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8. VIBRATION

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TABLE OF CONTENTS

8. VIBRATION 8-1

Nomenclature and Principles 8-1

Biomechanical Responses of Body to Vibration 8-6

Longitudinal Vibrations ($\pm G_z$) 8-9

a) Supine Vibrations ($\pm G_z$) 8-11

b) Semi-Supine Vibrations 8-13

Transverse Vibrations ($\pm G_x$) 8-19

Vibrations Transmitted to the Hand 8-21

Skull Vibrations 8-22

Transfer Functions and Power Spectra of Random Vibration 8-22

Tissue Impedance 8-32

Ultrasonic Vibrations 8-33

Patho-physiological Response to Vibration 8-34

Permanent Pathological Changes 8-34

Physiological Response 8-35

Subjective Response 8-36

Longitudinal or Vertical Vibration ($\pm G_z$) 8-36

Semi-Supine and Other Vibrational Axes 8-41

Threshold of Vibration Sensation 8-46

The Cardiovascular System and Blood 8-48

Respiratory Physiology 8-48

Metabolic Factors 8-51

Human Tolerance to Vibration 8-51

Visual Effects 8-67

Visual Acuity 8-67

Effects on Visual Tasks 8-75

Vigilance, Concentration and Reaction Time During Vibration 8-78

Simple Motor Performance 8-78

Performance of Complex Tasks 8-79

Performance Under Combined Vibration and Linear G 8-89

Performance on Launch Towers During Horizontal Oscillation 8-91

Protection Against Vibration 8-91

References 8-95

8. VIBRATION

The vibration environment in space operations covers a wide range of amplitudes and frequencies. One must consider vibration due to spacecraft booster and control rockets, aerodynamic loading, cabin machinery, and equipment, as well as vibration in land and water surface vehicles supporting operations. Much can be preplanned regarding the vibration environment but unexpected contingency resonances, especially in emergency modes of operation, may suddenly appear on the scene. A study of the accuracy of vibration predictions in spacecraft design is available (14).

Vibration seldom occurs in the operational situation as a single isolated variable. Other environmental variables such as weightlessness, linear acceleration, etc., can be expected to interact with vibration to either reduce or increase the debilitating effects. Equipment variables include such things as size of graduations or illumination of instruments, inflated pressure suits, etc.; procedural variables include such things as task load, variations in time of task performance, etc.; and finally, personal variables, such as fatigue and deconditioning from weightlessness or inactivity, etc., all may have effects. The effects of some of these can be predicted at this time; others must await further research.

After a review of nomenclature and principles, data will be presented on the biomechanical characteristics of the human; the physiological and biochemical response, and finally, degradation of performance in response to vibration.

NOMENCLATURE AND PRINCIPLES

Vibration is defined as the periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed. The vibration, therefore, may occur in air, liquid, or solid media; however, the primary concern here is with the oscillation of solid or semisolid bodies (e.g., structures of the spacecraft) in contact with the human body. Some nonauditory effects on the body are produced by transmission of vibration through the air; however, most of this occurs in the audio range and therefore is covered in Sound and Noise, (No. 9).

The parameters of vibration which are significant for an understanding of the effects of vibration on the human body are as follows:

Frequency

Frequency is usually specified in cycles per second (cps) or Hertz (Hz) and may extend from greater than zero to the megacycle range. The band of concern with respect to the effects on the human body is usually confined to that less than 1000 Hz. Most of the significant effects of vibration occur within the 0.5 to 50 Hz range. Within this range the human body responds as a complex system of masses, elasticities, and dampers having lumped parameters. Above 50 Hz, it is more appropriate to regard the body as a continuous viscous-elastic medium for vibration applied to the surface of the body. Below 0.5 Hz vibration is experienced as single jolts and as such, may be experienced as motion sickness. See Acceleration, (No. 7).

Displacement

Displacement, which is usually expressed in inches or centimeters, is defined as the maximum half-wave (single amplitude) or full-wave (double amplitude) displacement. The term amplitude is not synonymous with displacement. One refers to displacement amplitude or acceleration amplitude.

Velocity

Velocity, in inches/second or cm/second, is the first derivative of displacement and ordinarily is not used in describing the effects of vibration on the human body.

Acceleration

Acceleration inches/second^2 or cm/second^2, is the second time derivative of displacement and ordinarily is expressed as maximum or peak g. For sinusoidal vibration:

$$G = \frac{A(2\pi f)^2}{386} \qquad (1)$$

Where A = single amplitude of displacement in inches

f = frequency in Hz

For random vibration the acceleration is given as root mean square (r.m.s.) acceleration, or r.m.s. per frequency band.

Jolt

Jolt, in inches/second^3, is the third derivative of amplitude. The rate of onset of linear impact is a significant factor in evaluation of human tolerance to vibration of low frequency such as the 1/2 cycle vibration of impact.

Duration

Duration of vibration, in seconds or minutes, is important in establishing the effects of vibration. This includes short-term exposures, long-term exposures (over 1 hour) for which there is very little research data, and repeated exposures for which there is even less.

Figure 8-1 represents the relationship of some of these parameters. Vibrations may be considered sinusoidal when composed of a single sine wave; complex, when composed of any other wave form; and non-periodic, which may approach randomness, when composed of waves which do not repeat systematically. Random, or semirandom waves, are usually characterized in terms of a power density curve (PSD) which is derived from the frequency bands that characterize the random vibrations.

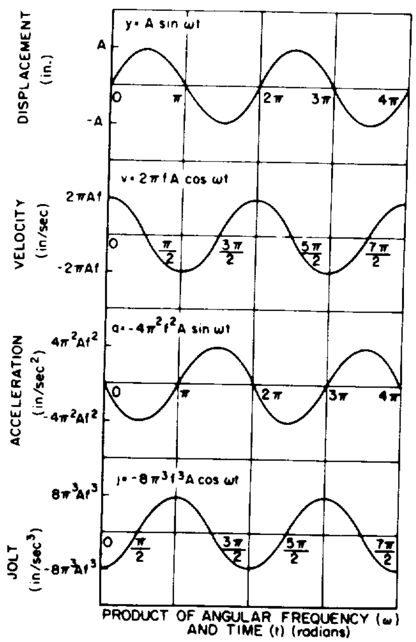


Figure 8-1

Relationship of the Parameters of Sinusoidal Vibration

(After Morgan et al (eds.)[114])

Figures 8-2 a and b represent a nomogram allowing interconversion of frequency, amplitude, and acceleration factors in sinusoidal vibration.

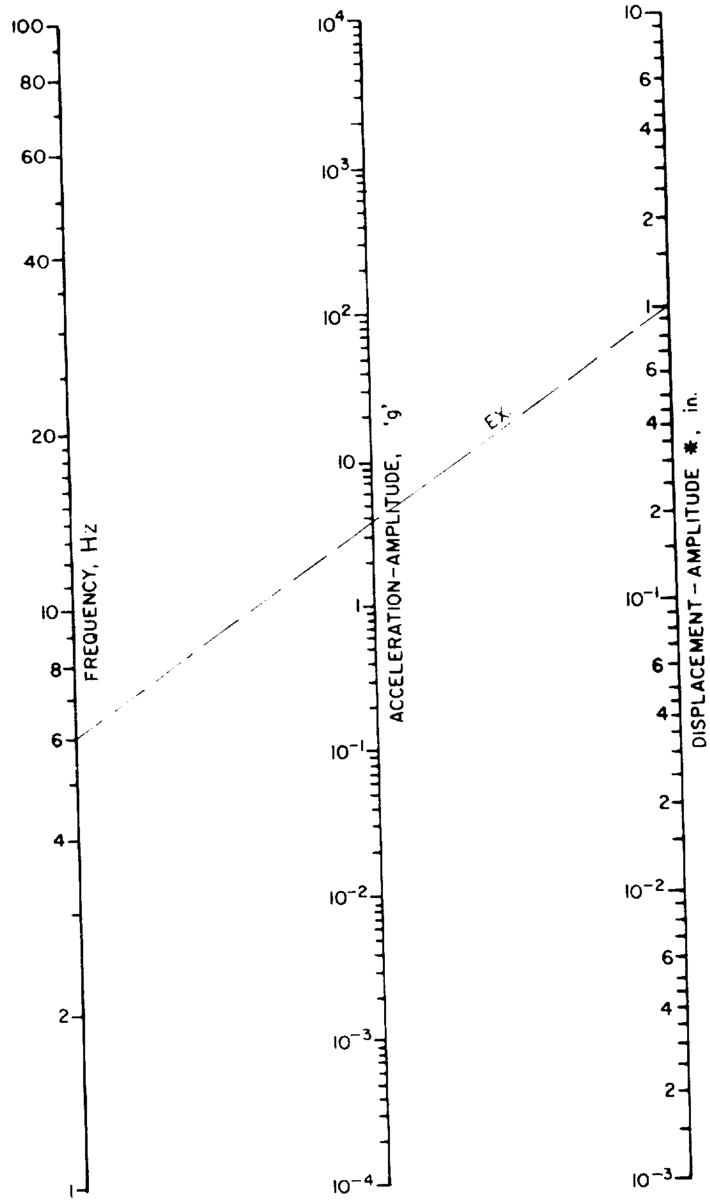
The transmission of vibration to and within the human body is dependent on the following:

- Direction of application of vibration to the human body which includes one, or any combination of the axes of the body. (See Figure 7-1 in Acceleration, (No. 7) for nomenclature of axes). Most vibration research has been confined to the longitudinal axis (Z) of the body, since this has been the most common condition in most vehicles. However, in space vehicles, vibration can be expected to also occur in the direction of the fore-aft (X) axis of the body, or laterally along the Y axis.

- Point of application of vibration to the human body which includes whole body vibration transmitted through seats (when subject is seated), through the feet (when standing), through the length of the body (when reclining), or combinations of these. Also, vibration may be transmitted via a body part such as the hand (when holding a vibrating control). Vibration of instruments may also be included in the latter category where the effects are primarily confined to the visual system.

Figure 8-2

Interconversion of Physical Factors in Vibration



* = HALF PEAK-TO-PEAK AMPLITUDE

Example of use: To determine the acceleration-amplitude of a vibration of 6 Hz at 1 in. (half-wave) amplitude (i.e. 2 in. peak-to-peak), lay a straight-edge across the chart joining 6 Hz with 1 in. amplitude.

Answer: The acceleration-amplitude is 4 g (approximately)

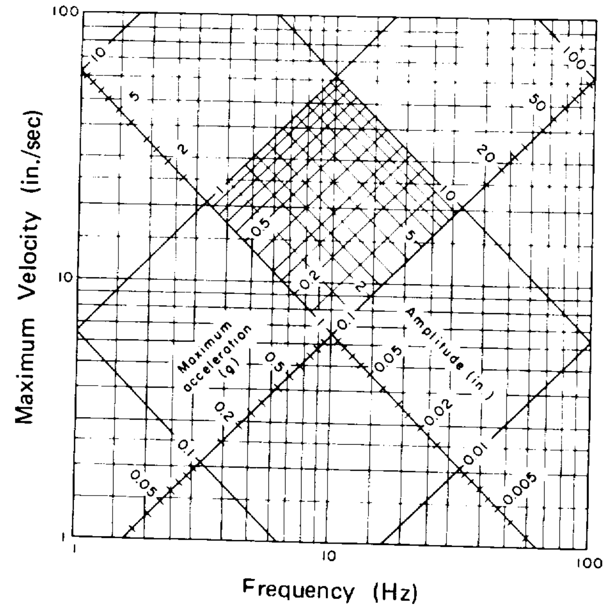
a. Nomogram of Frequency, Displacement-Amplitude and Acceleration-Amplitude for Sinusoidal Vibration

(After Guignard[80])

Figure 8-2 (continued)

b. Conversions Between the Parameters of Vibration

(After Morgan et al (eds.)[114])



- Position of the body also determines the effects of vibration on the body and is related to the point of application. Effects are different depending on whether the person is seated, standing, reclining, prone, supine, or crouched.
- Materials interposed between the body and source of vibration affects transmission of vibration to the body. This includes the effects of padding on seats, spring mountings, etc.
- Restraint of the body may attenuate or increase the effects of vibration depending on the frequency and amplitude. This includes the restraint of the person by seat belts and harnesses against a vibrating seat, support for the arm in operating a control, wearing of girdles (which restrain the abdominal region), etc.
- Interaction with other environmental variables may also enhance or reduce vibration and vibration effects. The presence of acceleration forces (e.g., linear $+G_z$), reduced gravitation, and null gravity can be expected to affect the transmission characteristics.

The transmission of vibration within the human body is dependent on the following:

- Body size, build, and weight with greater attenuation involving larger masses and densities
- Posture, whether erect or slumped; and
- Muscular tension and fatigue (91).

The response of the human body, which establishes the criteria for this Compendium, can be considered under the headings of physical or biomechanical, pathological, physiological, and performance. Of these, the biomechanical responses, which cause discomfort and pain, establish most of the physiological tolerance limits to vibration. Each of these responses will be described in some detail below.

BIOMECHANICAL RESPONSES OF BODY TO VIBRATION

Basic concepts in the biomechanical structure of the body have been covered under impact in Acceleration, (No. 7).

The physical responses of the body are primarily the result of the body acting as a complex system of masses, elasticities, dampings, and couplings in the low frequency range (i.e., up to 50 Hz). The impedance of the body and its parts and organs damp vibration over certain frequency and amplitude ranges. For certain other frequency/amplitude ranges, there are resonances which amplify the vibration within various portions or all of the body. In general, the impedance of the body and its parts and inherent resonance factors influence the transmission characteristics of the vibration through the body (137, 139).

Figure 8-3 is a model of the dynamic mechanical properties of the human body. The body system for the low-frequency range below 100 Hz can be approximated partially or in toto by a lumped-parameter system, i.e., a system consisting of rigid bodies and restraining elements of negligible mass.

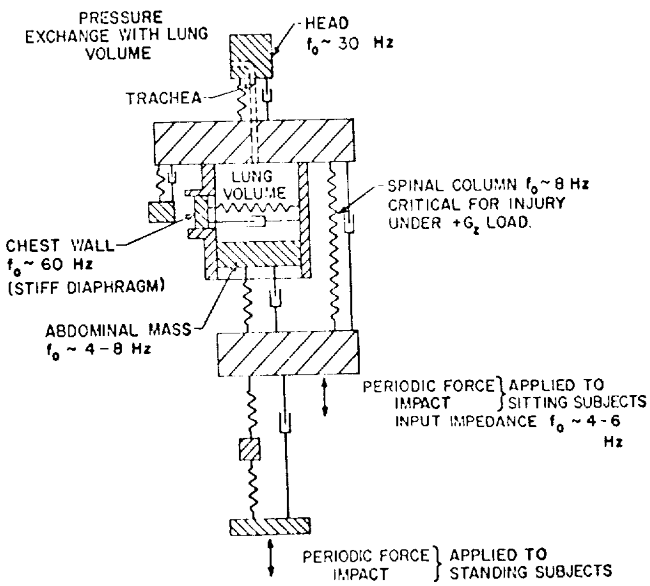


Figure 8-3

Mechanical Model for the Human Body for G_z Vibration and Impact Loads and External Pressure Loads (Acoustic, Blast, Decompression)

(After von Gierke[67])

Calculation of the response of such a system to static, transient or dynamic forces presents a "network" rather than a field problem. The characteristics of such a system can be determined experimentally by studying its resonance behavior when exposed to steady state vibrations of varying frequency (33).

The smaller the masses involved, the higher is the resonant frequency of the subsystem. The main torso resonances of the sitting or standing man are between 4 and 6 Hz, whereas the resonance of the head relative to the shoulder is in the order of 20-30 Hz (30, 33).

Mechanical energy, per se, transferred from the environment to the man is primarily deterministic of biologic effects (69, 179, 180, 182). The impedance model, then, is essentially an energy transfer model. As such, its purpose is to delineate the energy exchange characteristics of the human body. There are several pertinent aspects to the energy characteristics: the distribution of the real or dissipated energy over the frequency range, the distribution of the reactive or stored energy over the frequency range and the total amount of each. The model defines the energy transfer patterns and, while it gives no a priori estimate of absolute levels, it does indicate that certain types of environments will be more likely to present tolerance problems than others.

Also, the energy transfer to the human from the environment can be given in terms of the impedance and the power density spectrum of the velocity (105, 140, 141, 142, 143, 144, 171). This means that one can reduce a particular acceleration-time history to its power spectrum in order to judge its effect. This has the advantage that it eliminates the need for approximating very erratic acceleration-time histories. Therefore, knowledge of impedance and phase angles permits calculation of the coupling of mechanical energy transmitted to the body under different modes of application and protection. (See Figure 8-10.) (137, 139)

This approach is especially useful in non-sinusoidal forms of vibration as are often met in operational situations. In the case of the steady state non-sinusoidal excitation it is necessary to resolve the force and velocity wave forms into a finite or infinite (Fourier) series of sinusoidal components. In the case of the transient excitation it is necessary to break the aperiodic waveform into an infinite series of sinusoidal components by means of the Fourier integral. In the case of random excitation the problem is more difficult because the waveform cannot be broken into sinusoidal components. However, it is still possible to calculate the impedance factors by dealing with the auto- and cross-correlation functions of force and velocity. These functions are actually definitions of the average characteristic of the signals and they do have Fourier integrals. The electric analogues of these problems in power circuits have been amenable to computer treatment (85, 142, 179).

Above roughly 100 Hz, lumped-parameter models become more and more unsatisfactory; a distributed-constant, continuous medium must be introduced to describe the wave phenomena observed in these frequency ranges (68). The characteristics of their propagation and the internal damping of vibrations at higher frequencies tend to localize effects of such stimuli. For higher frequencies, through the audio-frequency range and up to about 100 kHz, the wave propagation of vibratory energy becomes more and more important but the type of wave propagation (shear waves, surface waves, or compressional waves) is strongly influenced by boundaries and geometrical configurations. Above 100 kHz and up into the mHz range, compression waves predominate and are propagated in a beam-like manner. This viewpoint permits not only a phenomenological description of the body's mechanical properties but, in an increasing number of cases, forms the basis for attempts to explain the behavior of tissue in terms of microscopic tissue- and cell-structure.

Vibration measurements of the body's response are usually made whenever possible by non-contact methods. New cineroentgenographic methods have been used successfully to measure the displacement of internal organs, while optical, cinematographic, and stroboscopic observation can give the displacement amplitudes of larger parts of the body (106, 181). Small vibrations can sometimes be measured without contact by capacitive probes located at small distance from the (grounded) body surface. The probe forms a condenser with the body; capacity changes due to vibrations can be measured in a high frequency carrier system. If vibration pickups in contact with the body are used, they must be small and light enough so as not to introduce a distorting mechanical load. This usually places a weight limitation on the pickup of a few grams or less, depending on the frequency range of interest and the effective mass to which the pickup is attached. For example, Figure 8-16b illustrates the effect of weight and size on the response of accelerometers attached to the skin overlying soft tissue.

New laser techniques are being developed to detect and measure vibration of mechanical structures (119). Measurement of transmission of external force through fluid systems of the body under vibration is currently under study (15).

