

Numerous psychological factors in the lives of individuals, such as their perceptions, beliefs, attitudes, and opinions, contribute to the manner in which they respond to noise from aerospace activities. These responses are generally treated in terms of annoyance, irritation, impacts to operations/performance, and speech communication, which is a special task addressed in a separate section of this chapter.

Annoyance

Acoustic energy is undesirable when it becomes a distraction or when it interferes with routine activities. Individuals become annoyed when the amount of interference becomes significant. Numerous techniques based on measurement of the physical stimulus are used to assess noise exposure effects on people in work and living spaces. One concept maintains that the human reaction to a sound is determined by the annoyance or unwantedness of the sound instead of its loudness. This subjectively judged unwantedness of sounds is described as perceived noisiness (PN). PN may be adequately determined by using the physical measurements of the sound to calculate PN in dBs, or perceived noisiness in decibels (PNdB).

A different concept of estimating annoyance incorporates both the duration and magnitude of all the acoustic energy occurring during a given time. The measurement is the L_{eq} as defined previously. The problem of quantifying environmental noise is greatly simplified using the statistical measures of the L_{eq}. The L_{eq} is one of the most important measures of environmental noise for assessing effects on humans, because experimental evidence suggests that it accurately describes the development of NIHL and that it relates to human annoyance resulting from noise.

Sleep Interference and Startle

Both sleep interference and startle have substantial psychological components in addition to the clear-cut physiological components discussed earlier. In fact, the major adverse reaction of annoyance is usually caused by being startled or awakened and not because of the changes in physiological response that occur. The personal feelings of the exposed individual regarding factors such as the reason for the disturbance, loss of control of one's environment, concern over the reason for the disturbance, concern over how to minimize and eliminate the disturbance, and other factors usually determine the degree of acceptance of or annoyance to the acoustic energy. In ISS, changes were made to lower the levels of intermittent vacuum venting of payloads because of startle concerns. Astronauts indicated that this noise source would sound just like a cabin leak.

Performance Degradation

The effects of noise on cognitive and sensorimotor performance remain unclear and very complex. The same general experimental conditions have produced performance enhancement on some occasions and performance degradation on others. However, performance degradation resulting from noise has been reported with reasonable consistency in a number of task situations. The efficiency of vigilance tasks (requiring alertness) over long periods was degraded in noise environments of approximately 100 dB. Mental counting tasks were influenced in a complex manner, and time judgments were distorted. High-frequency noise of sufficient intensity produces more harmful effects on performance than do low-frequency noises. Sudden and unexpected changes in noise level, either up or down, may produce momentary disturbances. Noise ordinarily increases the number of errors but does not reduce the speed at which work is performed. High tone levels can be irritating and wearing, if they last

TABLE 5-3

Performance Effects of Noise on Humans

	Condition of Exposure		
Performance Effects	*SPL (dB) Re: 20 μPa*	*Spectrum*	*Duration*
Reduced ability to balance on a thin rail	120	Broadband	—
Chronic fatigue	110	Machinery noise	8 hr
Reduced visual acuity, stereoscopic acuity, near-point accommodation	105	Aircraft engine noise	—
Vigilance decrement, altered thought processes, interference with mental work	90	Broadband	Continuous
Fatigue, nausea, headache	85	1/3-octave at 16 kHz	Continuous
Astronauts' degraded performance	75	Background noise in spacecraft	10–30 d
Performance degradation of multiple-choice, serial-reaction tasks	90	Broadband	—
Overloading of hearing due to loud speech	100	Speech	—
Affects person-to-person voice communication	Figure 1	—	—
Hearing temporary threshold shift at 2 min	70	4,000 Hz	—
Hearing temporary threshold shift at 2 min after exposure	155	—	8 hr 100 impulses

very long. In ISS, high noise levels have been a significant habitability concern and although their specific effects on performance have not been measured, they are recognized as a stressor that affects operations.