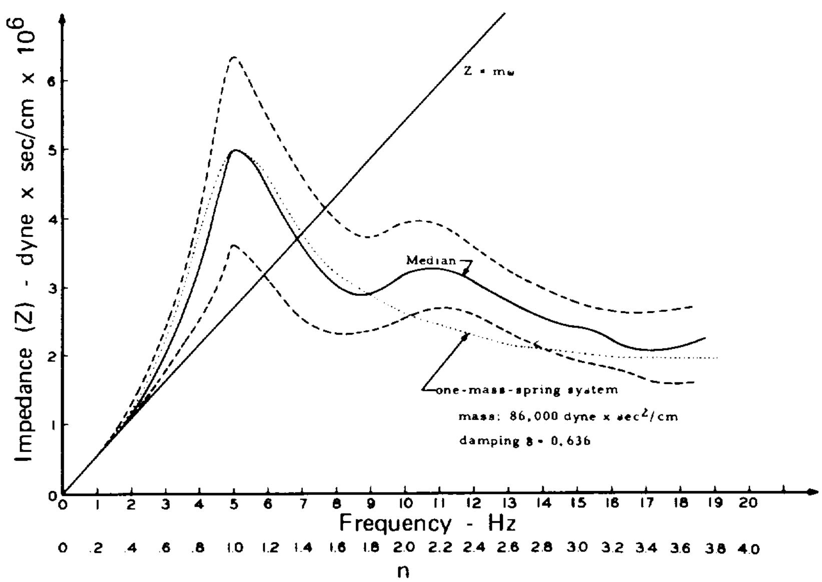
Living organisms have linear characteristics only in the low frequency range and for very small deformation. (See discussions of Figures 8-17 and 8-18.) For higher frequencies and large forces, a non-linear response must be expected. The damping coefficients, for instance, may depend on the instantaneous velocity of the organ displacements. This deviation from the assumed viscous damping and the participating mass may change with higher accelerations. There will be a difference, therefore, between the response of an organism to steady-state vibration with relatively low acceleration and to impact pulses with short, high accelerations (27). This consideration hold for the responses of the whole body as well as for a single organ or organ complex.

Since the natural frequency of the studied organ system in a given animal differs much from the related organ of man, their responses to a certain form of excitation cannot be compared. Also the posture of the living subject will have an influence on his dynamic response, necessitating a careful control of the subject's position during the test. Establishing tolerance criteria for man, using animals as substitutes, presumes that the tissue strength in animals is the same as in man. This is not a too unreasonable assumption (133). Scaling factors are now under study (66). In evaluating impedance curves, it should be kept in mind that the impedances, reflecting resonances and tissue damping are not independent of the shaking intensity whether expressed in terms of amplitudes or peak velocity or peak accelerations. It has been shown that the force between subject and support does not increase linearly with these parameters (24, 48, 103, 185). (See Figure 8-9a.) The nature of the padding material between shaker and subject as well as the level and direction of linear acceleration bias can influence the determination of the resonance spectrum of the body (26, 48). (See Figure 8-11a and b.)

Excellent reviews of impedance and transmission parameters of man are available from which the following discussion is taken (27, 28, 29, 33, 179, 180).

Longitudinal Vibrations ($\pm G_z$)

The average response of sitting human subjects to steady-stage vibration in the frequency range 0 to 20 Hz is illustrated in Figure 8-4. Up to two Hz, the impedance of the whole body is the same as the impedance of a pure mass (mω), indicating that the body moves as a whole unit. Around 5 Hz, a resonance peak produces the greatest deformation of the whole body, and a second peak around 10.5 Hz demonstrates a resonance of a subsystem in the body.



Median and the twentieth and eightieth percentile of the impedance of eight different subjects, compared with the impedance of a pure mass (mω) and a one-mass-spring system with damping.

Figure 8-4

Impedance of a Sitting Man

(After Coermann et al[28, 29])

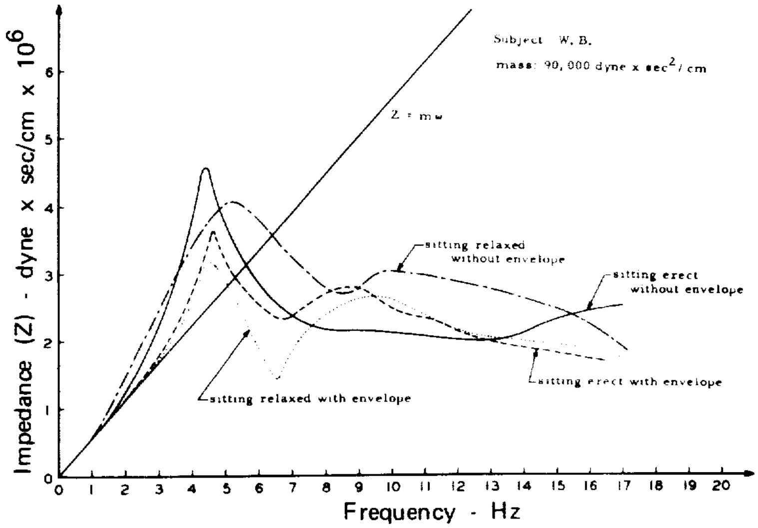
The calculation of the parameters for these two resonances leads to a model consisting of two mass-spring systems with dampers. The first system (dotted line) (Figure 8-4) represents about 90 percent of the body mass, has an elasticity of about 685 lbs per inch and a damping factor of about 0.32 of the critical damping; the second represents about 10 percent of the body mass, has an elasticity of about 186 lbs per inch and a damping factor of about 0.13 of the critical.

These parameters change considerably if the subject assumes a relaxed position or if the abdomen of the subject is restrained by a semi-rigid envelope (Figure 8-5a). While the first resonance frequency changes only little, the damping factor for this resonance varies over a wide range, indicating that the body reacts almost as a pure mass for frequencies up to

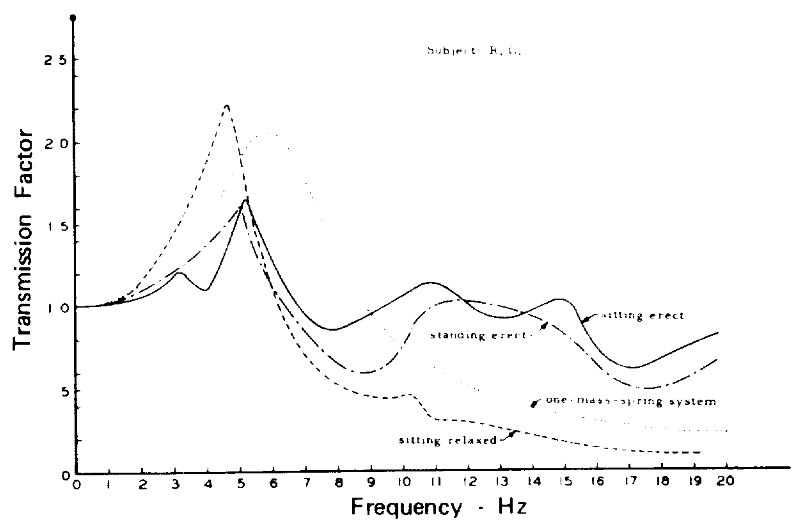
Figure 8-5

The Effect of Posture, Clothing or Envelopes, and Relaxation on Impedance and Transmission of Vibration in Man

(After Coermann et al[27, 33])



a. The Effect of a Semi-rigid Envelope Around the Abdomen on the Impedance of One Sitting Subject at Erect and Relaxed Postures



b. The Transmission of Vibrations from the Seat to the Head of One Subject at Varied Body Postures Compared with the Transmission Factor of a One-Mass-Spring System with Damping

6 Hz. The second resonance practically disappears. The same effect can be seen if the transmission of vibration from the seat to the head of a sitting subject is measured (Figure 8-5b). The peak of the fundamental resonance at around 5 Hz is reduced in a relaxed posture, and the higher resonances become insignificant. (See also Figure 8-10 comparing impedance in the semisupine seated and standing man.)

The greatest loads occur in the region of the eleventh thoracic to the second lumbar vertebra which can therefore be assumed as the hinge area for flexion of the upper torso. Since the center of gravity of the upper torso is considerably forward of the spine, flexion movement will occur even with the force applied parallel to the axis of the spine. Changing the direction of the force so that it includes an angle with the spine (for example by tilting the torso forward) influences this effect considerably. Similarly, the center of gravity of the head can be considerably in front of the neck joint which permits forward-backward motion. This situation results in forward-backward rotation of the head instead of pure vertical motion. Examples of relative amplitudes for different parts of the sitting and standing body are shown in Figure 8-6. The curves show an amplification of motion in the impedance resonance range and a decrease at higher frequencies. The impedances and the transmission factors are changed considerably by individual differences in the body and its posture, as well as support by a seat or back rest of a sitting subject; or by the state of the knee or ankle joints of a standing subject. The resonance frequencies remain relatively constant whereas the transmission ratio varies (for the condition of Figure 8-6b). Transmission factors as high as 4 have been observed at 4 Hz (145). Above approximately 10 Hz vibration amplitudes of the body are smaller than the amplitudes of the exciting table and decrease continuously with increasing frequency. The attenuation of the vibrations transmitted from the table to the head is illustrated in Figure 8-7. At 100 Hz this attenuation is around 40 dB. The attenuation along the body at 50 Hz is shown, although not for pure longitudinal excitation. (See Figure 8-8).

In the seated position, between 20 and 30 Hz, the head exhibits a resonance as can be seen clearly in Figure 8-6b. In this range the head amplitude can exceed the shoulder amplitude by a factor of 3. This resonance is of importance in connection with the deterioration of visual acuity under the influence of vibration. Another frequency range of disturbances between 60 and 90 Hz suggests an eyeball resonance (30). (See also Figs. 8-17 and 8-18.)

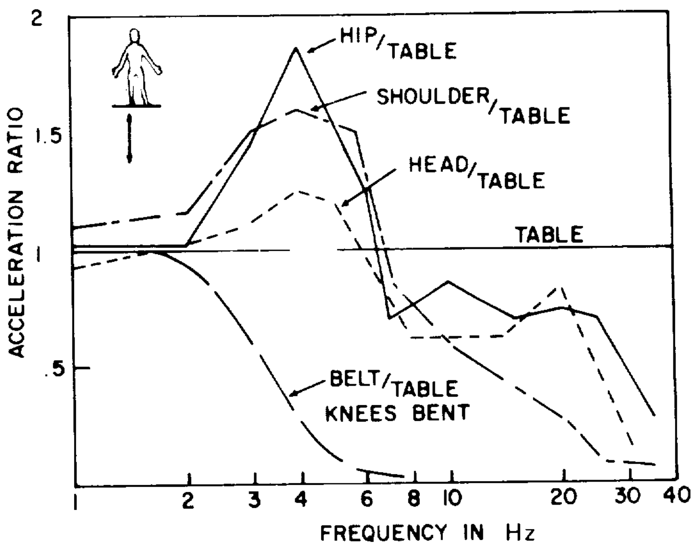
Maxima in horizontal seat-to-head transmissibility have been reported in the range 1.5 to 2.5 Hz (40, 91). Resonance near 2 Hz is the dominant mode in horizontal vibration of the seated man. If the seated subject is vibrated in more than one plane simultaneously, his physical response and subjective appreciation of the motion depend upon the amplitude and phase relationships between the component vibrations.

a) Supine $\pm G_z$

The impedance of the human body lying on its back on a rigid surface and vibrating in the direction of its longitudinal axis has been determined by ballistocardiograph studies (73, 187). The total mass of the body forms a

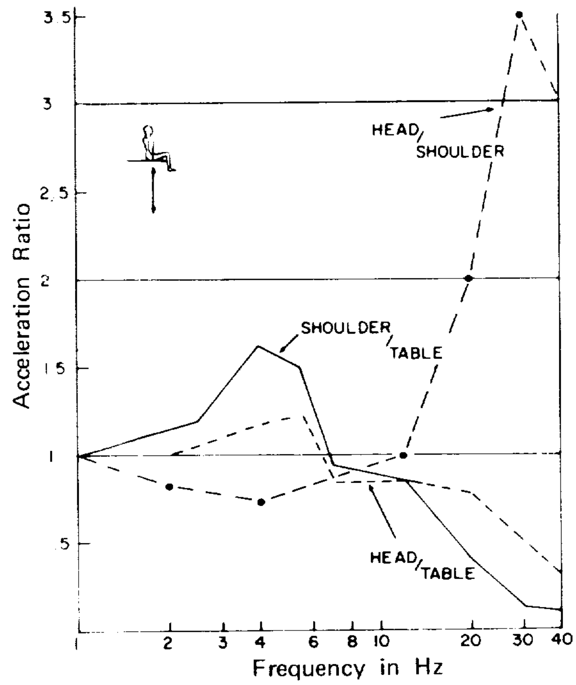
Figure 8-6

Transmission of Vertical Longitudinal Vibration to Body Parts in Standing and Sitting Subjects



a. Transmission of Vertical Vibration from Table to Various Parts of the Body of a Standing Human Subject

(After Dieckmann[41], data for transmission to belt after Radke[145])



b. Transmission of Longitudinal Vertical Vibration from Table to Various Parts of Body of Seated Human Subject

(After Dieckmann[41])

Figure 8-7

Attenuation of Vertical and Horizontal Vibration for Standing and Sitting Human Subjects

(Continuous lines after von Bekesy[5]. Shaded area is range of values for 10 subjects after Coermann[30])

(After von Gierke[70])

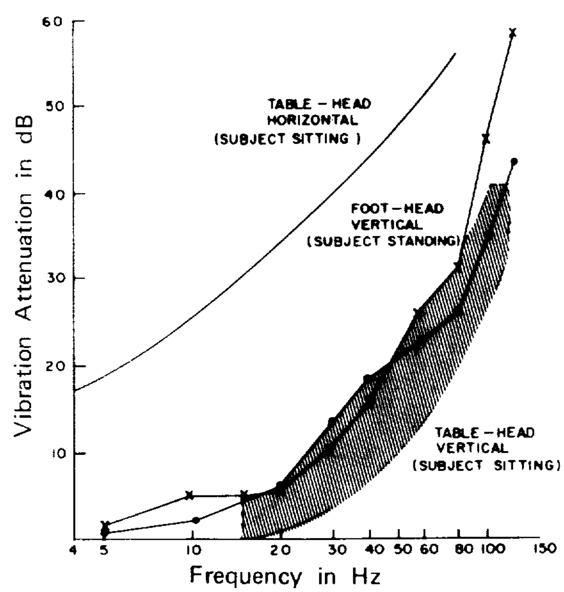
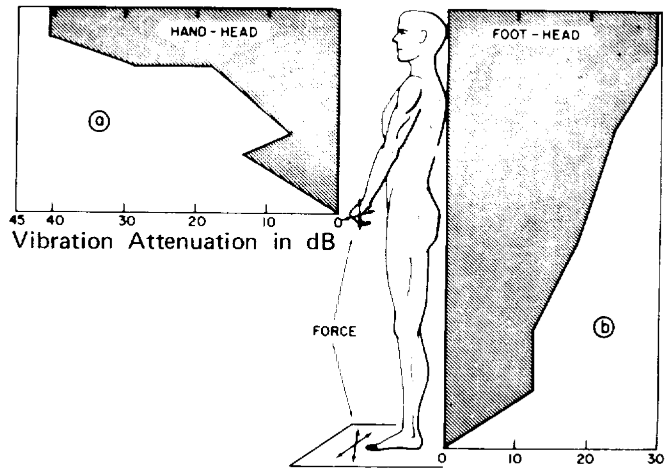


Figure 8-8

Attenuation of Vibration at 50 Hz Along Human Body

Excitation of a) hand and b) platform on which subject stands.

(After von Gierke(70), adapted from von Bekesy(5))



simple mass-spring system with the elasticity and resistance of the skin for tangential vibration. For the average subject the resonant frequency is between 3 and 3.5 Hz and the Q of the system is about 3. Q is defined as the rate of increase caused by resonance of the amplitude of an oscillating system and is measured as the ratio of the mass or spring reactance at resonance frequency to damping resistance. Restricting the subject's mobility by clamping the body at the feet and shoulders between plates connected with the table changes the resonant frequency to approximately 9 Hz and the Q to about 2.5. More recent studies on shake tables in the 0.2 to 0.5 g range indicate that at 4-8 Hz, as in the sitting position, subjects can tolerate less intensity than at other frequencies. Tension-relaxation factors also hold here. These results are indicated in Figures 8-9a and b. In Figure 8-9a the nonlinearities of the intensity response are noted as g-load is increased.

b) Semi-Supine

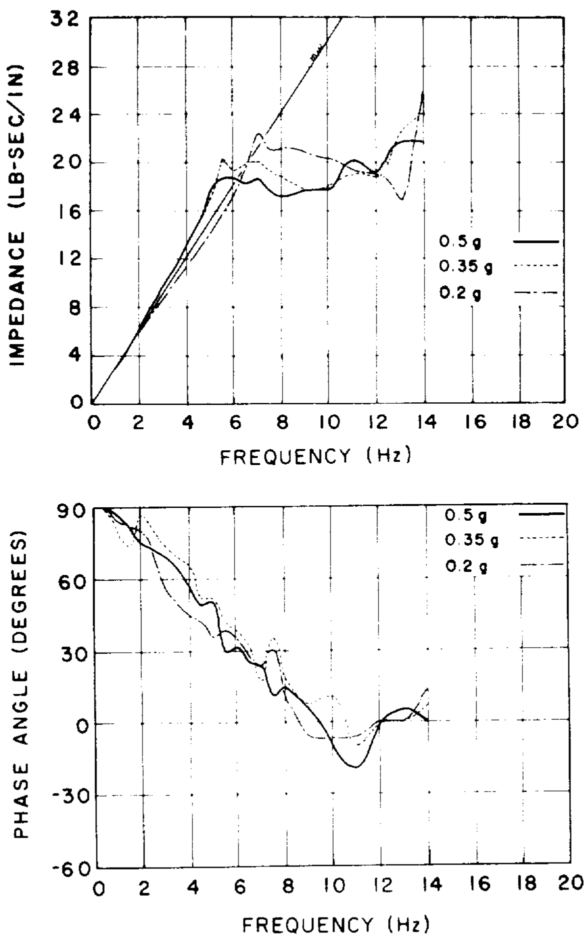
In semi-supine position used in spacecraft liftoff, the response of the human body to steady-state sinusoidal vibration is definitely different, as shown in Figure 8-10 (middle curve). The general course of the impedance curve follows very closely the m ω-line up to about 15 Hz, except at around 8 Hz where a slight peak due to a resonance in the pelvic area becomes evident. The second enhancement of the curve around 14 Hz indicates a very high damping in the body, and the phase angle signifies the domination of the damping forces at higher frequencies. The other curves of Figure 8-10 can be used to compare the impedance factors for steady-state sinusoidal, longitudinal vibration in the seated, semi-supine and standing human.

Figures 8-11 a and b indicate the effect of a constant, linear-G bias on semi-supine impedance and resonance peaks (176). The subjects were placed in a seat position similar to that described in Figure 8-24a and vibrated in the Z axis, exposed to vibration (±0.4 G at 2-1/2 to 20 Hz in 1/2 Hz increments) combined with linear acceleration of 1, 2-1/2, and 4 G. The absolute quantities (impedance magnitude and phase angle) shown in Figure 8-11a and 8-11b for one of the subjects are the magnitudes of the undistorted fundamental

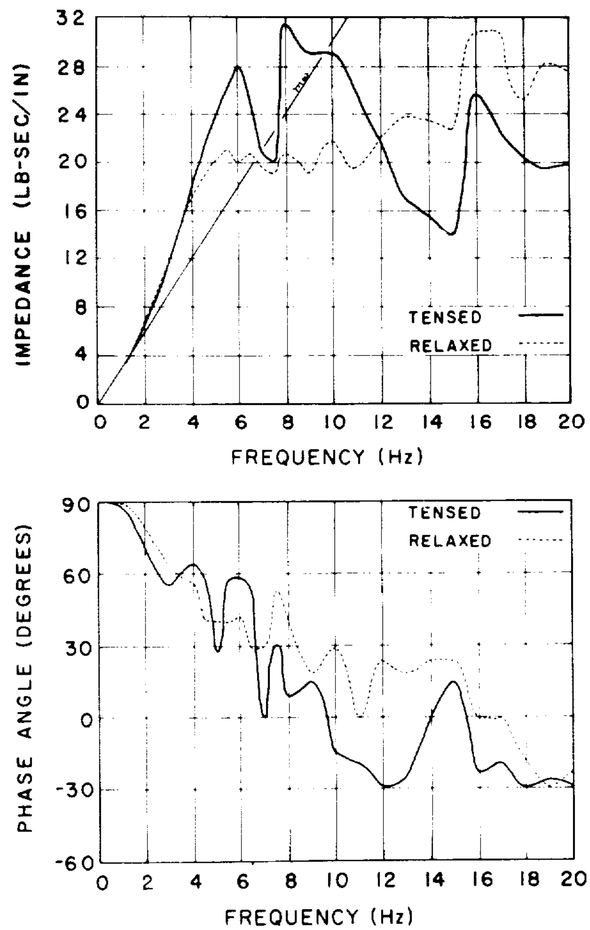
Figure 8-9

Mechanical Impedance in the Supine Position

(After Edwards and Lange[48])



a. Whole-Body Mechanical Impedance Versus Frequency, with Table Acceleration Level as a Parameter, Subject RGE, Supine Relaxed



b. Whole-Body Mechanical Impedance Versus Frequency, Subject RGE, Supine Tensed and Supine Relaxed

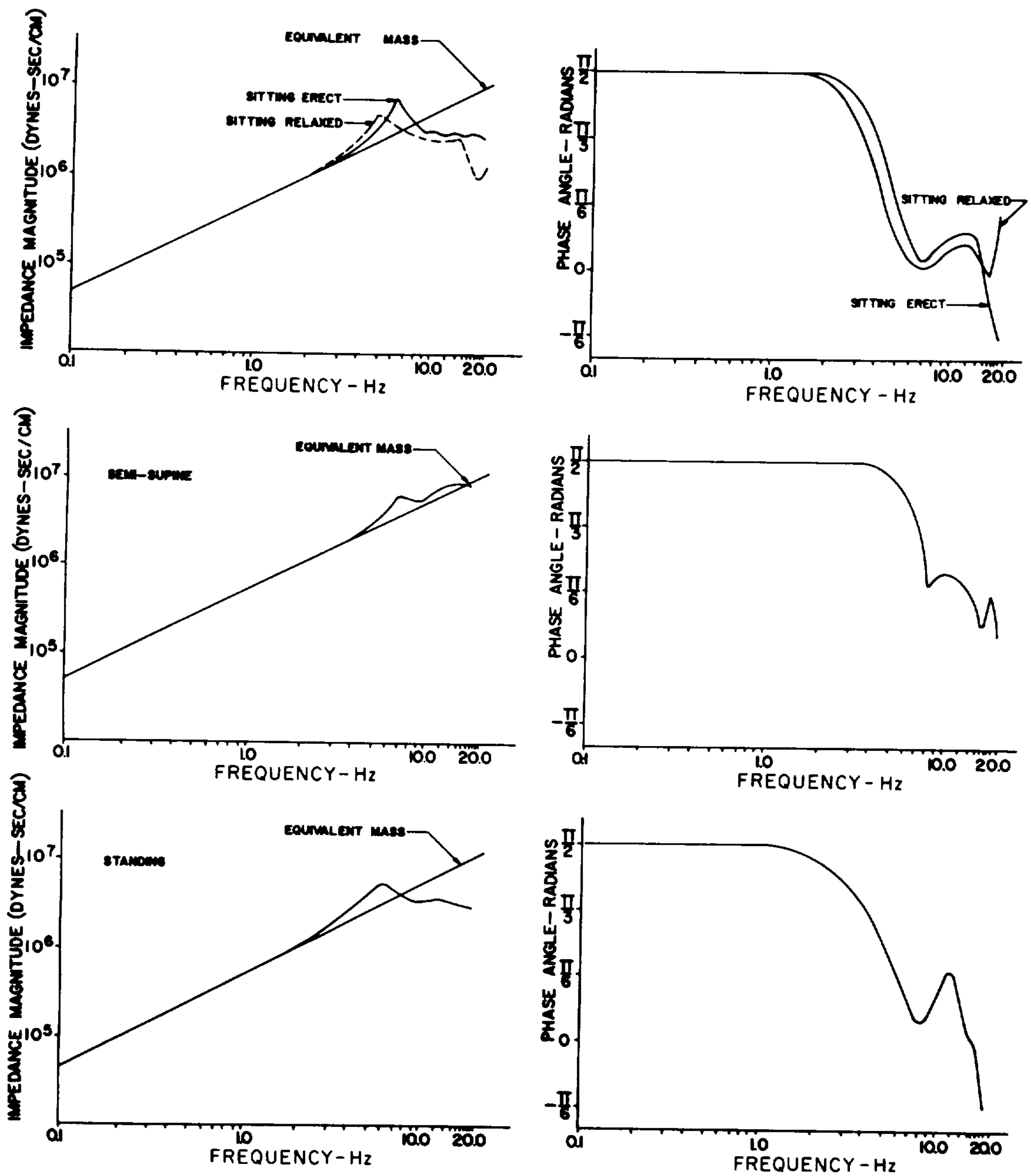


Figure 8-10

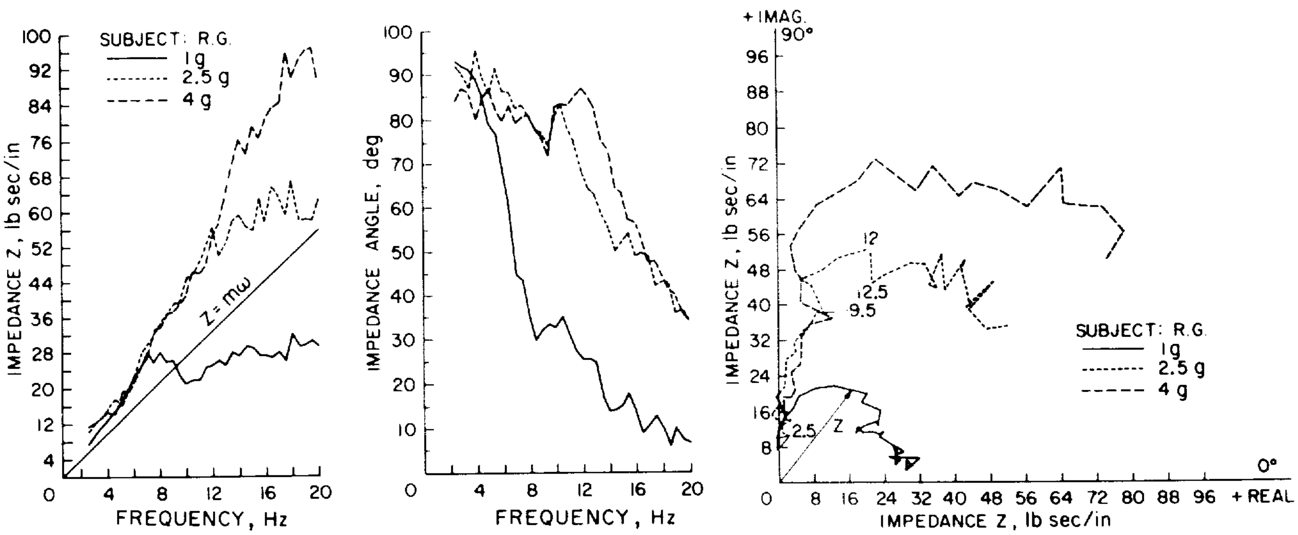
Human Mechanical Driving Impedance in the Steady-State Sinusoidal (Vibration) Environment

(After Weis et al[179], from data of Coermann[27])

Figure 8-11

Effect of Linear G Bias on Vibrational Impedance

(After Vykukal[176])



a. Whole-Body Mechanical Impedance Measured at Constant Vibration and Bias G Levels of 1, 2-1/2, and 4 G

b. Measured Whole-Body Mechanical Impedance Plotted in the Complex Plane

waveforms of the frequencies tested. As shown by these results, the influence of an increased bias G on the dynamics of the human body is quite significant. The differences in the nature of the body position and seat damping structure are probably responsible for the difference in impedance between the 1 G condition in 8-11a and 8-11b. Resonances at 7, 11, 13, 15, and 18 Hz were detected as expected (48, 179).

The complex plane or polar coordinate representation of impedance data in Figure 8-11b allows for a more detailed analysis of the system dynamics. Resonances and curve trends appear as deviations from ideal element responses (mass, spring, dampers). As noted, the resonances indicated appear as small loops (actions of subsystems resonating by themselves); the major loop trend represents whole body response in the frequency range tested.

The most significant effects of increased bias G on dynamics of the body are increased stiffness, reducing damping, and higher energy transmission to internal organs. The observance of pain by the subjects at certain measured resonant frequencies would indicate a lower tolerance to vibration at that frequency when combined with higher linear accelerations. No significant subjective impressions were noted at the 1-G bias level. However, at 2.5 and 4g, the subject became dramatically aware of local resonances, such as in the abdomen, chest, and extremities. Visual decrements were also noted. The correlation of resonance measurements and subjective impressions is quite significant. For example, in the frequency range of 9.5 to 12.5 Hz at 2.5-G bias, the subject noted the following sensations: at 9.5 Hz, "awareness of stomach vibrating," 11.5 Hz, "stomach vibration continued," 12.5 Hz, "stomach sensations decreasing." The polar plot (Figure 8-11b) indicates a deviation from the major loop in this frequency range. Subjective observations indicate a direct relationship with other deviations also shown in Figure 8-10c. Additional studies are needed to determine the effects of increasing the vibration G magnitude on impedance for higher bias-g levels simulating booster liftoff to orbital insertion.

One of the most important subsystems of the body, which is excited in the standing and sitting position as well as in the lying position is the thoraco-abdomen system (151, 187). The abdominal viscera have a high mobility due to the very low stiffness of the diaphragm and the air volume of the lungs and the chest wall behind it. Under the influence of both longitudinal and transverse vibration of the torso, the abdominal mass vibrates in and out of the thoracic cage. These vibrations not only take place in the (longitudinal) direction of excitation but, during that phase of the cycle when the abdominal contents swing towards the hips, the abdominal wall is stretched outward and the abdomen appears larger in volume; at the same time the downward deflection of the diaphragm causes a decrease of the chest circumference. At the other end of the cycle the abdominal wall is pressed inward, the diaphragm upward, and the chest wall is expanded. This periodic displacement of the abdominal viscera has a sharp resonance between 3 and 3.5 Hz. (See Figure 8-12.) Oscillations of the abdominal mass are coupled with the air oscillations of the mouth-chest system (8, 15). Measurements of the impedance of the latter system at the mouth (by applying oscillating air pressure to the mouth) shows that the abdominal wall and the anterior chest wall respond to this pressure. The impedance has a minimum and the phase angle is zero between 7 and 8 Hz. The abdominal wall shows maximum response between 5 and 8 Hz, the anterior chest wall between 7 and 11 Hz. Vibration of the abdominal system resulting from exposure of a sitting or standing subject is clearly detected as modulation of the flow velocity through the mouth. (At large amplitudes, speech can be modulated at the exposure frequency.) Electrical equivalent circuits and mechanical models for the abdomen-chest-mouth system are available (8, 67, 73).

Recent studies focused on the transmission of sinusoidal abdominal pulses to the cerebrospinal fluid of animals suggest that the amplitude ratio of intro-cranial pressure to the airflow velocity is relatively constant for 2-30 Hz driving frequencies (15).

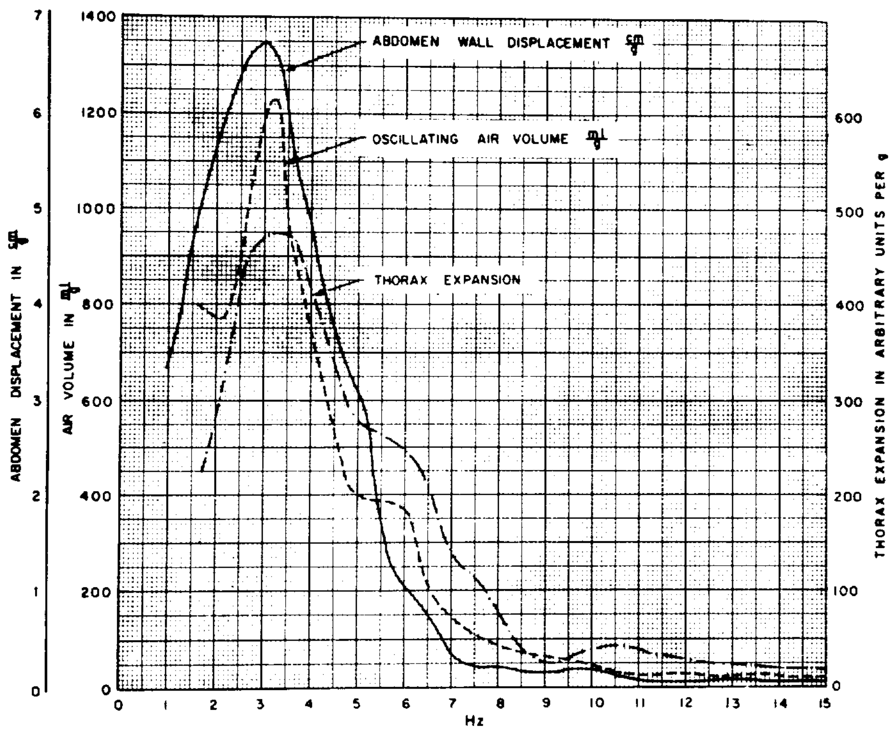
The bear is often used as a substitute for man in vibration and impact research because it is assumed that his body structure is most similar to that of man. In the steady-state impedance curve of a 126-lb Himalayan bear, the first resonance frequency is a little lower than that of the average man but still in the range of the standard deviation. Also at higher frequencies the characteristic of the impedance curve is similar if the difference in weight is considered.

An anatomical review of organ morphology related to vibration is available (73). The movements of the visceral organs can be a limiting factor for human tolerance to steady-state vibration in the frequency range 4 to 8 Hz. To measure the resonant frequencies of the thoraco-abdominal system as a whole, an air-filled balloon on a catheter was inserted in the

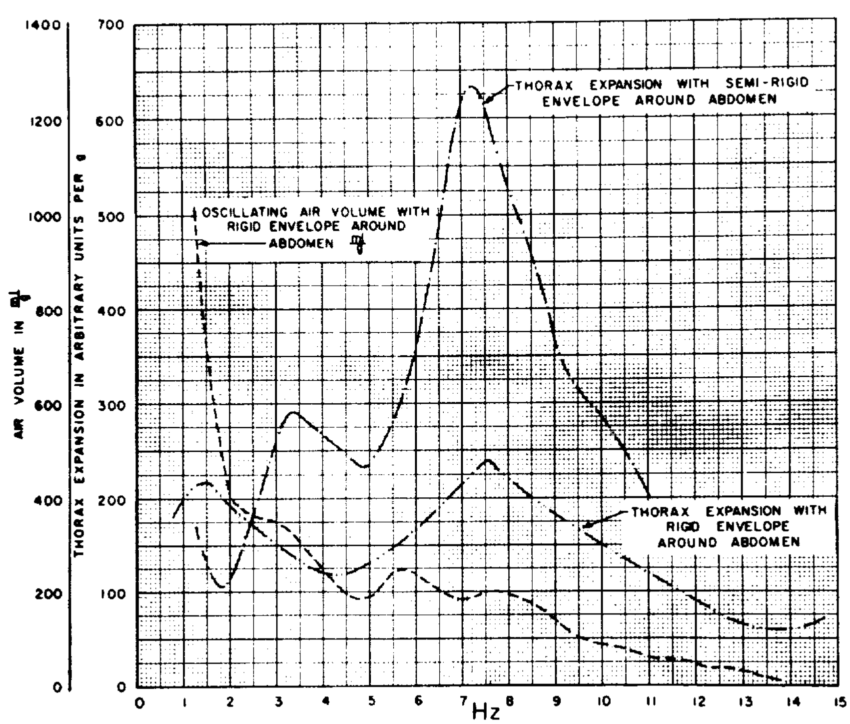
Figure 8-12

Thorax Expansion and Oscillating Air Volume of a Human Subject
with and without Envelope Around Abdomen
(supine position, shaken horizontally)

(After Coermann et al[33])



a. Without Envelope about Abdomen



THORAX EXPANSION AND OSCILLATING AIR VOLUME OF A HUMAN SUBJECT WITH ENVELOPE AROUND ABDOMEN (SUPINE POSITION; SHAKEN HORIZONTALLY)

b. With Envelope about Abdomen

colon of human and animal subjects sitting on a vertically vibratory shake table (185). The changes of the pressure within the balloon and the phase of this pressure relative to the movement of the shaker were recorded at frequencies from 1 to 20 Hz. In Figure 8-13 the pressure changes per G of the shaker are plotted versus frequency for a man sitting erect, sitting relaxed, and semi-supine, as well as for a sitting rhesus monkey and mouse.

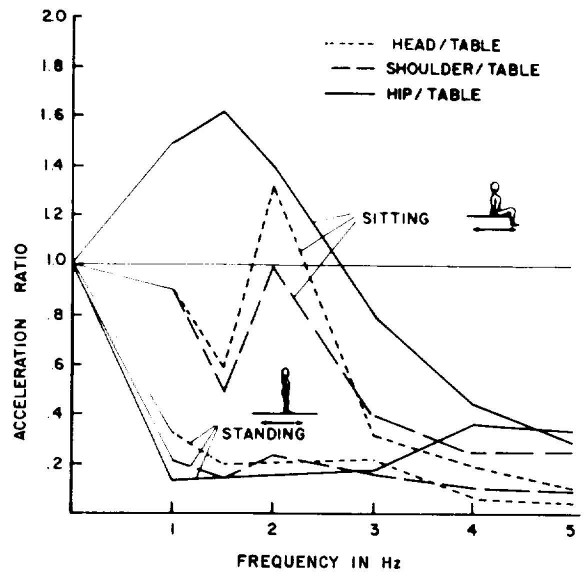


Figure 8-13

Transmission of Transverse, Horizontal Vibration from Table to Various Parts of Sitting and Standing Human Subject

(After Goldman and von Gierke[73], adapted from Dieckmann[40])

Man and monkey show in the sitting position main resonances between 4 and 5 Hz, while the man in semi-supine position has maximum movements of the thoraco-abdominal viscera between 7 and 8 Hz. The abdominal viscera of other animals have different resonance systems (131, 132, 150). Thus, before animals are used to study the influence of transient forces on the abdominal organs, it must be assured that their thoraco-abdominal systems have dynamic characteristics similar to those of man. There appears to be little evidence that anesthesia, 100% oxygen, or feeding have significant effects on resonant frequency of organs in animals (130).

Transverse Vibrations ($\pm G_X$)

The physical response to transverse vibration -- i.e., horizontal in the normal upright position -- is quite different from that described for vertical vibration (73). Instead of thrust forces acting primarily along the line of action of the force of gravity on the human body, they act at right angles to this line. The direction of the body masses along this line is therefore of the utmost importance and greater differences must be expected between sitting and standing subjects than for vertical vibration where the supporting structure of the skeleton and especially the spine have been designed for vertical loading.

Impedance measurements for transverse vibration are available. In fore and-aft vibration, the resonant frequency occurs due to flexion of the lumbro-dorsal spine and articulation at the hip joints. There is also a lateral bending mode at 1.6 Hz (80).