A NASA summary of performance effects of noise on humans for exposure conditions described by SPL, frequency spectrum, and duration is provided in Table 5-3 (43). Other observed performance effects of noise are listed in Reference (43) including the following:

- Continuous regular periodic and aperiodic noise reduces performance on a complex visual tracking task.
- Increasing noise intensity causes increased arousal and improved task performance up to the point where overarousal degrades task performance.
- Psychological effects of noise can include anxiety, learned helplessness, degraded task performance, narrowed attention, and/or other adverse after effects.

Noise Effects on Communications

Direct Voice Communications

The vocal effort and quality of face-to-face communications in background noises and at talker–listener separation distances are summarized in terms of A-weighting and PSIL in Figure 5-9. Satisfactory communication, approximately 90% to 95% correct perception of sentences, is expected with a normal voice at a distance of approximately 3 m in a noise level of 55 dBA (48 dB PSIL). Talkers must shout to be understood at the same separation distance in a noise level of approximately 74 dBA. To maintain good communication, voice level must increase from 3 dB (in lower noise levels) to 6 dB (in higher noise levels) for every increase of 10 dB in noise level. Generally, the average male voice is approximately 4 dB higher than the female voice. NASA standards for intelligibility (43) document AIs in the very good to excellent range, 0.7 to 1.0. For ISS, the minimum AI requirement is 0.75.

Normal voice conversations are not possible in most high-noise environments at distances greater than approximately 1 m. Aerospace environment noises that require an above-normal voice effort place additional stress on talkers and listeners. The amount of stress on the vocal cords is dependent on the level of vocal effort and frequency of required communications. Infrequent or occasional raised voices and shouts may be tolerated; however, sustained above-normal vocal effort should be avoided. Electronically aided communications should be used in these situations, when practical, to protect the health and well-being of personnel and to minimize errors resulting from inadequate communications. Figure 5-12 shows the AI levels plotted versus the NC curves or dBA levels, for the Orbiter and ISS communication distances from 5 to 8 ft, with the NASA minimum 0.75 AI requirement also shown (51). This figure is based on English male-to-male, face-to-face communications, not including mixed gender crews, different accents, or unusual orientation relative to each other (talking to someone who is upside down to you), which could affect normal communications.

Noise masking of speech and other audio warning signals threaten operator safety and performance. Intense noise levels at the ear may also cause aural overload, distortion, and temporary hearing loss producing additional interference with reception. The effectiveness of these acoustic maskers varies with the frequency content of the noise and with the ratio of the signal level to the noise level (S/N). In ISS, concern with the masking of the caution and warning signals in modules with higher noise levels has led to review of

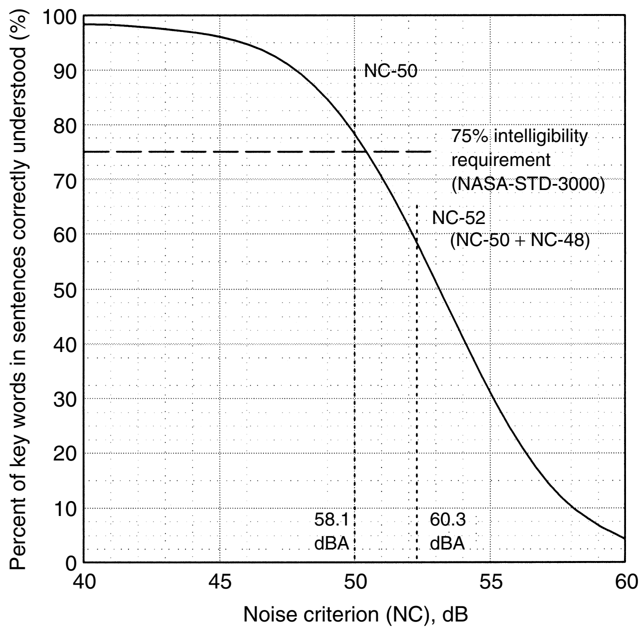

FIGURE 5-12 Recommendations for noise levels in the Space Shuttle based on the percent of key words in sentences correctly understood (Articulation Index) as function of the noise criterion. (From Pearsons KS. *Recommendations for noise levels in the space shuttle.* Bolt, Beranek, and Newman Report, BBN Job No. 1571160. February, 1975.)

military and international standards, analyses, and testing to ensure signals can be heard with confidence.