The transmission of vibration along the body is illustrated in Figure 8-14 (40). For a standing subject the shoulder and head amplitudes are of the order of 20 to 30 percent of the table amplitude at about 1 Hz and decrease

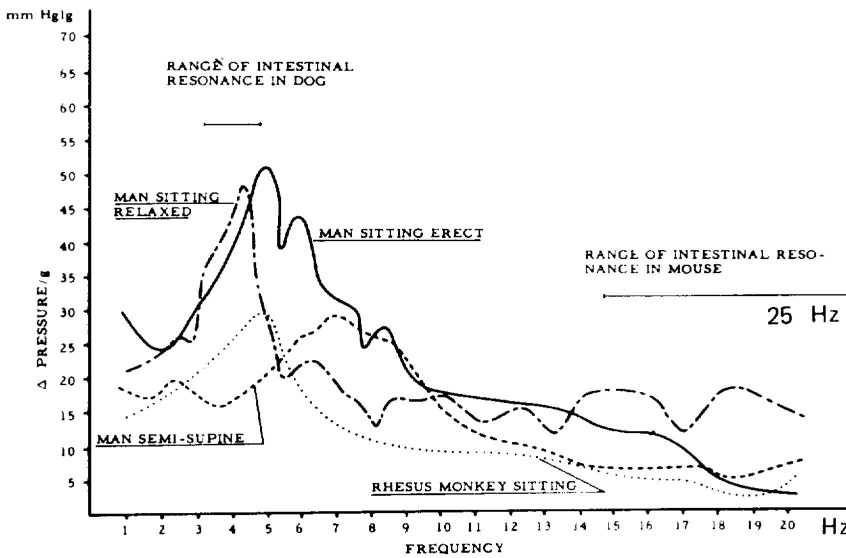


Figure 8-14

Comparison of Intestinal Pressure Change During Sinusoidal Vibration in Man at Different Postures and in Rhesus Monkeys (Anesthetized)

(After Coermann[27])

with increasing frequency. Relative maxima of shoulder and head amplitudes occur at 2 and 3 Hz respectively. The sitting subject exhibits amplification of the hip (1.5 Hz) and head (2 Hz) amplitudes. All critical resonant frequencies appear to be between 1 and 3 Hz. Investigation of experimental results of the type of Figure 8-10 in connection with phase measurements shows that the transverse vibration patterns of the body can be described as standing waves, i.e., as a rough approximation one can compare the body with a rod in which transverse flexural waves have been excited. One has, therefore, in agreement with the experimental results, nodal points on the body which become closer to the feet as the frequency increases since the phase shift between all body parts and the table increases continuously with increasing frequency. At the first characteristic frequency at 1.5 Hz, the head of the standing subject is observed to have a 180° phase shift compared with the table; between 2 and 3 Hz this phase shift becomes 360° (40).

There are longitudinal head motions excited by the transverse vibration in addition to the transverse head motions shown in Figure 8-14. The head performs nodding motion due to the anatomy of the upper vertebrae and the location of the head's center of gravity. Above 5 Hz the head motion for the sitting and standing subjects is predominantly vertical of the order of 10 to 30 percent of the horizontal table motion.

Many kinematic processes, physical loadings, and gross destructive anatomical effects can be studied on dummies which approximate a human being in size, form, mobility, total weight, and weight distribution in body segments (27). Several such dummies are commercially available. They have been used extensively in aviation and automotive crash research and in other studies to precede work with human subjects and to study protective seats and harnesses. Such dummies attempt to match the "resiliency" of human flesh by some kind of padding, but they are crude simulations at best and the dynamic mechanical properties are, if at all, only reasonably matched in a very narrow low frequency range (27). This and the passiveness of such dummies must be kept in mind as important mechanical differences between them and living subjects.

Vibrations Transmitted to the Hand

In connection with studies on the use of vibrating hand tools, several measurements have been made of vibration transmission from hand to arm and body (2, 6, 39). The impedance measured on a hand grip for a specific condition representative of hand tool use is presented in Figure 8-15.

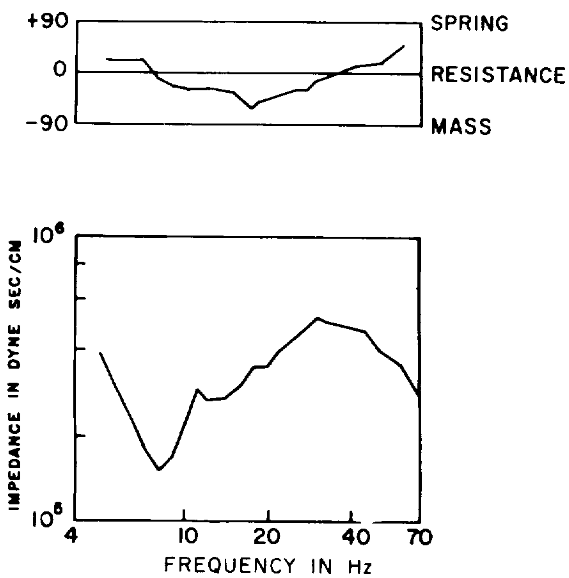


Figure 8-15

Impedance and Phase Angle of Arm Measured at a Vibrating Hand Grip

Elbow flexion 20° to 25°, static pressure on grip 22 lbs. Measurements on one subject.

(After Goldman and von Gierke[73], adapted from Dieckmann[39])

The impedance has one maximum in the range below 5 Hz probably determined by the natural frequencies for transverse excitation of the human body between 1 and 3 Hz. A second strong maximum appears between 30 and 40 Hz; the effective mass of the hand (approximately 2.2 lbs. 1 kg.) is here in resonance with the elasticity of the soft parts on the inside of the hand. This elasticity between force and hand has been estimated at 2.10^{-8} cm/dyne. With a practical hand tool, which operates between 40 and 50 Hz, it has been found that the vibration amplitude decreases from the palm to the back of the hand by 35 to 65 percent. Further losses occur between the hand and the elbow and the elbow and the shoulder. Figure 8-8 which shows this decrease of vibration amplitude from the hand to the head, indicates that the strongest attenuation occurs in the shoulder joint.

Thresholds of sensitivity to vibrating tools vary with age, experience, and simultaneous exposure to noise (172).

Skull Vibrations

The vibration pattern of the skull agrees approximately with the pattern of a spherical elastic shell (7, 57). The nodal lines observed suggest that the fundamental frequency lies between 300 and 400 Hz with resonances for the higher modes around 600 and 900 Hz. The frequency ratio between the modes is approximately 1.7 while the theoretical ratio for a sphere is 1.5. From the observed resonances, the elasticity of skull bone can be calculated. The value obtained for Young's modulus (1.4×10^{10} dynes/cm^2) agrees fairly well with static test results on dry skull preparations. (See also Sound and Noise, (No. 9). Vibrations of the lower jaw with respect to the skull can be explained by a simple mass-spring system, which has a resonance, relative to the skull, between 100 and 200 Hz (35).

Transfer Functions and Power Spectra of Random Vibrations

Recent studies have attempted to quantitate responses to random vibration from power-frequency encountered in ground vehicle simulators (88, 174). Random vibrations best describe the environment in most transportation systems. Power-spectral histories and other techniques such as time histories, peak distribution, and probability records describe the vibratory input to the subject but often fail to quantitate the response especially where angular mode such as pitch and roll are also present. Transfer functions relating "average absorbed power" to onset of fatigue have received preliminary study (140, 142). Since absorbed power is a time-sensitive scalar quantity it is hoped that this parameter may be summed in complex multidegree of freedom environments and symptoms related to this value.

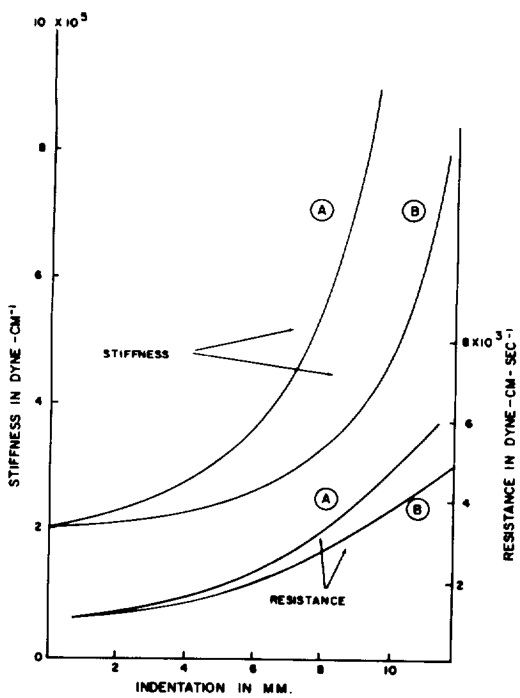
The essential premise controlling the use of the transfer function is that the system be linear. Therefore, application of the transfer function to human dynamics requires the establishment that man behave as a linear system within the bounds of interest. The body cannot always be treated as a linear, passive mechanical item. Linearity is an idealization which holds only for relatively small amplitudes. Nonlinearity must be kept in mind if mechanical injury to tissue is considered (73). There is actually considerable non-linearity of response well below amplitudes required for the production of damage. An example of this is given in Figure 8-16a. Studies at 0.2, 0.35, and 0.5 g indicate not only that non-linearities exist between intensity and impedance, but that the non-linear response is most prominent at resonance frequencies (48). Animal data up to 3 g's have corroborated these findings (24, 103, 185). Another variable controlling impedance and resonance patterns is the nature of the absorbing medium between shaker and subject (48). A technique should really be developed by which the impedance of the padding may be subtracted from the total impedance to yield that of the subject alone, principally in the same manner by which the impedance of the mass of the support is now subtracted (179). The adjusted impedance of the subject may then be compared to that of the impedance of the subject without padding, and consequently a true measure of the force-transmitting characteristics of the padded support may be obtained. Distortions also arise from the effects of the mass of the accelerometer (Figure 8-16b).

Studies have recently been performed in an attempt to define the range of linearity of the human response to $\pm G_z$ vibration for subsequent determination of transfer functions (144). The following discussion is taken directly from these studies.

To gather response data concerning random vibration, experiments were conducted using a uniform spectrum, white-noise vibration filtered through a 2-Hz band-width filter at center frequencies of 3, 5, 7, 10, 13, 15, 20, 25,

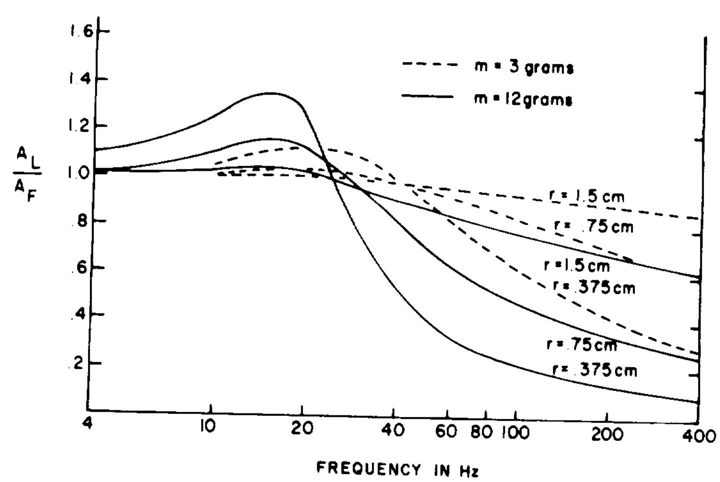
Figure 8-16

Measurement Distortion and Non-Linearity of Tissue Response to Vibration



a. Effect of Loading Distortion of Body Surface on Surface Impedance of Soft Tissue for Two Experimental Human Subjects A and B

(After Goldman and von Gierke[73], adapted from Franke[56])



b. Amplitude Distortion Due to Size and Weight of Accelerometer Attached to Body Surface Over Soft Tissue of Human Subject Exposed to Vibration

This graph gives the ratio, $\frac{A_L}{A_F}$, of the response of a loaded accelerometer of mass m and radius r of contact surface area for several values of m and r.

(After Goldman and von Gierke[73])

and 30 Hz. The tolerance condition was a combination of vibration severity where pain, loss of physical stability, or advanced stages of blurred vision were considered unacceptable. When tolerance was reached, the subject actuated a buzzer which began the rms data collection procedure. Each subject was held at the tolerance level for 20-60 sec. The time interval was dependent upon the stability of rms data. In order to examine more carefully human response to random vibration of greater frequency content, a third experiment was conducted using 10 subjects exposed to random motions filtered with a 10 Hz band width filter. These data established the upper boundary of human response in accordance with the experimental control described for tolerance testing. To validate the hypothesis that whole body response is linear below this level, tests were performed at seven different acceleration levels to very low intensity. Regression analysis (Figure 8-17a) indicated strong linearity throughout the frequency spectrum.

To evaluate the variability of human response with changes in wave form, the same test was conducted using white noise passing through 2 and 10 Hz band-width filters. A comparison of the response at a center frequency of 5 Hz is shown in Figure 8-17b. Although response varied with the three types of input, strong linear characteristics were evident for each input.

The study of linearity was also approached in a manner analogous to that of a constant-rate spring:

$$k = \sqrt{(F/_D)^2 - (\delta\omega)^2} \qquad (2)$$

Where D = Deformation - (deflection)

F = Force

k = Spring constant

δ = Damping

ω = $2\pi f$

For head acceleration responding to body displacement or deflection, D, (see Figure 8-18a):

$$D = \frac{(A_{in} - A_H)\ 386}{4\pi^2 f^2} \qquad (3)$$

Where A_H = Head acceleration

A_I = Input acceleration

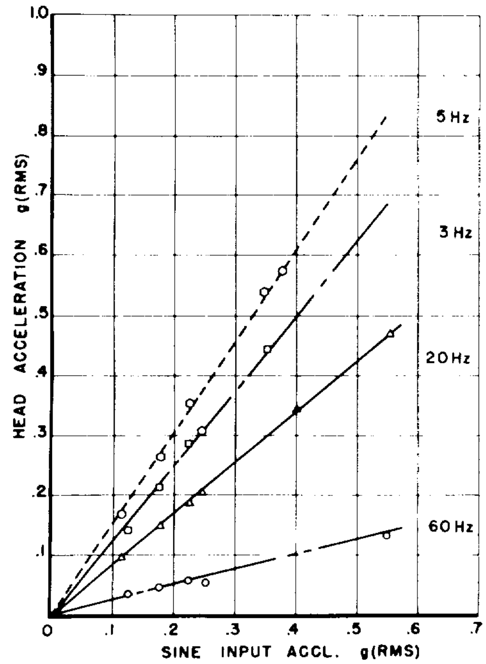
f = Frequency, Hz.

When the applied or restoring force is proportional to the spring deformation, the system is considered to be linear. However, if the force magnitude is not proportional to the displacement, or if the damping is not proportional to the velocity, the system is nonlinear. Figure 8-17c describes the use of

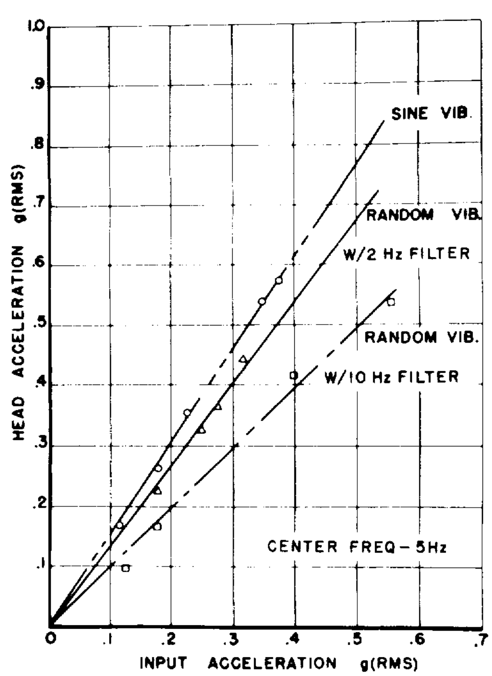
Figure 8-17

Determination of Acceleration Transfer Functions from Human Tolerance Data to Random Vibration in the $\pm G_z$ Axes (Seated)

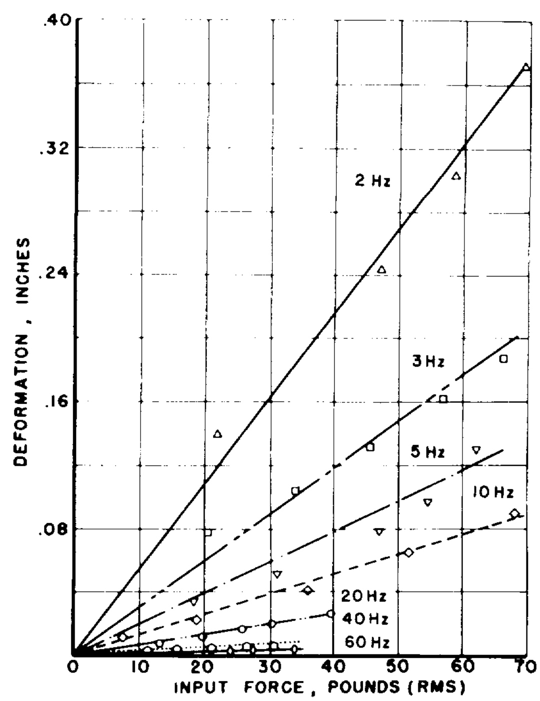
(After Pradko et al[144])



a. Frequency Response Comparison



b. Response of Human Head to Different Types of Vibration in the $\pm G_z$ Axis (Seated)



c. Human Deflection Characteristics in the $\pm G_z$ Axis (Seated)

Equation (3) again verifying the previous findings that the mechanical response characteristic of man in a seated erect position within the limits of this evaluation may be treated as a linear system.

With the establishment of linearity, the transfer function can be experimentally determined. Transfer functions are expressed as continuous functions, using the Laplace transform. The schematic representation is shown as

$$[\text{Input, } I(s)] \times \begin{bmatrix} \text{Element transfer} \\ \text{function, } G(s) \end{bmatrix} = \text{Output, } O(s)$$

$$G(s) = \frac{\text{Output }(s)}{\text{Input }(s)} = \frac{O(s)}{I(s)} \qquad (4a)$$

where $I(s)$ = Laplace transform of the input

$O(s)$ = Laplace transform of the output

$G(s)$ = Transfer function

The general form of the transfer function $G(s)$ is the ratio of output to input transform,

$$G(s) = \frac{\text{Response function}}{\text{Input function}} = \frac{O(s)}{I(s)} \qquad (4b)$$

A graph of the ratio of the output to the input is a graph of the transfer function. The curve is then mathematically fitted by a ratio of polynomials. The early manual techniques of curve matching were laborious and now have been replaced and simplified by computer methods (50). For the specific case the data used were the means of rooted values. The transmissibility of head acceleration to input acceleration gave a curve similar to the dashed line of Figure 8-5b. From the ratio described in Equation 5a, the complex variable (S) is obtained:

$$G_A(S) = \frac{A_{head}}{A_{input}}(S) \qquad (5a)$$

where $G_A(S)$ = Acceleration transfer function

(S) = Complex variable

This transfer function, under both sinusoidal and random vibration, should be in good agreement with experimental data.

The force transfer function, $G_F(S)$, can be defined as

$$G_F(S) = \frac{F_{input}}{A_{head}}(S) \qquad (5b)$$

The $G_F(S)$ can be determined from characteristic curves of F/A_{input} and F/A_{output} shown in Figure 8-18a to c.

By combining Equations 5a and 5b, the analytical transfer function can be obtained. There is close agreement between the statistical impedance data collected during these experiments (similar to dash dot line of Figure 8-5a) and the response calculated from the analytical transfer function. It is thus concluded that human response to sinusoidal and random vibration displays linear characteristics in the range where equilibrium or physical self-control is maintainable; transmissibility ratios of force and motion are sufficiently stable to be used for determining human transfer functions in the 1-60 Hz frequency spectrum; and transfer function statements of motion and force accurately describe human response to sinusoidal and random vibrations.

Transfer functions allow analytical solutions for the dynamic response of the human body, but the transfer functions do not give any apparent way to determine the severity of the vibration. A parameter that will relate the vibration to the subjective response is required. Extensive testing has shown

Figure 8-18

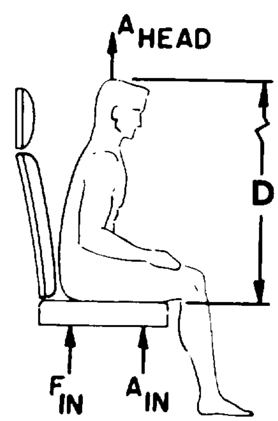
Force to Input and Output Acceleration Ratios Used in Calculation of Force Transfer Functions

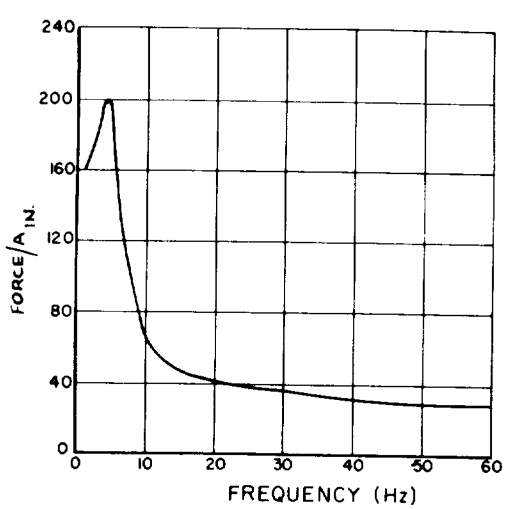
(After Pradko et al[144])

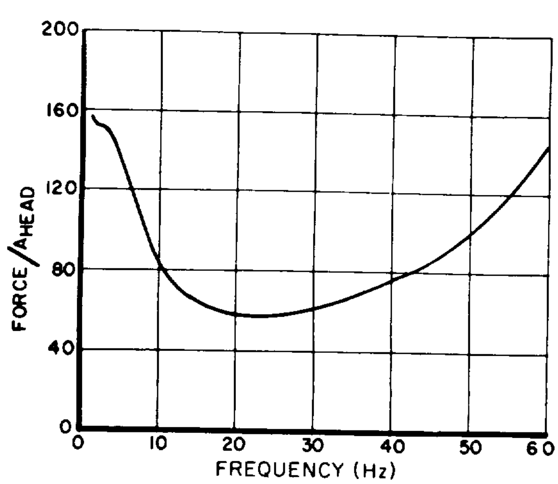
a. (right) Diagram of Force Accelerations and Deformation, D

b. (bottom left) Force Input Acceleration Characteristics

c. (bottom right) Force Ouptut Characteristics for Head







that the rate of flow of energy becomes the parameter that characterizes the interaction of the vibrating human and the environment. The energy flow takes place as a result of the complex damped elastic properties of the anatom· This energy flow has been designated as average "absorbed power" (105, 143).

These are two distinct concepts employed to obtain the analytical solution for a vibration environment: the transfer function and the absorbed power. The utility of the transfer function is manifested in the assessment of human response for skewed or oblique orientations (141). On the other hand, the absorbed power concept is a self-contained procedure that correlates with the nonlinear subjective response to vibration intensity (143).

The transfer function describes the mechanical response characteristics analytically as effective mass and inertial. These functions provide the means of conducting vibration analysis mathematically without using human test subjects in laboratory experimentation. The transfer functions were developec for a normal seated position without armrests or backrests. Consequently, when attempting to assess these or other specific features of seating arrangements, one must resort to direct measurement of absorbed power. It was noted that under linear vibration conditions when seat belts were used, absorbed power was not appreciably affected. When man is seated, the vibration input to the feet becomes significant when the frequency is above 10 Hz. This is especially true when the man is seated on a cushioning device. In this case the input to the feet should be included in the analysis.

Absorbed power has a physical significance and interpretation. Consequently, it is possible to measure the variation of this parameter for different people and different seating arrangements. A muscular person generally has, for the same body weight, a lower absorbed power for the same vibration than a more obese person. On the other hand, if a rigid mass were used in place of a human test subject, the rate of flow of energy would be zero because of its rigid, inelastic properties. A contoured seat generally has a larger contact area than one that is not contoured. This larger area will reduce body movement, owing to its elastic properties, and thus generally produce a lower absorbed power. Under very severe conditions where the man moves relative to the seat, the assumption of linear equations is no longer valid; consequently, transfer functions and absorbed power cannot be used under these conditions. Under normal vibration conditions, using absorbed power as a criterion, one can modify the input or a seating arrangement and measure directly the effect upon comfort. This versatiliby of absorbed power is not realized in other known methods of determining human discomfort due to vibration. If one is using sinusoidal boundary curves to assess the effects of various seating arrangements and positions, for the same vibration input, the curves are not helpful. Sinusoidal boundary curves are a function of the vibration input and are not sensitive to position and seating arrangement.

Because of the importance of this approach, the following discussion is taken directly from Reference (105). In the time domain, absorbed power can be written for an infinite time or a finite averaging time. For an infinite averaging time it is

$$\text{Average absorbed power} = \lim_{T \to \infty} \frac{1}{T} \int_0^T F(t)\, V(t)\, dt \qquad (6)$$

where $F(t)$ = Input force

$V(t)$ = Input velocity

For a finite averaging time, it can be written in the form of a differential equation as follows:

$$\frac{d^2 P_{av}(t)}{dt^2 W_n^2} + \frac{dP_{av}(t)}{dt}\left(\frac{2\delta}{W_n}\right) + P_{av}(t) = KF(t)\, V(t) \qquad (7)$$

where $P_{av}(t)$ = Finite average absorbed power

δ = Damping factor

W_n = Lowest frequency to be averaged, rad/sec

$F(t)$ = Input force

$V(t)$ = Input velocity

K = Conversion constant

Absorbed power can also be described in the frequency domain. It is computed as the product of the mean squared acceleration A_i^2 rms and the parameter K_i, at each frequency "i". K_i is a function of frequency, but does not vary at any one frequency (143).

$$P_{av} = \sum_{i=0}^{N} K_i A_i^2 \text{ rms} \qquad (8)$$

Since absorbed power is a scalar quantity, it possesses the desirable feature of being directly additive. For multidegree of freedom systems, the individual absorbed power values are readily summed for a single quantitative and qualitative measure of human vibration. From the previous equations it becomes apparent that absorbed power can be determined in both the time domain and the frequency domain. When absorbed power is determined in the time domain, it can be determined by direct measurement of force and acceleration or by obtaining force from the transfer functions. Absorbed power can be determined from the output of a triaxial accelerometer, utilizing the transfer functions to generate the force. (See Reference 105). Filters can be included only if one is interested in determining the contribution of specific frequencies to the absorbed power.

For many purposes it is convenient to describe vibration in terms of its frequency domain characteristics. For deterministic vibrations this is usually done by stating the time-domain equations; for example, Fourier series, single sinusoids, or line-spectra graphs. Random vibration characteristics, however, are commonly described in the time domain by correlation functions and in the frequency domain by power spectral density.

Absorbed power can be calculated for each of these conditions when the K_i in Equation 8 are known at each frequency, or are known as a function of frequency. Transfer functions that relate force to acceleration can be manipulated to give phase angle, force, and power by the following three equations: (143).

$$\sin \phi = \frac{(F_2F_3 - F_1F_4)w}{\sqrt{\left(w^2F_4^2 + F_3^2\right)\left(F_1^2 + w^2F_2^2\right)}} \tag{9}$$

$$\text{Force} = K_0\sqrt{\frac{F_1^2 + w^2F_2^2}{F_3^2 + w^2F_4^2}}\ A_i\,\text{rms} \tag{10}$$

$$\text{Power} = \sum_{i=0}^{N} K_1k_0 \frac{(F_1F_4 - F_2F_3)}{\left(F_3^2 + w^2F_4^2\right)} A_i^2\text{rms} \tag{11}$$

The F quantities that appear in Equations 9-11 are the F that are given with the constant power graphs, Figures 8-38a to d. In the equations, ϕ is the angle between acceleration and force, force is in pounds when $A_i$rms is in feet per square second, and power is in watts when K_1 is equal to 1.356.

The F and numerical constants are derived from experimental data. For vertical vibration they are ($\pm G_z$)

$$F_1 = -0.10245296 \times 10^{-9}w^6 + 0.17583343 \times 10^{-5}w^4$$
$$-0.44600722 \times 10^{-2}w^2 + 1$$

$$F_2 = 0.12881887 \times 10^{-7}w^4 - 0.93394367 \times 10^{-4}w^2$$
$$+ 0.10543059$$

$$F_3 = -0.45416156 \times 10^{-9}w^6 + 0.37667129 \times 10^{-5}w^4$$
$$-0.56104406 \times 10^{-2}w^2 + 1$$

$$F_4 = -0.21179193 \times 10^{-11}w^6 + 0.5172811 \times 10^{-7}w^4$$
$$-0.17946748 \times 10^{-3}w^2 + 0.10543059$$

and

$$W = 2\pi f, \quad K_0 = 4.35373, \quad K_1 = 1.356$$

The F and numerical constants for the feet are

$$F_2 = -0.18706955 \times 10^{-4} w^2 + 0.074036789$$

$$F_3 = 0.33913154 \times 10^{-6} w^4 - 0.23697592 \times 10^{-2} w^2 + 1$$

$$F_4 = 0.17013499 \times 10^{-8} w^4 - 0.39439090 \times 10^{-4} w^2 + 0.074036789$$

and

$$W = 2\pi f, \quad K_0 = 1.182, \quad K_1 = 1.356$$

The above analysis assumes that the vibration input is the same for both feet. Where this is not the case, K_0 must be divided by 2 and the transfer function used for each individual foot.

The F and numerical constants for the fore and aft motion ($\pm G_x$) are:

$$F_1 = 1$$

$$F_2 = 0.219106$$

$$F_3 = -0.0185309w^2 + 1$$

$$F_4 = -0.000618934w^2 + 0.219106$$

and

$$W = 2\pi f, \quad K_0 = 4.3532 \quad K_1 = 1.356$$

The F and numerical constants derived for the side to side motion ($\pm G_y$) are:

$$F_1 = 0.24052124 \times 10^{-3} w^4 - 0.066974483w^2 + 1$$

$$F_2 = 0.57384538 \times 10^{-5} w^4 - 0.50170413 \times 10^{-2} w^2 + 0.33092592$$

$$F_3 = -0.14979958 \times 10^{-5} w^6 + 0.0010088882w^4 - 0.10108617w^2 + 1$$

$$F_4 = -0.17137490 \times 10^{-7} w^6 + 0.53137351 \times 10^{-4} w^4 - 0.011096507w^2 + 0.33092592$$

and

$$W = 2\pi f, \quad K_0 = 4.353, \quad K_1 = 1.356$$

Inserting these F into Equations 9-11, one can solve for phase angle, force, power, or acceleration for any frequency, sum of frequencies, or power spectral density (PSD). This calculation is best performed on a digital computer. However, tables of constants are available for hand calculation of several different problems relating to comfort threshold. These are seen in Figure 8-38. Examples of these calculations are available (105, 141).

Tissue Impedance (73)

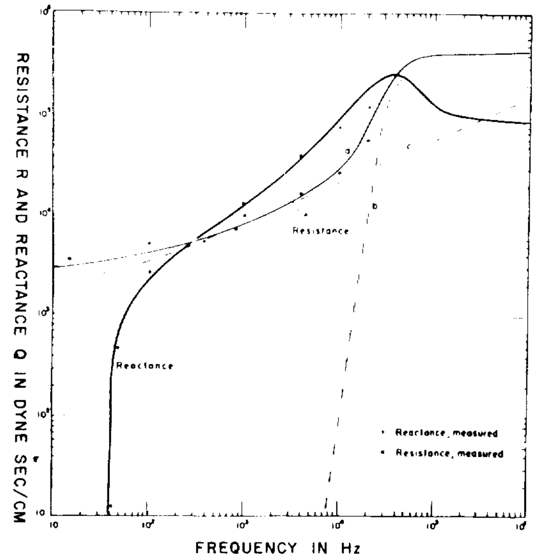
The mechanical properties of body tissue are summarized in Table 7-74 of Acceleration, (No. 7). Whereas bone behaves more or less like a normal solid, soft elastic tissues, such as muscle, tendon, and connective tissue, resemble elastomers having similar Young's moduli, S-shaped stress-strain relations and high stretchabilities. Their properties have been studied in connection with the quasistatic pressure-volume relations of hollow organs such as arteries, the heart, the urinary bladder, etc. (160), but linear properties have always been assumed when dynamic responses were studied. Soft tissue can then be described phenomenologically as a visco-elastic medium and plastic deformation has to be considered only if injury occurs.

Impedance measurements of small areas (1 to 17 cm^2) over soft human tissue have been made with vibrating pistons between 10 Hz and 20 kHz. This impedance starts out at low frequencies as a large elastic reactance. With increasing frequency the reactance decreases, becomes zero at a resonance frequency, and becomes a mass reactance with still further increase in frequency. (See Figure 8-19a.) (64, 71). These data cannot be explained by simple lumped-parameter models, but require a theory of wave propagation in a visco-elastic medium, such as the tissue constitutes for this frequency range (71). The high viscosity of the medium makes possible the use of simplified theoretical assumptions such as a homogeneous isotropic infinite medium and a vibrating sphere instead of a circular piston. The results of such a theory agree well with the measured characteristics. As a consequence it has been possible to assign absolute values to the shear viscosity and the shear elasticity of soft tissue. (See Table 7-74 in Acceleration, No. 7.) The theory, together with the measurements, shows that over the audio-frequency range most of the vibratory energy is propagated through the tissue in the form of transverse shear waves and not in the form of longitudinal compression waves. Such shear waves have a much smaller propagation velocity (and therefore wave length) than sound and a strong dispersion. The velocity is about 20 m/sec. at 200 Hz and increases approximately with the square root of the frequency. This may be compared with the constant sound velocity of about 1500 m/sec. for compressional waves. Some energy is propagated along the body surface in the form of surface waves which have been observed optically. Their velocity is of the same order as the velocity of shear waves.

From the mechanical impedance of the body surface one can calculate the acoustic absorption coefficients. This indicates what percentage of an incident air-borne sound wave is absorbed at the body surface and propagated through the tissue and what percentage is reflected (64). At 100 Hz a small area of the forehead or of soft tissue absorbs only about 2 percent of the incident

Figure 8-19

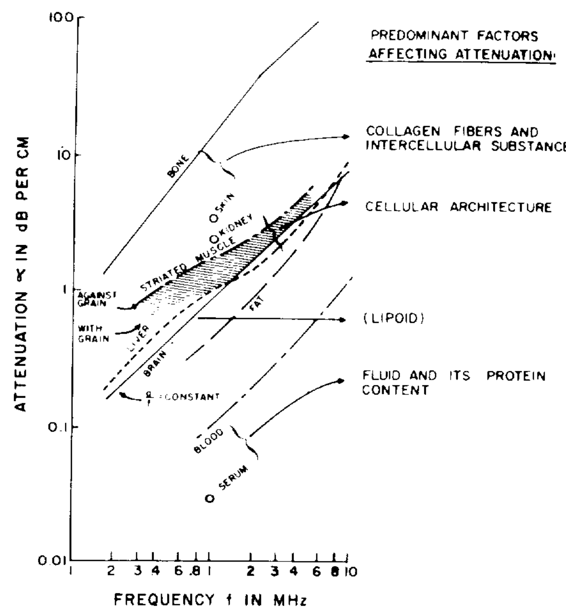
Response of Body Tissues to High Frequency Vibrations



a. Resistance and Reactance of Circular Area 2 cm. Diameter, of Soft Tissue Body Surface

Smooth curves calculated for 2 cm. sphere vibrating in a) visco-elastic medium with properties similar to soft tissue, b) frictionless compressible fluid, c) incompressible fluid.

(After Goldman and von Gierke[73], adapted from von Gierke et al[71])



b. Approximate Values of High Frequency Sound Attenuation in Various Tissues

(After Goldman and von Gierke[73], adapted from Goldman and Hueter[74], and Dussik et al[47])

sound energy. At higher frequencies a still smaller percentage is absorbed. Only the specialized structure of the ear allows a small area of the body surface, the tympanic membrane, to absorb much more energy; for example, at 1000 Hz, 50 to 80 percent. This is achieved by the middle ear transformer action which matches the tissue structures of the inner ear to the characteristic impedance of air. (See Sound and Noise, No. 9, for aural, local, and diffuse body effects.)

Ultrasonic Vibrations (73)

Above several hundred kHz in the ultrasound range, most of the vibratory energy is propagated through tissue in the form of compressional waves and geometrical acoustics offers a good approximation for the description of their path (20, 156). Since the tissue dimensions under consideration are almost always large compared with the wavelength (about 1.5 mm at 1 mHz) the mechanical impedance of the tissue is equal to the characteristic impedance, i.e., sound velocity times density. This value for soft tissue differs only slightly from the characteristic impedance of water (74). The most important factor in this frequency range is the tissue viscosity, which brings about an increasing energy absorption with increasing frequency. At very high frequencies this viscosity also generates shear waves at the boundaries of the medium, at the boundary of the acoustic beams, and in the areas of wave transition to media with somewhat different constants, (e.g., boundary muscle to fat tissue, or soft tissue to bone). These shear waves are attenuated so rapidly that they are of no importance for energy transport but are noticeable as increased local absorption, i.e., heating.

From 500 kHz to 10 mHz the attenuation coefficient describing the decrease of the sound intensity in a plane ultrasound wave, is only in fair agreement with the value one would calculate from the tissue viscosity measured in the audio-frequency range. The tissue deviates in this frequency range from the behavior of a medium with constant viscosity. In Figure 8-19b, attenuation coefficients measured in different types of tissue are summarized (47, 74). On this graph a curve, $\frac{\alpha}{f^2}$ = constant, would be indicative of classical viscous absorption with constant shear viscosity. A smaller slope, or a change in slope, indicates a change in viscosity with frequency (relaxation phenomenon). The graph gives only a few examples and typical functions from a large body of attenuation data available. The absorption of most soft tissues is in the range from 0.5 to 2dB/cm/m Hz. The order of increasing absorption is: brain tissue, liver tissue, striated muscle, smooth muscle, kidney, skin and tendon. Bone has the highest value with approximately 10 dB/cm.

PATHO-PHYSIOLOGICAL RESPONSE TO VIBRATION

The effects of vibration on the physiological functioning of the body may be considered in two categories: a) those changes which are directly attributable to the differential vibratory movement or deformation of particular body structures giving permanent or transient damage, and b) generalized responses to vibration as a non-specific stress. These are more dependent on magnitude and duration and less on frequency than the primary effects.

Permanent Pathological Changes

Permanent pathological changes may follow very severe vibration. Animals can be killed by vibration (73). There is a poorly defined dependence on frequency of the lethal accelerations above 10 G which coincides with the resonant displacement of the visceral organs (116). Post-mortem examination of these animals usually shows lung damage, often heart damage, and occasionally brain injury. The injuries to heart and lungs probably result from the beating of these organs against each other and against the rib cage. The brain injury, which is a superficial hemorrhage, is not yet interpretable in definite terms; it may be due to relative motion of the brain within the skull, to mechanical action involving the blood vessels or sinuses directly or to secondary mechanical effects transmitted through the cerebrospinal fluid (15). Tearing of intra-abdominal membranes is rarely seen. Exposure for several minutes to peak acceleration of about 5 g often produces heart damage as indicated by delayed changes in the electrocardiogram. An increase in body temperature is found on exposure to vibration. Since this occurs also in dead animals it is probably mechanical in origin. Calculations of heat absorption based on body impedance data suggest that appreciable heat can be generated at large amplitudes. Exposure of monkeys to 5g at 10 and 20 Hz for several hours seems to produce some damage to the vestibular system but these findings require confirmation (148).