The speech signal level must be greater than the noise level at the ear for good intelligibility. Intelligibility, as a function of the signal to noise (S/N) ratio, varies with the type of speech material. Speech intelligibility for familiar phrases is approximately 0% correct at −12 dB S/N and greater than 95% correct at 0 dB S/N (range of 12 dB). Intelligibility for nonsense syllables is also 0% correct at −12 dB S/N ratio, but requires approximately +15 dB S/N to exceed 95% correct. Both spectra and levels of aerospace noises must be considered to minimize masking of the speech signal and to ensure successful communication. The World Health Organization recommends an S/N of 15 dB for full sentence intelligibility in listeners with normal hearing (52).

Electronic Audio Communications

Audio communication systems are optimized for human speech, which is vulnerable to environmental, personal, and message elements in aerospace environments. Noise, both acoustic and electrical, is the most disruptive factor. Acceleration, whole-body vibration, artificial atmospheres, high workloads, and threats to personal safety can also alter communications. Operator speech performance is influenced by accents, dialects, word usage, hearing loss, amount and type of communication experience, and even emotional state of the individual. Messages are altered by speech elements that include message set, type of material, vocabulary size, unexpected terms, and infrequently used phrases.

The performances of talkers and listeners vary greatly under the same communication situations. These variances can be increased to unsatisfactory levels in such hostile conditions as intense noise, fatigue, high workload, and jammed audio communications. It is important that communicators be trained for the environments in which they communicate. Inexperienced subjects of both genders showed dramatic improvements with voice communications in high-level noise and with electronically jammed speech as a result of training (53). Talkers and listeners steadily improve when they use a communication system over time. Those who were initially the best communicators appear to remain the best over time.

Noise Regulations, Measurements, and Control

Noise Regulations

Occupational Noise Exposure Regulations

The most common noise exposure criterion for prevention of hearing loss is a TWA of 85 dBA for 8 hours with a 3-dB/doubling exchange rate (30). When a 3-dB exchange rate is used, a doubling of the 85-dBA noise level (to 88 dBA) halves the allowable exposure time from 8 hours to 4 hours. A halving of the 85-dBA level to 82 dBA doubles the permissible exposure time from 8 hours to 16 hours. This criterion is used worldwide and by most U.S. agencies except for OSHA and the U.S. Navy. OSHA currently uses 90 dBA for 8 hours with a 5-dB/doubling criterion as its permissible exposure level and the U.S. Navy is using a criterion of 84 dBA for 8 hours with a 4-dB/doubling exchange rate. The goal in most hearing conservation programs is to keep the exposure less than the criterion TWA. The risk of NIHL can be reduced with the use of hearing protection devices (HPDs), limiting exposure times, and noise controls (such as increasing the distance between the worker and the sound source or engineering modification) to reduce the overall sound levels. HPDs need to be provided during exposure to noise levels of 85 dBA or greater. NASA considers occupational exposure to an 8-hour TWA of 85 dBA or greater to be hazardous to hearing. In space flight, constant sound levels of 85 dBA or greater are considered hazardous, regardless of the duration of exposure.

Space Vehicle Noise Limits

An OASPL of 68 dBA was applied as a common continuous noise limit for operating systems in all areas of the Orbiter and manned laboratories. Payloads had to meet the equivalent of 58 dBA individually with their total noise added to the systems noise level to determine overall noise. Intermittent limits were levied on payloads and government furnished equipment (GFE). Space Shuttle Orbiter flight rules were implemented that required actions to power off noise sources or take actions such as wearing hearing protection, when levels reached 74 dBA for a 24-hour TWA (54).