Rarely has permanent damage been produced in humans by total body vibration. Observations on man have been made in a few instances and indicate that above about 3g, sharp pain in the chest may occur (184, 193). Traces of blood have occasionally been found in the feces after exposure of 6g at 20 to 25 Hz for about 15 minutes suggesting mechanical damage to the intestine or rectum. (See Figure 8-31 - uppermost curve.)

At very severe levels of vibration, chromosomal changes have been produced in microbes and insects along with mutations (3, 100). The significance of these changes to man is not clear.

Chronic injuries may be produced by vibration exposure of long duration at levels which produce no apparent acute effects (73). In practice, such effects are usually found after exposure to repeated blows or to random jolts rather than to sinusoidal motion. When such shocks or blows are applied to the human body at relatively short intervals, the relation of the interval to tissue response times becomes very important. Exposure to such forces frequently occurs in connection with the riding of vehicles. Buffeting in aircraft or in high-speed small craft on the water, and shaking in heavy vehicles on rough surfaces, give rise to irregular jolting motion. Acute injuries from exposure to these situations are rare but complaints of discomfort and chronic minor injury are common. Truck and tractor drivers often have sacroiliac strain. Minor kidney injuries are occasionally suspected and, rarely, traces of blood may appear in the urine. The length of exposure and the details of the ways in which the body is supported play an important role.

Chronic injuries are also produced by localized vibration, such as the pain and numbing of the fingers on exposure to cold which affects many people after several months of using such equipment as pneumatic hammers and drills or hand-held grinders or polishers (58, 71). The heavier, slow-moving devices appear to produce more severe jolting. Little is known of the mechanism of the injury or of the actual forces responsible, although many high frequency components may be present (2). The repeated insults to the tissues directly or through vasoconstrictor responses seem to gradually affect the arterioles, capillaries, and their nerve supply giving a Renaud's syndrome (58). Repeated vasoconstriction in response to high intensity sound may also increase the incidence of this syndrome (97). Injuries resembling these have been produced in the feet of rats exposed to 60 Hz at 8 to 9 g for 10 to 12 hours per day up to about 1000 hours (84). This vascular condition has been treated with ultrasound (156, 191).

Physiological Response

The primary physiological responses to vibration include:

- Subjective sensation of pain and discomfort.
- Neurological function, including the perception of vibration and regulation of posture.
- Cardiovascular changes in blood pressure, electrocardiographic outputs, and blood cell counts.
- Respiratory changes in tidal volumes, rates, and valsalva response.
- Metabolic imbalances.
- Endocrine malfunction.

Subjective Response

The nature of the subjective response varies with the axis of vibration.

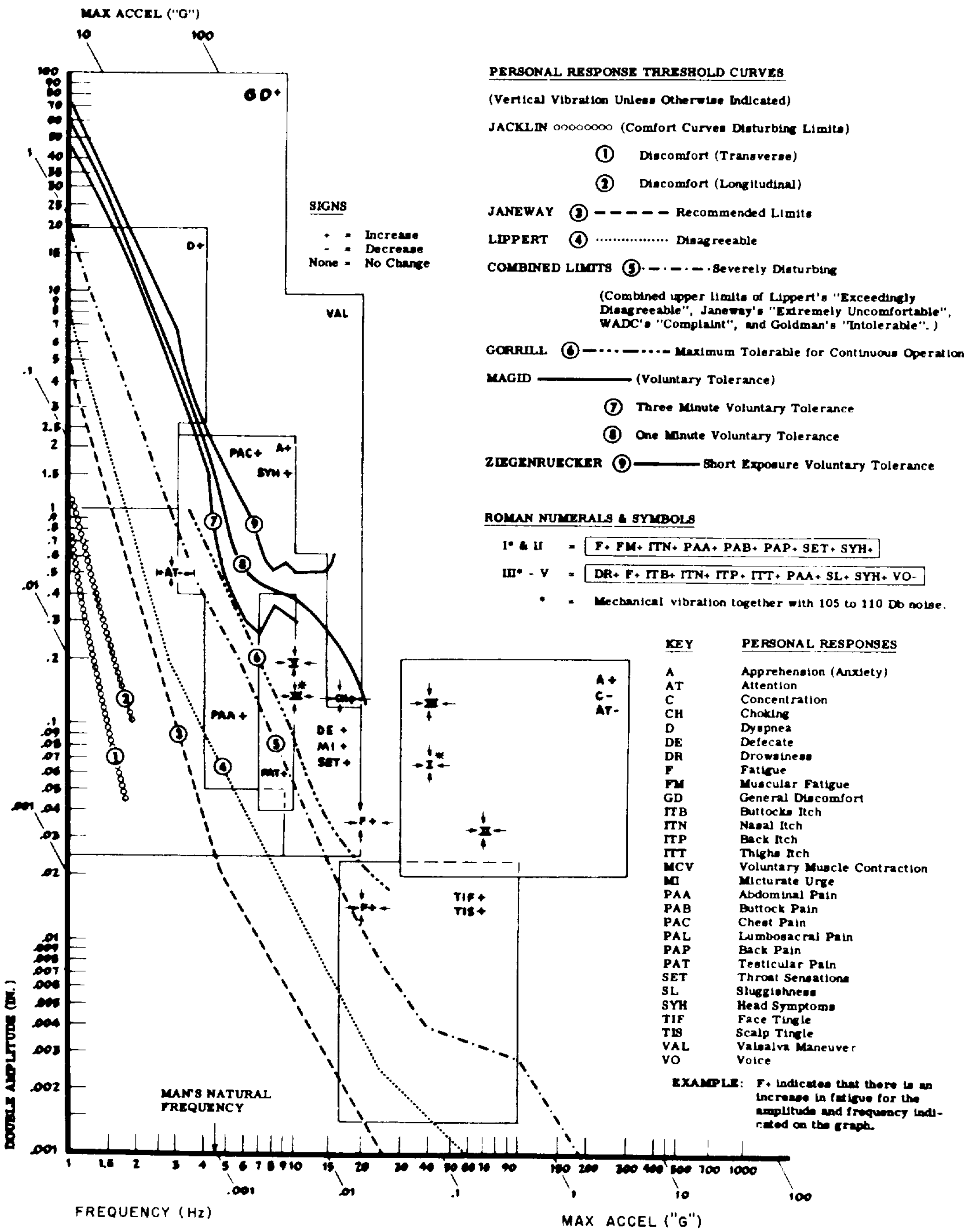
Longitudinal or Vertical Vibration ($\pm G_Z$)

The subjective and symptomatic responses to vertical sinusoidal vibration are reviewed in Figures 8-20 and 8-31 (70, 94, 96, 107, 123, 168, 178, 193). The subjective responses of the subjects range from the perception of feeling through discomfort, apprehension to pain and are the primary sensations correlated with the physical response of the body. Most tolerance criteria are based on these subjective responses. Testing to the point of serious physical or physiological damage to the body is, of course, unacceptable for human subjects. It may be assumed that, in most cases, these levels are well below those that would cause damage to bodily tissue. Table 8-20 indicates the gross variability in previous attempts to set thresholds for tolerance to vibration.

Table 8-21 is a descriptive summary of the symptoms during vertical vibration plotted in Figure 8-22.

Generally there are three apparently simple criteria: the threshold of perception, of unpleasantness, and of tolerance. The latter two are difficult to identify and reproduce, although agreement to within a factor of about 3 has been obtained. In studies lasting up to 20 minutes, no single subjective end point is found for a whole population, although some reactions are more common than others (115, 126, 193). There is a general tendency for those body organs with high mobility to give symptoms at low frequency and those with little mobility to be affected at higher frequencies. Very long exposure to vibration much above the level of perception seems to be irritating and fatiguing.

Subjective responses to vertical sinusoidal vibration while standing have been studied (19, 41). In general, standing subjects tolerate this form of vibration more readily than when sitting, probably because of the damping factor of leg flexion (90). Except for body sway and balance difficulty, physiological effects are similar. Figure 8-23a compares the subjective symptom threshold for standing and sitting subjects with acceleration recorded on the shake table. Figure 8-23b gives the body areas affected. At the higher



This chart summarizes the reported reactions to a wide range of vibrations, plus some objective signs of physiological change, as reported in the literature up to 1960.

Figure 8-20

Subjective Response to Vibration

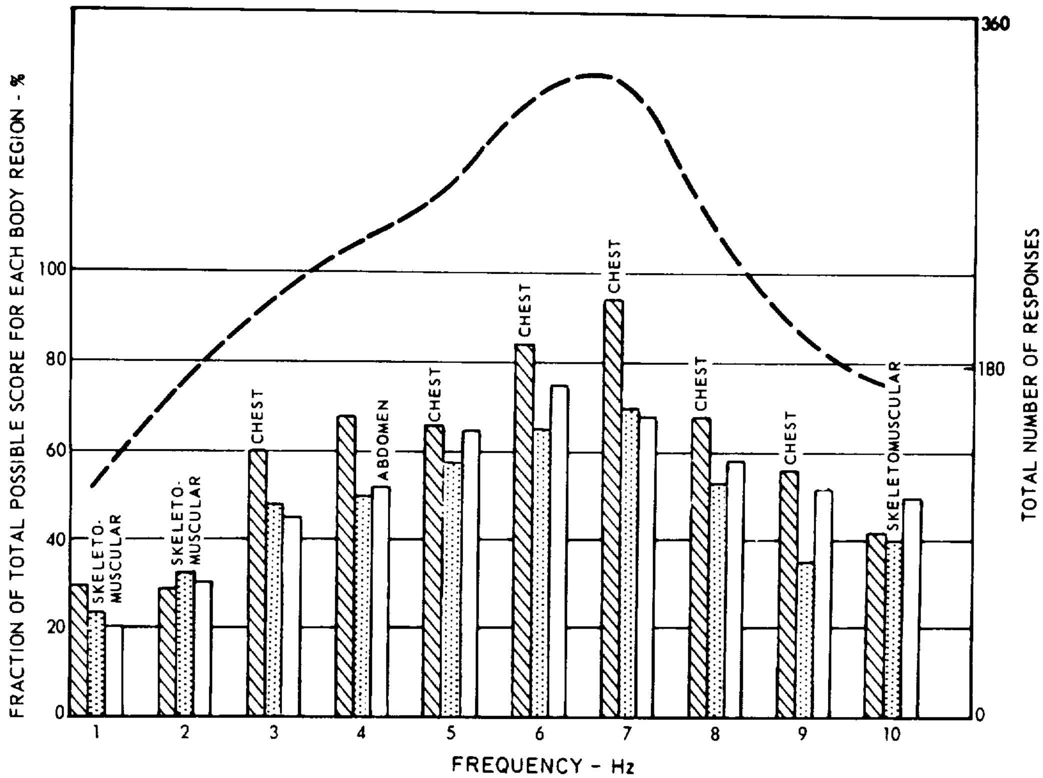
(After Webb[178], adapted from Linder[107])

Table 8-21

Regional Symptomatology During Vertical Vibration

(After Magid et al[117])

HEAD-NECK	
Head Sensations	Vibration or "tight" sensation of facial skin
Pharynx	Pharyngeal tug or "lump in throat"
Jaw	Sensation of vibration
Speech	Lower frequencies secondarily affected due to reactions of thorax and abdomen, high frequencies due to superimposed transmitted vibrations to laryngeal tissues and possibly main stem bronchi
THORAX	
Respiration	Decreased ability to perform physiological respiratory movements of the thoracic cage due to superimposed forces from oscillating platform
Dyspnea	Actual air hunger
Valsalva	Partial or complete closure of glottis resulting in increased intrathoracic and intra-abdominal pressure
Pain	Dull-to-severe pain of the precordium occasionally radiating to the sternum, no other radiations, pain subsiding immediately after cessation of vibration
ABDOMEN	
Voluntary Abdominal Musculature Contraction	Degree of contraction or "bearing down"
Pain	Usually periumbilical with tendency to radiate to right lower quadrant
SKELETAL MUSCULATURE	
Skeletal Musculature	Sensation of "muscle tightness" or possibly increased muscle tone primarily of the lower extremities, dorsum, and neck
Voluntary Muscle Contraction of Extremities	Muscular contraction in an effort to counteract movements of oscillating platform
Lumbosacral Pain	Dull-to-severe pain at midline with bilateral radiation, subsiding immediately after cessation of vibration
PELVIC-PERINEAL COMPLEX	
Micturate (Urge)	Mechanical stimulation of bladder neck and proximal portion of urethra
Defecate (Urge)	Mechanical stimulation of distal portion of sigmoid colon and rectum
GENERAL DISCOMFORT	
	Overall estimation of each frequency ridden



This chart summarizes the subjective responses of ten experienced subjects exposed to vertical sinusoidal vibrations ranging from 35 inches double amplitude at 1 Hz to about 1/4" double amplitude at 6-10 Hz, which produced accelerations of 1.2 ± 0.6 G. They were seated on a hard surfaced aircraft seat and were restrained by a lap belt and shoulder harness. The total number of subjective responses for each frequency was summed; they reached a peak at 6 and 7 Hz, as shown by the upper dashed curve and the right hand vertical scale. The vertical bars show the approximate magnitude of the following groups of symptoms:

Chest (cross-hatched bars) - Respiratory difficulty, pain, and breath holding (Valsalva maneuver).

Skeletomuscular (stippled bars) - Muscle pain, back pain, general discomfort.

Abdomen (open bars) - Contraction, pain.

The words above each set of bars state what symptoms set the limit for voluntary tolerance for that particular frequency.

Figure 8-22

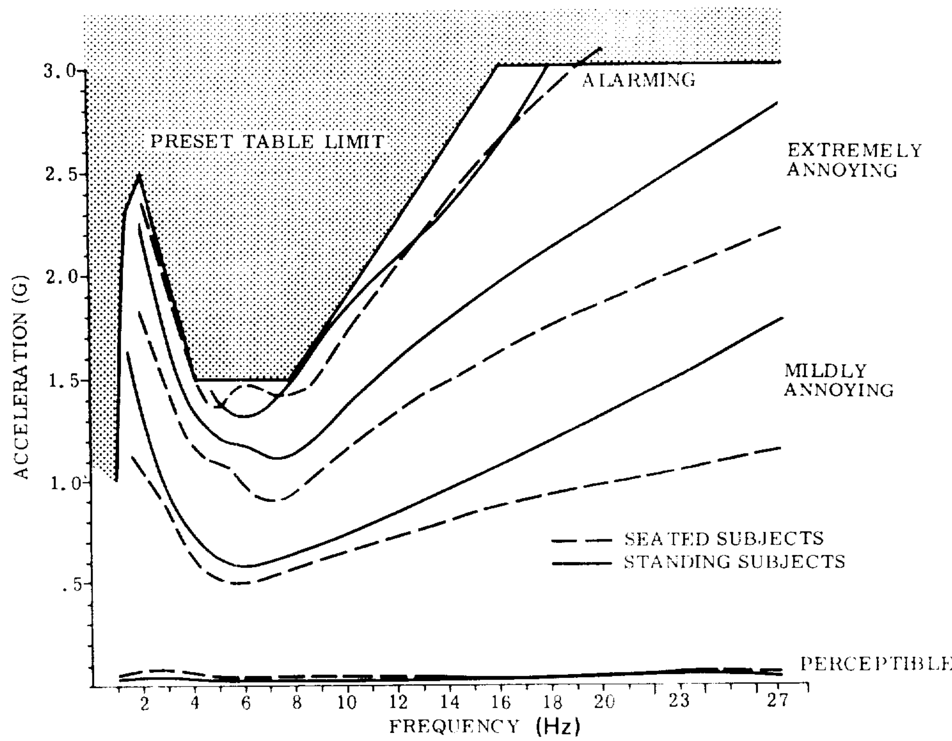
Subjective Responses to Vertical Vibration While Seated

(After Webb[178], adapted from Magid et al[115, 117])

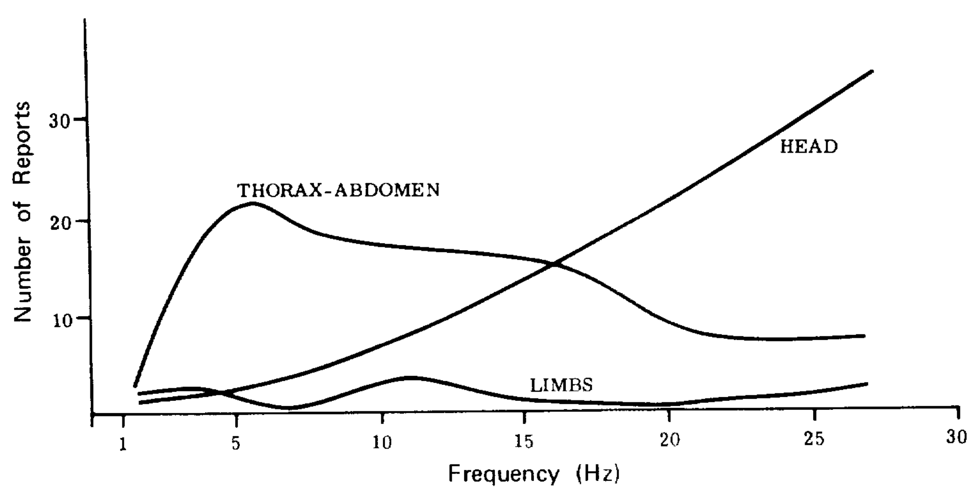
Figure 8-23

Subjective Reactions and Body Areas Affected by Vibration in Seated and Standing Subjects

(After Chaney[19])



a. Subjective Reaction Curves - Seated and Standing Subjects



b. Relationship Between Body Areas Affected by Vibration When Standing frequencies, a higher acceleration is generally accepted on the second encounter with a given frequency.

Semi-Supine and Other Vibrational Axes

There are few data available on symptoms during semi-supine vibration In transverse vibration (in the fore-aft direction) of a seated subject, there is a shearing force applied to the buttocks which must be considered (80). Data are available on symptoms during sinusoidal vibration in the X, Y and Z axes in contoured and adjustable couches proposed for spacecraft use. A detailed review will be presented of this study with the acceleration of gravity vectored through the X-axis. The contoured couch was similar to the project Mercury couch. Restraint was provided by two-inch straps; no helmet was used; the head was unrestrained. The adjustable couch had leg and foot supports, torso and lower extremity support straps, and provided closer coupling than the contoured couch. During exposures in the contoured couch each subject was told to maintain his position in the couch with his head in the headrest as long as possible by whatever bracing or straining maneuvers that were useful. However, if head buffeting against the headrest contour did become intolerable before other symptoms became tolerance limiting, he was to lift his head from the headrest and continue until forced to stop by other symptoms. In the contoured couch the head was restrained. Pertinent angles and g-load nomenclature are noted in Figure 8-24a.

At a preset frequency, the double amplitude of sinusoidal vibration was increased at a rate of 0.75 mm per second until the subject signaled that he had reached his limit of voluntary tolerance. The acceleration level thus reached was considered a subjective tolerance value for that frequency.