ISS continuous noise limits for the habitable space in the U.S. segment have been set at NC-50 (Figure 5-13). Maximum SPLs for each individual payload rack are established at NC-40, and the total complement of payloads

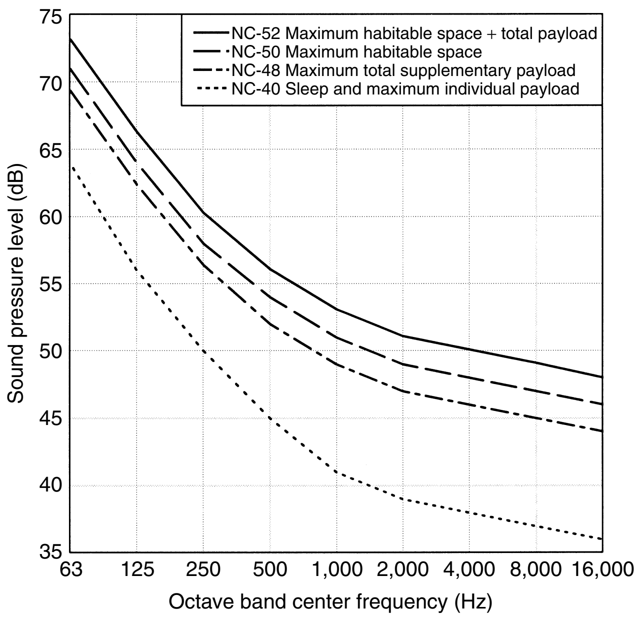

FIGURE 5-13 International Space Station (ISS) continuous noise specifications.

is limited to NC-48. The resultant maximum sound levels for the modules plus payloads are constrained by the NC-52 levels in Figure 5-13 (approximate total of NC-50 + NC-48). Intermittent noise limits were implemented for the payloads, but were set lower than in the Orbiter because of significant differences in flight duration and configuration, and the need for ISS to provide levels acceptable for long-term communications, habitability, and health. Flight rules require the crew to wear hearing protection when levels exceed 66 dBA for a 24-hour TWA. For 24-hour exposures, at the listed dBA levels the specified wear times are 67 dBA for 2 hours, 68 dBA for 7 hours, 69 dBA for 11 hours, 70 dBA for 14 hours and so on, until above 77 dBA wearing hearing protection full time is required (55). Hazardous overall noise limits adopted in the NASA standards are for continuous noise levels during flight to be limited by 85 dBA at the crewmember's ear (43). Impulse sound, a change in SPL of more than 10 dB in 1 second or less, is not allowed to exceed 140 dB peak SPL (43). Noise from hardware associated with accepted short-term operations during launch, entry, or burns should be kept lower than 105 dBA according to recent NASA efforts for the Exploration Mission vehicles (56). This level was based on a 1.5-minute exposure. A summary of acoustic requirements recommended in space flight programs is provided in the section on Acoustics in Reference (57).

Noise Measurements

The basic instrumentation components used for sound measurements consist of a microphone, an amplifier, and an analysis device. The sound level meter (SLM) contains these components and displays SPLs referenced to 20 μPa. It provides a single-number overall reading of the SPL in the audible frequency range. Most SLMs contain three standardized electrical weighting or filter networks (A, B, and C).

The SLM is used for general purpose and survey work such as continuous monitoring of noise at a workstation, the identification of noise hazardous areas, or for measurements of acoustic compliance in work spaces. When noise conditions exceed exposure criteria and noise control measures are indicated, an analysis of the SPL as a function of frequency is usually required. Instruments that perform this function are frequency analyzers, which commonly assess levels in one octave, one-third octave, or constant frequency bandwidths and may be used independently or in combination with SLMs. Some higher-end SLMs have the capability to perform a frequency analysis. Frequency analyzers are imperative because effective noise control measures deal with the problem areas in the frequency spectrum identified by octave band, one-third octave band, or constant bandwidth descriptions of the sound. In the Orbiter, SLMs were periodically flown and used to measure the acoustic levels and spectra. In the ISS, SLMs are used on-orbit, in periodic surveys to characterize the noise in preestablished measurement locations within the modules.

Personal noise dosimeters are small, lightweight devices worn by individuals to indicate their exposure to noise over a specified time period, typically for hearing conservation purposes. A dosimeter consists of a microphone, a unit that integrates acoustic energy over time, and a readout that displays the exposure or dose at the time the unit is read. A noise dosimeter is designed with one or more built-in displays that can report TWA levels and noise exposure doses in terms of the criteria used by the relevant regulatory standard. Various commercially available noise dosimeters differ somewhat in operation and readout, with some providing continuous 24-hour monitoring important for long-duration space flights. The general principle of operation is essentially the same among dosimeters, with the final output indicating the percentage of the allowable daily noise dose actually experienced by the individual wearing the unit. In the Orbiter, modified commercial dosimeters were periodically flown to record the crew exposure levels/dosage. In the ISS, similar dosimeters are used on-orbit in a crew-worn mode of operation to determine the crew dosage, and are affixed in local areas of the module to determine the average levels at those locations. The dosimeters can be used in an SLM mode or for readout of the maximum level experienced during the dosimeters operation.

Noise Control

Environmental Noise Control

In atmospheric flight, external noises originate from propulsion units and aerodynamic flow over the fuselage. In aerospace vehicles, internal noise is generated by fans, air conditioners, blowers, and pumps. These noises must be controlled. Noise control of the source and the pathways that lead to the receiver is a well-established engineering discipline that is amenable to quantitative analysis and design. Noise reduction is usually not designed to satisfy optimum comfort criteria but to guarantee allowable safe exposure conditions and communication capabilities for the crewmembers. In ISS, a substantial effort is made in designing quiet payloads and controlling the complement that is flown or used at any time during a mission. The fans and pumps in payloads are prime contributors to cabin noise levels in ISS. GFE such as exercise equipment (treadmill, bicycle, or resistive device), personal hygiene equipment (hair dryers and shavers) add intermittent noise and affect overall exposure. Design efforts are focused on developing quieter equipment, adding mufflers at the inlet and outlet of fans, and structurally isolating fans, pumps, and compressors through mechanical isolators. The noise level of most modules has been controlled close to NC-52, which is considered the equivalent of 60 dBA. The effectiveness of overall ISS noise control is enhanced by implementation of noise control plans, good design requirements, testing of hardware for compliance, constant oversight of compliance, and by participation in module design reviews and review meetings with the suppliers of modules, payloads, and other hardware. A summary of ISS noise control approaches and examples of design implementation is provided in the section **Noise Control** in Goodman and Grosveld (58).

Personal Protective Equipment

The SLM and dosimeters previously discussed are used to determine acoustic levels or dosage that personnel are exposed to and provide a basis for hearing protection needs. In many operational noise environments, the use of passive personal HPDs such as earplugs, earmuffs, or helmets are the only feasible means of reducing noise to an acceptable level at the ears. However, some HPDs can produce pressure points or become uncomfortable, produce infections, or may require removal to allow communications. The attenuation achieved by individuals under operational conditions varies considerably among the different devices depending on factors such as the selection, effectiveness, use, and care of the hearing protectors. All personnel should receive periodic training on HPDs and hearing conservation. Representative ranges of mean attenuation values of various types of HPDs are summarized in Figure 5-14. The mean values shown in the figure express the real-ear attenuation determined in the laboratory by a standardized psychophysical method with human subjects wearing the devices. The average attenuation values are extended to cover 98% of the population by subtracting two standard deviations from the mean values. Even with maximum attenuation, intense levels of sound can bypass the HPDs, enter the head and upper torso through areas not covered by the protectors, and reach the inner ear through tissue and bone conduction.