Curves describing the averages of these acceleration and velocity-time tolerance levels at each of the frequencies studied in the contoured couch are presented in Figure 8-24b and d. This figure reveals that the Y and Z axis curves are similar throughout their extent, rising from the 2 G level at the low frequencies to the 12 to 14 G level at 20 Hz. The X axis curve is slightly higher than the other two below 8 Hz but rises more slowly as frequency increases above this point, reaching a maximum of only about 50% of the Y and Z axis values at 20 Hz. The X axis curve is slightly higher than the other two below 8 Hz but rises more slowly as frequency increases above this point, reaching a maximum of only about 50% of the Y and Z axis values at 20 Hz.

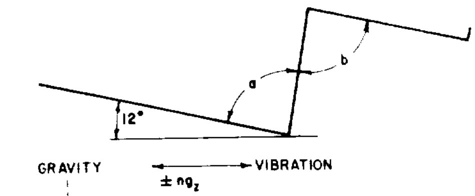
Curves tracing the average values of accelerations and velocity seconds tolerated in the adjustable couch are shown in Figure 8-24 c and e. Although representing fewer data points, they permit axis tolerance above 8 Hz with a slight improvement below this frequency. The X axis curve is considerably higher below 12 Hz but flattens out at the higher frequencies. Except for some drop-off above 15 Hz, Z axis tolerance is quite similar to that attained in the contoured couch.

Table 8-25a summarizes the symptoms occurring during X axis exposures. With both couches, the principal focus of complaints was the thorax. Using the contoured couch, these complaints were present throughout the frequency

Figure 8-24

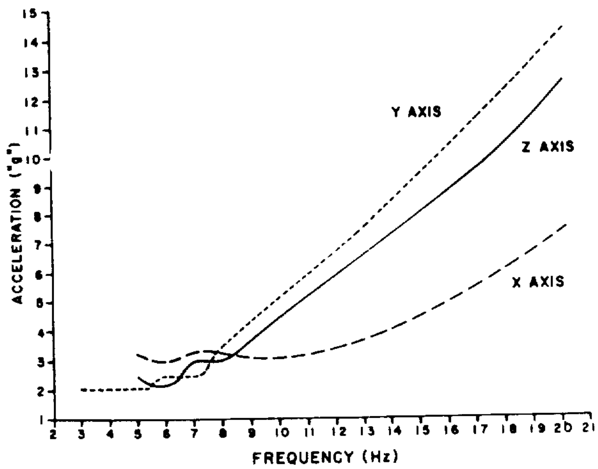
Couch Parameters and Tolerance Levels During Vibration in the X, Y, and Z Axes

(After Temple et al[168] and Weis et al[179])

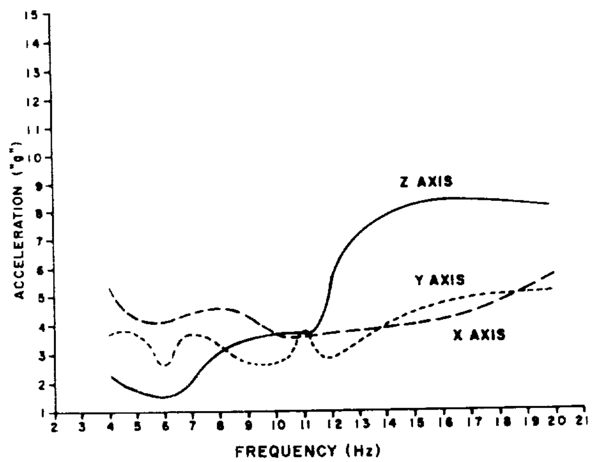


COUCH	ANGLE a	ANGLE b
CONTOURED	102°	100°
ADJUSTABLE	78°	69°-83°

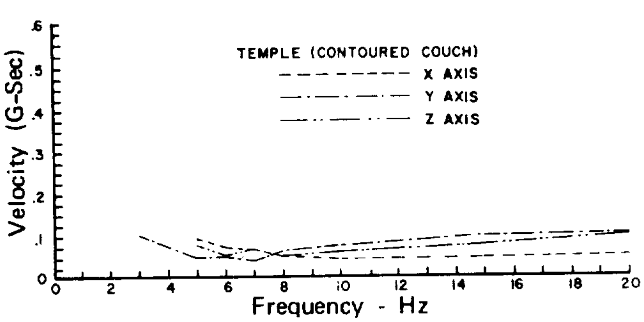
a. General Orientation of the Body (Semisupine) and the Principal Body Angles in Both Couches



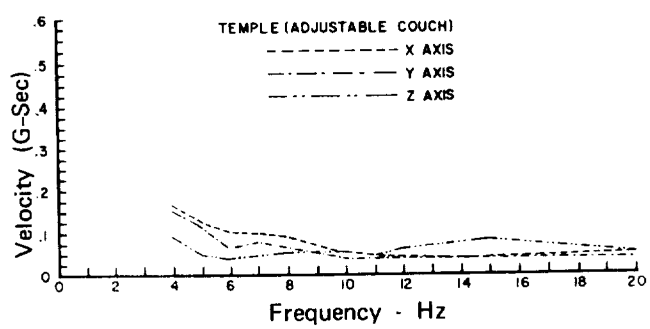
b. Average Levels of Acceleration Tolerance in the Contoured Couch



c. Average Levels of Acceleration Tolerance in the Adjustable Couch



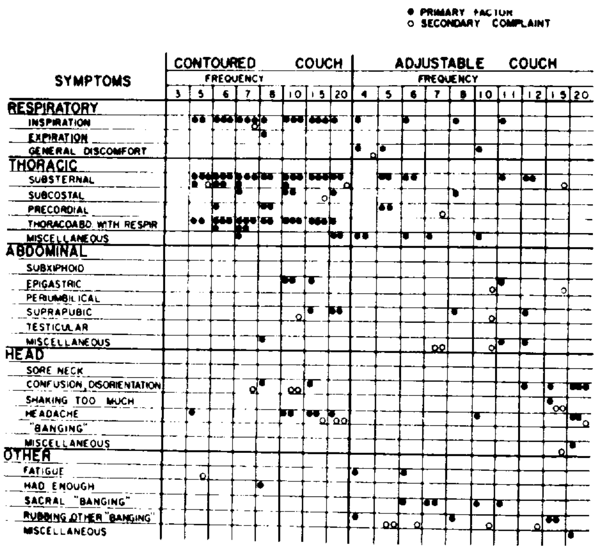
d. Velocity - Time Plots of Tolerance in Contoured Couch



e. Velocity - Time Plots of Tolerance in Adjustable Couch

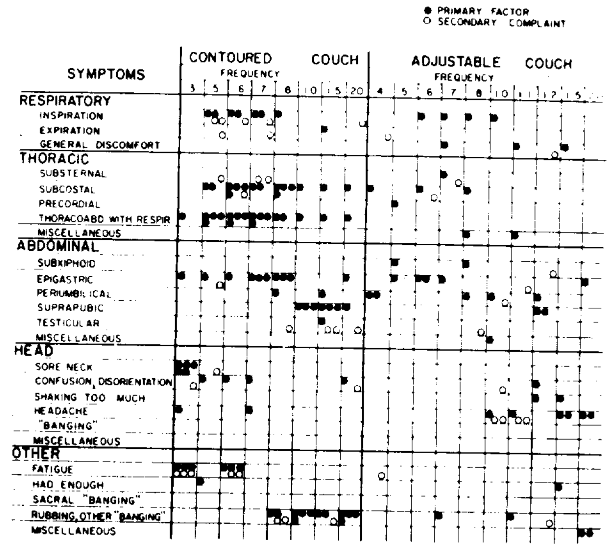
Figure 8-25

Symptoms During Vibration in the X, Y, and Z Axes
(After Temple et al[168])



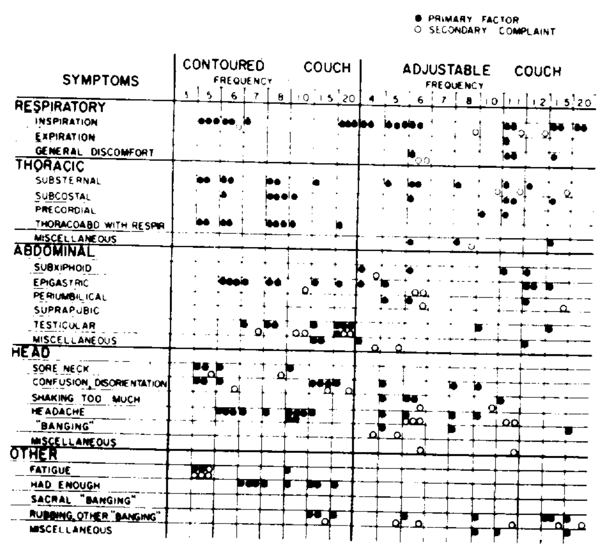
Note: Frequency in Hz

a. Occurrence of Symptoms in the X Axis



Note: Frequency in Hz

b. Occurrence of Symptoms in the Y Axis



Note: Frequency in Hz

c. Occurrence of Symptoms in the Z Axis

range studied but with the adjustable couch they occurred at, and below, 12 Hz. In both systems the majority of the complaints were of pain or a poorly defined "pressure" referred to the substernal area. Considerable difficulty with respiration, particularly inspiration, was encountered in both couches. In the contoured couch this difficulty was almost invariably associated with abdominal or other thoracic symptoms. Complaints referable to the abdomen were relatively more frequent in the adjustable couch, occurring at and below 12 Hz, but with no predominant localization. These complaints were in the nature of a poorly defined "dull discomfort." There were complaints of headache in the contoured couch, occurring across the frequency range, but head complaints were relatively more common in the adjustable couch, almost entirely at the frequencies above 14 Hz. These included headaches and poorly characterized, transitory feelings of "confusion" or "disorientation" which cleared almost immediately upon cessation of the exposure. Sharp, repetitive impact of various body segments, occurring alternately against couch and restraint with each vibratory cycle, caused considerable difficulty in the adjustable couch at frequencies up to 15 Hz. This "banging," as it was described by the subjects, was a particular problem in the sacral area where, apparently, point-loading was occurring. "Banging" was not encountered in the contoured couch in this axis.

Symptoms occurring during Y axis exposures are summarized in Table 8-25b. Again, with the contoured couch, the thorax was a major source of difficulty. In this instance, however, the complaints were primarily of a "pressure" referred subcostally. As in the X axis respiratory difficulties were present, albeit not quite as frequently, and were associated again with abdominal or other thoracic symptoms. Thoracic and respiratory symptoms were relatively less frequent with exposures in this axis in the adjustable couch and, with both couches, the symptoms were largely confined to the frequency range below 10 Hz. Abdominal complaints were more frequent in both couches here than in the X axis. They were present across the frequency range in the contoured couch but were largely limited to the region below 12 Hz in the adjustable couch. The symptoms were, again, poorly described "pressures" or discomforts. In the contoured couch, below 9 Hz, they were largely referred to the epigastrium and, above this level, to the suprapubic area while in the adjustable couch they were principally referred to the epigastrium and periumbilical area. In the frequency range 3 to 6 Hz subjects in the contoured couch frequently complained of significant general fatigue and neck muscle soreness and "spasm." There were some complaints referred to the head, principally headache, in the adjustable couch at and above 10 Hz. Another problem of significance in the contoured couch in this axis was that of frictional rubbing against the couch or restraint straps, giving rise to erythema and abrasions (occasionally blisters) of the hips, thighs, and calves and other areas underlying the restraint straps. This was occasionally associated with reports of "banging" such as were previously encountered in connection with the adjustable couch in the X axis. Both problems became more severe as the frequency increased.

Symptoms occurring during Z axis exposures are seen in Table 8-25c. There were more complaints referable to the head in this axis in both couches than had been previously noted. In the contoured couch these consisted primarily of headache and neck-muscle soreness in the 5 to 10 Hz range; and instances of "confusion" or "disorientation," such as occurred in the X axis, scattered across the frequency range. In the adjustable couch the head symptoms occurred almost completely below 12 Hz and included headache, "confusion" or "disorientation," some head "banging" and general unpleasantness. There was a major difficulty with respiration, particularly inspiration, in the adjustable couch in this axis. This was quite often unassociated with any other complaints, in contrast with the other two axes, and occurred across the frequency range. Complaints of this nature were much less frequent in the contoured couch. Thoracic complaints were similar with both couches but were noted up to a slightly higher frequency in the adjustable couch. Abdominal symptoms in both couches followed patterns very similar to those present for the respective couches in the Y axis. In the contoured couch, below 9 Hz, the complaints were again referred to the epigastrium while above 6 Hz testicular symptoms, described as "fullness," "tapping," or "squeezing," replaced the suprapubic symptoms noted in the Y axis. These testicular symptoms occurred very infrequently in the adjustable couch. A number of subjects in the contoured couch stopped simply because they had just "had enough." This complaint was not frequency-related.

Almost all symptoms, such as thoracic "pressure," abdominal discomfort, or headache, of which subjects complained following exposures in any of the axes were gone within 5 to 10 minutes. The abrasions and occasional blisters were medically treated and healed without complication. Infrequently, a headache or sore neck persisted beyond the immediate post-exposure period for 12 to 24 hours or, more rarely, for longer periods but no serious problems arose.

Further analysis of the contoured couch data directs attention to two factors that influenced the results. The first relates to the complaints of intolerable frictional rubbing (and, less frequently, "banging") of body segments against the couch or restraints which occurred, especially at the higher frequencies, in the Y and, to a lesser extent, the Z axis. Two conditions appear to have been responsible for this problem. One was the variable, occasionally loose, body-to-couch coupling which often resulted in dead space between subject and couch, or in unavoidable slackness in the restraint. The other, arising from the first, was the development during vibration of phase shifts between body segments and the couch due to the mechanical response characteristics of the system.

The second factor pertains to the lack of head restraint. One objective of the contoured couch exposures had been to determine the desirability of raising the head, when its buffeting against the couch became unbearable, in an attempt to prolong the duration of the exposure and increase the level of acceleration reached. It appears, however, that the benefits accruing to this procedure were negated by the resulting fatigue and the precipitation of, or accentuation of, head, neck, and thoracoabdominal symptoms.

In composite vibration, the direction and magnitude of the resultant acceleration are important in determining its subjective acceptability (76). If a subject is exposed to simultaneous vertical and horizontal (fore-and-aft) vibrations of equal frequency and amplitude, a circular motion of the seat may be produced by suitable phasing of the two vibrations. It has been demonstrated that, if the direction of circular motion of the seat is backward-running (i.e., anti-clockwise as viewed from the right), the subject's physical and subjective responses are essentially those characteristic of horizontal excitation; but, if the circular motion is forward-running, the response resembles that to vertical vibration (80).

Threshold of Vibration Sensation

Whole-body accelerations of sufficient intensity can be appreciated as oscillatory at frequencies down to 0.1 Hz, a frequency corresponding with the slowest, noticeable, heaving-movements of a large ship, and possibly lower. The threshold of sensation for linear oscillation in the long axis of the body, as determined by parallel swings, is about 0.005 g at frequencies of 1 Hz and below (177). At such frequencies, the sensation is mediated by the vestibular organs and by somatic receptors in the areas of application of the vibration to the body. The sensation of motion may, of course, be augmented by seeing surrounding objects in relative oscillation. At higher forcing frequencies, where body resonances and phase shifts in the transmission of vibration occur, the sensation of vibration is presumed to be mediated by mechano-receptors throughout the body. The threshold of perception of whole-body vertical vibration in the range 1 to 20 Hz lies between 0.01 and 0.002 g, with the lowest threshold (maximum sensitivity to vibrational acceleration) at 3 to 6 Hz (72). When standing, the sensitivity at low frequencies less than in the seated position is shown in Figure 8-23a.

The threshold of sensitivity of the finger tips to sinusoidal vibration is recorded in Figure 8-26. The difference limens (DL) for rate of intermittent stimuli at the finger tip in comparison with those of the ear are shown in Figure 8-27. The mechanism which allows these skin receptors to distinguish between rates in the vicinity of 300 Hz with less than a 10% error are under study (124). No gross change in sensitivity to vibration appears to be brought on by previous vibration exposure (80).

Even though the pattern of the vibration be quite complex, habituation to vibration occurs, as it does to noise, if the quality of the stimulus is constant. For example, one can quickly cease to notice considerable intensities of noise and vibration on board ship. Low frequency (1 to 2 Hz) steady-state oscillation of moderate intensity can be soporific in man, as exemplified by the practice of baby-rocking and the relaxation afforded by the rocking chair. Random vibration, on the other hand, tends to increase arousal, as does the sudden onset, alteration, or cessation of a particular condition of vibration. Irregularity and intermittency of stimulation oppose habituation. Habituation to sustained vibration is probably a central phenomenon, although some adaptation may occur at the receptor level. Sinusoidal oscillations at frequencies between 0.1 and 1 Hz, or random vibration with a spectral representation in that region, can induce motion sickness. (See Acceleration, No. 7).

The nature of the synchronous electrical activity which can be recorded from the brain during vibration remains an open question (1, 80). There is no published evidence that the human E.E.G. can be driven by low frequency vibration in a manner analogous to photic driving. The likelihood of motion

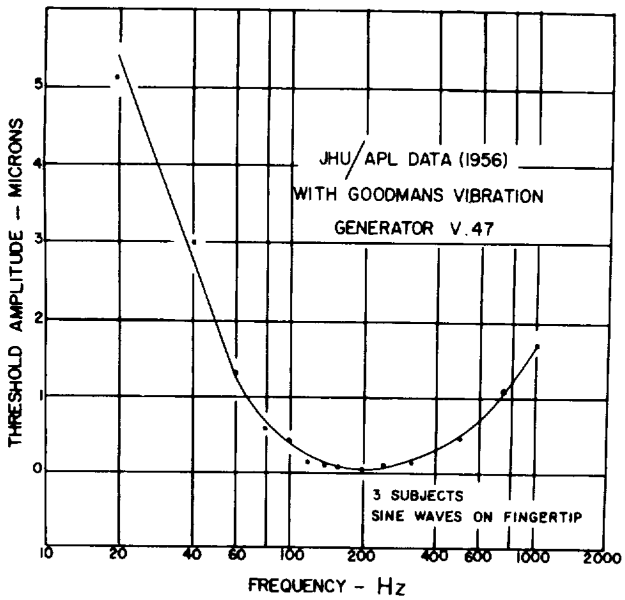


Figure 8-26

Observed Relation Between Threshold Amplitude of Vibration and the Frequency of Sine Waves for the Finger Tip

(After Mowbray and Gebhard[124])

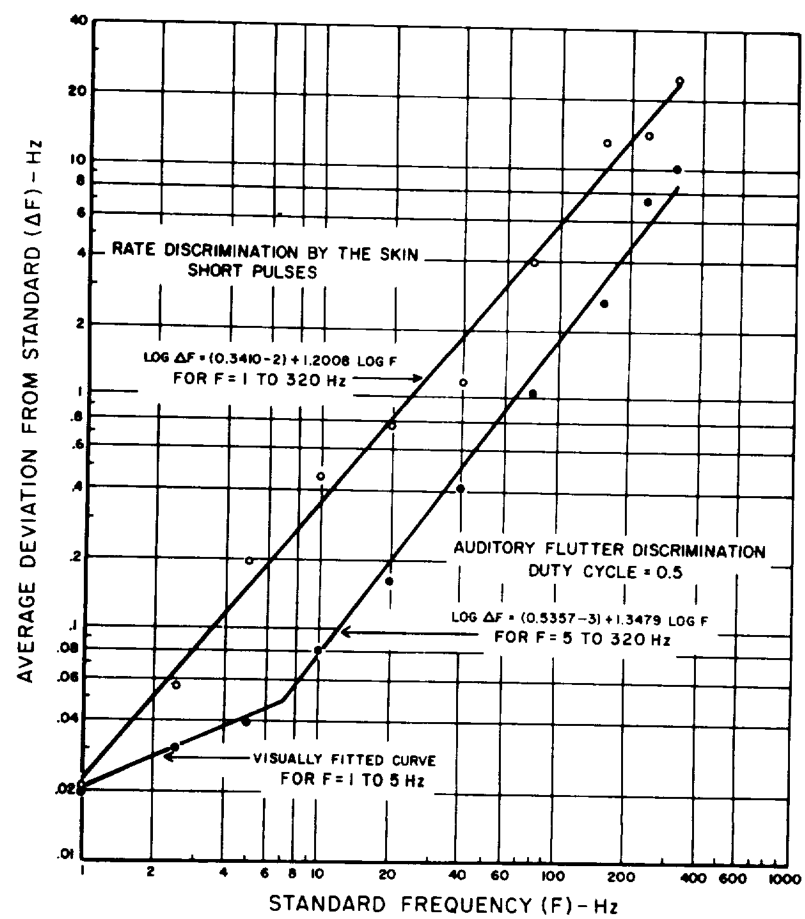


Figure 8-27

Different Limens for Finger Tip Vibration Sensitivity and Acoustic Sensitivity

Upper curve: Relation Between Δf and log f for the tactile data. Lower curve: The same relation for the auditory flutter data.