The performance of an HPD can be conveniently described by a single-number rating, such as the noise reduction rating (NRR) required by the Environmental Protection Agency (EPA) in its regulation on the noise

Type of protection	Third-octave band center frequencies (Hz)						
	125	250	500	1,000	2,000	4,000	8,000
	Attenuation (dB)						
Earplugs (Premolded, user formable)	10–30	10–30	15–35	20–35	20–40	30–45	25–45
Foam earplugs (Varies with depth of insertion)	20–35	20–35	25–40	25–40	30–40	40–45	35–45
Earplugs (first generation custom molded)	5–20	5–20	10–25	10–25	20–30	25–40	25–40
Earplugs (Custom molded deep insertion ± 1 SD)	23–41	22–36	26–40	30–42	31–39	37–41	40–48
Semi-insert earplugs	10–25	10–25	10–30	10–30	20–35	25–40	25–40
Earmuffs/headsets (with or without communications)	5–20	10–25	15–30	25–40	30–40	30–40	25–40
Earplugs and earmuffs/headsets (in combination)	20–40	25–45	25–50	30–50	35–45	40–50	40–50
Headsets with active noise reduction	20–35	25–40	30–45	Identical to earmuffs above 1,000 Hz			
Helmets	0–15	5–15	15–25	15–30	25–40	30–50	20–50
Space helmets (total head enclosure)	8–12	10–15	15–25	15–30	25–40	30–50	30–60

FIGURE 5-14 The ranges of attenuation (in dB) shown for good hearing protection devices represent the approximate minimum and maximum protection available.

labeling of hearing protectors (59). The effective A-weighted noise exposure for a person wearing the device is estimated by subtracting the NRR from the measured C-weighted level of the noise. For example, a wearer of a device with an NRR of 25 dB is exposed to an effective noise level at the ear of 80 dB when the C-weighted level of the measured noise is 105 dB. When only A-weighted sound level is measured, the effective noise exposure level is obtained by subtracting the NRR from the measured noise, as well as subtracting an additional 7 dB to compensate for the A-weighting. A more accurate exposure is obtained by performing the calculations on an octave band basis. Field studies have revealed that, owing to inadequate earplug insertion and fit, users often achieve as little as 33% of the attenuation reported from laboratory studies, or the NRR. Consequently, a earplug's NRR is often derated owing to factors in the workplace such as lack of training, incorrect size and fit, poor compliance, deterioration of devices, and modifications to the devices by personnel. The maximum noise reduction achievable with the best HPDs is not typically obtained because of air leaks, vibration of the protector, and sound passing through the materials.

The EPA has received funding and approval to update the NRR in 2007. A two-number range (perhaps called *noise reduction range*) may be adopted that expresses the 20th and 80th percentile of attenuation among users. The rating is designed to be subtracted from A-weighted noise levels, not C-weighted, as the current NRR requires.

Active noise reduction (ANR) HPDs reduce the low-frequency noise at the ear under the earmuff by means of noise cancellation. The ANR system cancels a significant amount of the low-frequency noise below approximately 1,000 Hz, as shown in Figure 5-14. The ANR system detects the noise at the headset, processes it, and produces a sound field that creates destructive interference reducing the level of the perceived noise. ANR headsets provide an improved quality speech signal resulting in better intelligibility, increased comfort, less hearing loss, and less fatigue than the same headset with only passive attenuation. ANR headsets are widely used in general aviation aircraft. Some ANR headsets can be customized for personnel with non-normal hearing. The passive attenuation is increased, the ANR boosted, and the band-pass and gain of speech configured to match the user's residual hearing. In ISS, where noise levels in some modules are high, the use of various types of insert earplugs and ANR headsets has provided adequate hearing protection. To ease concerns with infection or discomfort with HPDs, a variety of HPDs are used on-board.

Noise canceling microphones significantly reduce low-frequency noise without affecting sensitivity to the speech signal. Improved voice communications effectiveness is needed in high noise level aerospace environments, such as helicopters and fighter jets. The use of insert earplugs under communications headsets and helmets often achieves the additional voice communications and sound protection required in these very high level noise environments. The insert earplug provides equal attenuation of the noise and the speech signal. Then, the level of the voice signal is increased while the level of the noise remains unchanged. Significant improvements are achieved in the speech-to-noise ratio at the ear and in the speech intelligibility. Noise-excluding personal equipment is not always adequate for satisfactory communications when used in environments with the highest levels of noise. However, in most other noise environments the equipment provides satisfactory voice communications. The communication earplug (CEP) is a technology featuring two small sound transducers that are connected to the voice communication system and are paired with foam ear tips, which provide passive noise attenuation. The mini-CEP is even smaller, more comfortable, and more rugged, and fits completely in the ear canal providing approximately 30 dB of noise attenuation. Because the signal is routed to the medial side of the hearing protector, rather than peripherally, speech intelligibility is significantly greater compared to passive or ANR headsets. Helicopter and fighter jet cockpit environments greatly benefit from the CEP technology.

Speech-Based Control, Response, and Localization

Aerospace operations remain a fertile area for applications of speech-based control and voice response technologies. Speech-based systems continue to be evaluated in atmospheric and space flight environments. Excellent comprehensive contemporary reports on *The Technology of Speech-Based Control* (60) and *Applications of Speech-Based Control* (61) in aerospace environments are available.

Automatic Speech Recognition

Human speech is a very complex and sophisticated acoustic signal. Automatic speech recognition (ASR) systems must substantially reduce and transform elaborate speech code to very small signals recognizable by the systems while preserving the important speech code information. All speech recognition systems are similar in that they acquire the speech signal, digitally process the signal, and transform the processed speech signal into a pattern that is matched to the patterns of the recognition system. This process is successful in benign environments but is very vulnerable to disruption and masking, particularly by acoustic noise. Recognition rate decreases as noise increases. ASR systems are continually being evaluated for human operator interfaces to minimize excessive workloads and increase overall efficiency. Multiple visual and manual tasks, time-critical responses, and highly specialized situational actions can constitute a threat to safety as well as mission accomplishment. Speech-based control as a supplement to conventional controls is becoming more common. Speech recognition depends heavily on speaker vocal traits, quality of training, and speaker assimilation. Accent in any language degrades the performance of present day systems that must have a built-in feedback loop to learn to recognize the accent. Accent is a concern and a challenge in military multinational forces, commercial applications on personal computers, the telephone network, and in air traffic control.

Voice control technology is included in the US multiservice joint strike fighter (JSF) aircraft. Speech input is incorporated in the single-seat European fighter aircraft EF2000 and is used for control of displays, radar, radios, target designation, navigation aids, and other functions. Pilots assessing the EF2000 program regard speech recognition as "essential to the safe and efficient operation of the aircraft" (61). Stress experienced by the crew may negatively influence the speech signal. The gravity-load effect on speech production is a relative factor. Highly experienced personnel can speak relatively normally at up to 5-G sustained acceleration with only approximately 5% loss in recognizer performance. Inexperienced subjects may encounter 30% loss in recognizer performance even at low sustained acceleration levels. In addition, G-protection requires increasing the breathing gas pressure in the oxygen mask by as much as 50 mm Hg or more, which affects speech production. Vibration is present on most aerospace vehicles; however, it is a dominant problem for speech recognition in rotary wing aircraft. Reliability or correct word recognition may vary from 95% to more than 99% under favorable conditions, but may drop to essentially 0% under the most severe conditions. Pilots of both fixed- and rotary wing aircraft consider that positive speech recognition experiences increase their capabilities while decreasing their workload.

One of the challenges of using voice input for space applications continues to be reduced recognition rates due to the relatively high ambient noise levels within a spacecraft. In the 1980s, the Orbiter successfully used voice input/output as the main method for astronauts to interact with the five flight computers. A commercially available speaker-dependent speech recognition system was used as an alternative to the manual keyboard. In 1990, the operational effectiveness of voice control in space systems was further demonstrated. Two astronauts successfully panned, tilted, and focused four TV cameras in the payload bay. In 2005, a NASA-funded research project resulted in the development of a speech enhancement system based on Independent Component Analysis. The custom microphone developed as part of the system filters noise from a voice signal input, thereby enhancing speech recognition rates. This system is being tested for use with a variety of other NASA projects, including integration with a head mounted display (HMD).

Machine Voice Response

Voice response systems are already deeply imbedded in the commercial marketplace. Microprocessors provide a wide variety of preprogrammed words and phrases in typical male or female voices. Among the aerospace applications of machine voice responses are advisory, validation, and warning functions. Present microprocessor-type systems are highly flexible and can be developed to be adaptive in terms of message management, including priorities. The application of an adaptive voice response database involves the effective integration of voice warning with nonvoice warning signals, visual displays, annunciator indicators, and the audio communications function. Crew on commercial and military aircraft benefit from the annunciation voices and verbal resolution instructions from warning systems such as the Traffic Alert and Collision Avoidance System (TCAS) minimizing the chances of midair collisions between aircraft. The Terrain Avoidance Warning System/Enhanced Ground Proximity Warning System (TAWS/EGPWS) alerts pilots of such hazards as wind shear, excessive glide slope, and unsafe terrain clearance. Aircraft-related warnings such as stall, fire, overspeed, altitude, and autopilot disconnect are incorporated in the Central Aural Warning System (CAWS). In the Space Shuttle Orbiter, auditory alerts and fault messages are generated in response to sensor readings exceeding preset limits.

Localization

A relatively new technology, 3-D audio, enables localization information to be added to audio signals perceived over headphones. Audio signals such as voice communication, target location, warning signals, and aircraft advisories are recognized as coming from the location of their source relative to the receiving operator. Comprehension of competing messages has been significantly improved by 3-D separation. Localization of sounds is a natural, automatic response in humans. Operator use of 3-D audio technology is also natural, requires no training, and is not affected by ambient noise unless it is masked. This technology reduces workload and adds valuable precision to aircrew performance.

Virtual prototyping allows designers to view and analyze prototypes of aircraft and space vehicle interiors using 3-D virtual reality technology (62). Noise sources can be simulated on the basis of their individual or collective characteristics and the sound quality of the acoustic environment and response of the crewmembers can be evaluated before and during the design and manufacturing stages of the actual vehicle. A noise mitigation process, if required, can be applied to individual sources or any combination thereof and allows for relocation or acoustic control of offending contributors. The International Space Station Environment Simulator (ISSES) is a virtual reality development that uses sound rendering over headphones and speaker systems to simulate potential, arbitrary ISS acoustic environments in real time (63). The design approach allows the prospective crewmember or analyst to move to different locations inside an ISS mockup and hear a combination of nonspatial reverberant noise, such as the air handling system, as well as direct sound contributions associated with being in the close proximity of specific rack equipment, such as fans or compressors. The consequences of noise mitigation measures, including the treatment and control of the noise sources, paths, and receiving space, could be simulated and analyzed to assess compliance with the noise requirements. The subjective, human response to the noise may be evaluated through binaural simulation, which represents the sound as heard independently by the left and the right ear and includes interaural signal time, intensity differences, and the acoustic scattering about the head, pinna, and torso (64).

Virtual prototyping may help to incorporate acoustics in the early design and assessment of future aerospace acoustic environments.

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