(After Mowbray and Gebhard[124])

artifacts and the possibility of E.E.G. changes produced by indirect physiological mechanisms, such as hyperventilation, should be borne in mind if abnormal E.E.G. recordings are seen during vibration.

The Cardiovascular System and Blood

In man, measurements of cardiovascular activity during whole-body vibration have generally been restricted to the pulse rate, the blood pressure and the electrocardiogram. The changes in pulse rate, blood pressure, and cardiac output reported in the literature have been varied and non-specific, resembling the responses associated with alarm or moderate exercise (23, 112, 149, 152). The rise in systolic radial arterial pressure during vibration at frequencies above 3 Hz was unaccompanied by a fall in the diastolic pressure (153). Figure 8-28a and b indicate the oxygen consumption and cardiovascular response to $+G_x$ vibration.

At low frequencies of vibration (2 to 3 Hz), beating has been observed between the pulse and vibration frequencies during arterial pressure recordings in the dog (4). A fall in the skin temperature has been noted in the lower limbs during whole body vibration of human subjects. Other changes in peripheral vasomotor activity, mediated by autonomic efferent impulses, have been demonstrated by workers using the galvanic skin reflex as a measure of vibration stress (41). Changes in the formed elements of the blood appear to be related to general stress response (80, 152). (See also Reynaud's phenomenon in section on permanent pathology.)

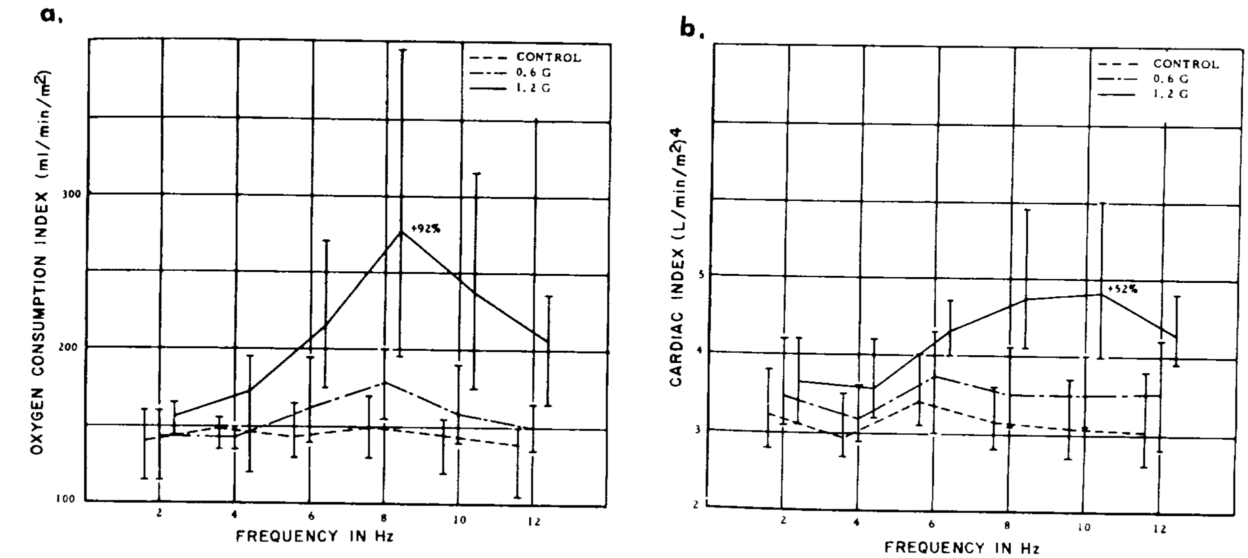
Respiratory Physiology

The increases in oxygen consumption and respiratory quotient have been attributed to a raised metabolic activity due to the muscular effort of maintaining the posture during vibration. This explanation is supported by the fact that the increases in these respiratory indices were found to be greater when the subjects were standing up than when they were seated during low frequency vibration of the same intensity. The differences produced by varying g load and direction of vibration are seen in comparison of graphs in Figures 8-28a and 8-28c. Exposure to altitude above 10,000 feet lowers vibration resistance in animals (121).

The relation of respiratory response to resonance is not clear in that a significant increase only at forcing accelerations exceeding 0.5 g at 9.5 Hz was recorded in one experiment (50, 51), while a fairly linear increase in oxygen consumption with increasing frequency from 6 to 15 Hz, at a fixed displacement-amplitude of 0.132 in. at 0.46 to 2.88 g was recorded in another (60). Increase in oxygen consumption has also been found to be greatest at the lowest frequencies of vibration, at constant acceleration-amplitude, in the range 2 to 7 Hz (46). Some of these responses are seen in Figures 8-28d and 8-29a and b. The changes are more pronounced early in the exposure and appear to be compounded of a passive mechanical effect added to a physiological response to vibration stress. Hyperventilation with hypocapnia, on occasion, may be caused by stress or discomfort; also increased muscular demand for oxygen may be augmented by superimposition

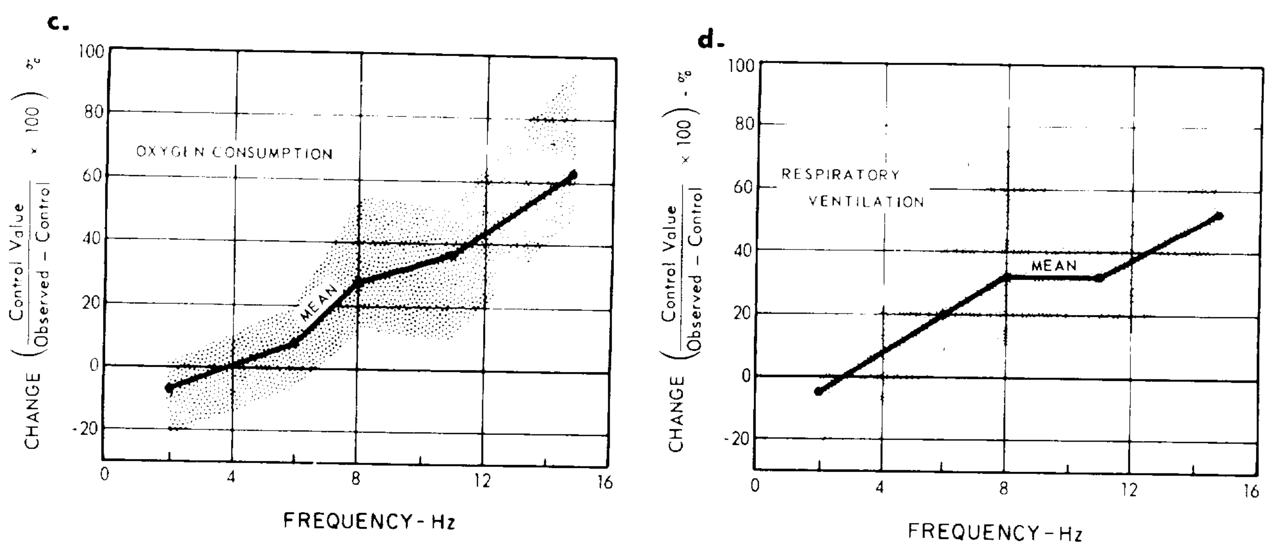
Figure 8-28

Cardiovascular and Respiratory Response to $+G_z$ Vibration



Average oxygen consumption (a) and cardiac index (b) of four human subjects vibrated in the (front to back) direction. The subjects were in the semi-supine position and vibrated for 6 minutes at two vibration intensities (0.6G and 1.2G). (The bars indicate the range of the data).

(After von Gierke[65], from data of Clarke et al[23])

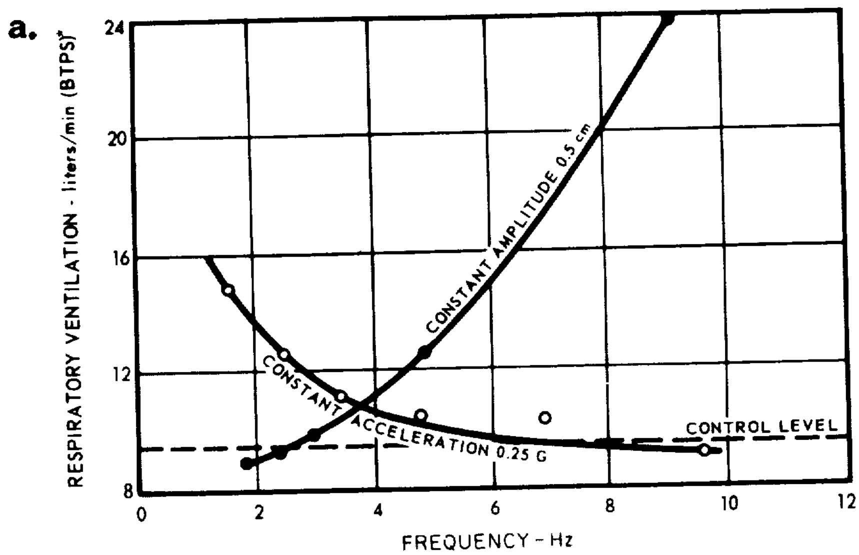


The change in oxygen consumption for four male subjects during vibration is shown in (c) as a percentage change from the control value, with the mean values being connected by a line and the range shown with shading. Similar data are shown in (d), where respiratory ventilation is also shown to increase as a function of frequency, when amplitude is held constant. The subjects were exposed to 20 minutes of G_z vibration at an amplitude of 0.132 inch while seated on a chair and entirely unrestrained.

(After Webb[178], adapted from Gaueman et al[60])

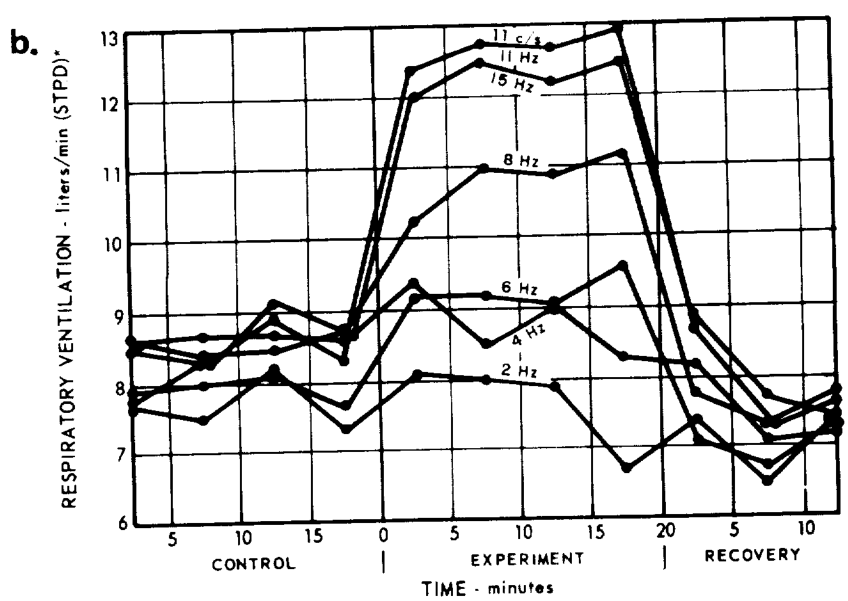
Figure 8-29

Respiratory Ventilation During Longitudinal Vibration While Seated



Average respiratory ventilation rates are shown for 12 men who were vibrated while seated on a hard platform at the amplitudes, rates, and acceleration shown.

(After Webb[178], adapted from Ernsting[50])



Mean values of respiratory ventilation are shown for 5 seated men exposed to a 20-minute period of vibration at 0.125 inch amplitude, at frequencies from 2 to 15 Hz as marked on each curve.

(After Webb[178], adapted from Hoover and Ashe[89]) of oscillations at forcing frequency (89, 192). Labyrinthine factors may be at play during very low frequencies of 1.76 Hz (52). The hypocapnia, occasionally seen, may affect performance (23, 42).

Metabolic Factors

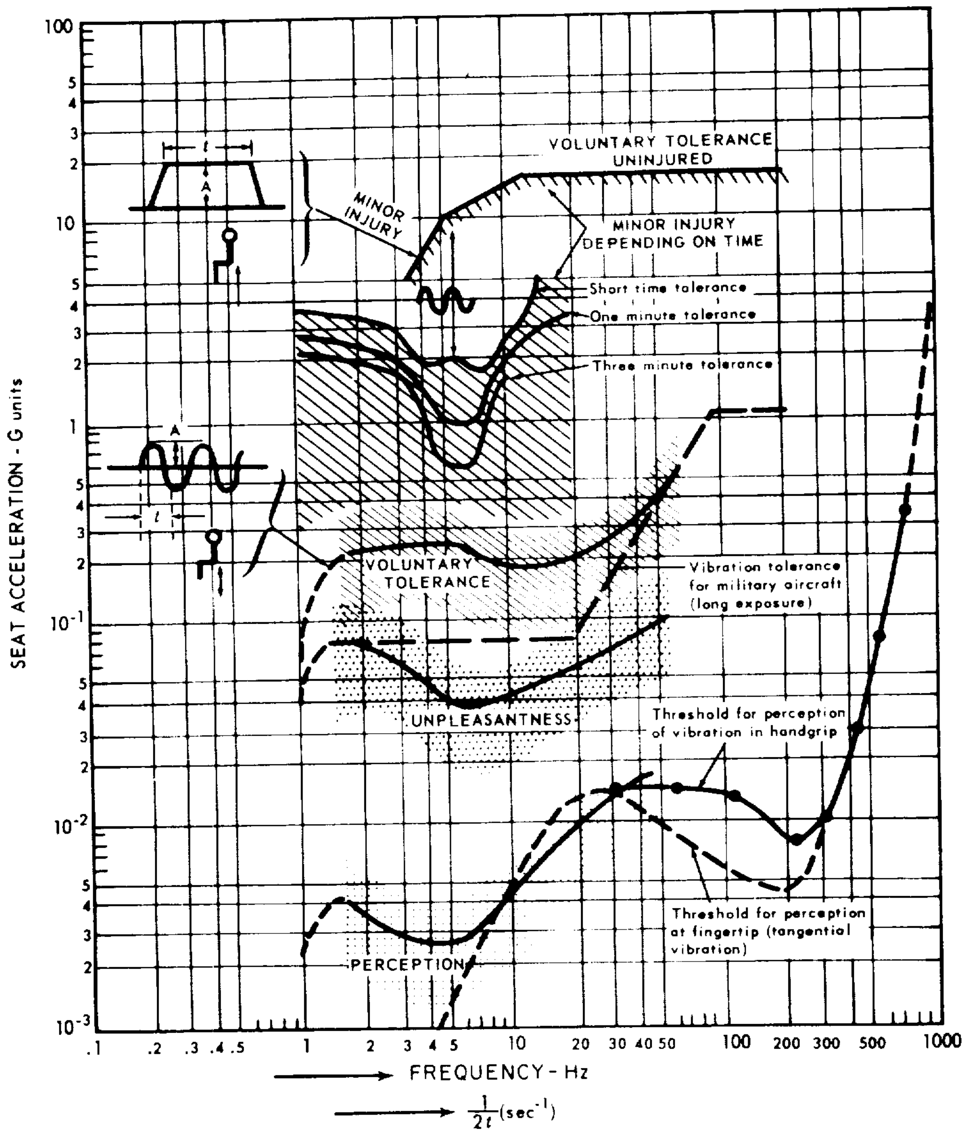
The increase in oxygen consumption and endocrine changes in animals have been attributed to several stress factors in chronic exposure to vibration (80). Loss of body weight can also be found (89). In humans, 9 minutes of vibration at the predicted 3 minute tolerances (118) (see curves in Figure 8-30) for selected frequencies ranging from 1-20 Hz produced statistically significant increase in 17-OHsteroids and 17-ketosteroids which were in the upper reaches of normal. No significant changes in serum PBI were noted (108).

Combinations of thermal and vibratory stress in mice tend to show synergistic effects (122). Hematocrit, hemoglobin and SGOT responses reflected this synergism.

HUMAN TOLERANCE TO VIBRATION

Tolerance criteria for vibration exposure established by various investigators agree only within certain limits since evaluation criteria, positioning and support of the subjects have a marked effect on such limits. Threshold data on longitudinal sinusoidal vibration while seated have been summarized in Figure 8-30. Figures 8-31a and b elaborate on these thresholds with subjective and performance end points for several other vibration modes and conditions. Some past tolerance thresholds may be seen in Figure 8-20. Other reviews of tolerance criteria are available (10). Tolerance thresholds to vibration in the X, Y, and Z axes while sitting in contoured couches or adjustable vibration-absorbing devices in spacecraft liftoff position are found in Figures 8-24b and c. (See below for restraint variables.)

Sources of vibration in land and aircraft are seen in Figure 8-32. The range of vibration levels found in aircraft, trucks, and tractors is indicated in Figure 8-33. Individual points represent flight vibration data obtained in various types of military aircraft. The solid circles, squares, and triangles indicate vibrations at seat levels which were reported as excessive and undesirable in actual service; the open marks indicate conditions accepted as tolerable. The linearized dividing line between tolerable and excessive vibrations is the WADC tolerance criterion shown in Figure 8-30, used as a long-time vibration tolerance criterion in military aviation aircraft. This curve is based on subjective pilot comments with respect to tolerable and intolerable levels in military aircraft (62). Levels below this line are tolerated, in general, for long times (up to 8 hours) without observed detrimental effects on performance or health. For short flight durations (for example in helicopters) vibration levels considerably above this line but not above the voluntary tolerance area, are routinely tolerated.



This illustrates schematically a number of tolerance criteria for vibration. The four shaded zones represent: threshold for perception; the unpleasant area of vibration; the limits of voluntary exposure, unprotected, for 5-20 minutes; and the voluntary tolerance limits for subjects with lap belt and shoulder harness for three minutes, one minute, and less than one minute. Above this, minor injuries occur, depending on time. At the top of the chart is plotted the voluntary tolerance curve for impact, which may be considered to be half-cycle vibration of large magnitude. The conventional way of measuring durations (t) and amplitudes (A) is shown in the small diagrams at the left.

Figure 8-30

Criteria for Vibration Tolerance in Longitudinal Axis While Seated

(After Webb [178], adapted from von Gierke and Hiatt[70])

Figure 8-31

Reactions to Mechanical Vibrations

(After Mohr and von Gierke [123])

a. Summary of Tolerance Limits to Sinusoidal, Whole-Body Vibration (Numbers refer to Table 8-31b. See original source for references.)

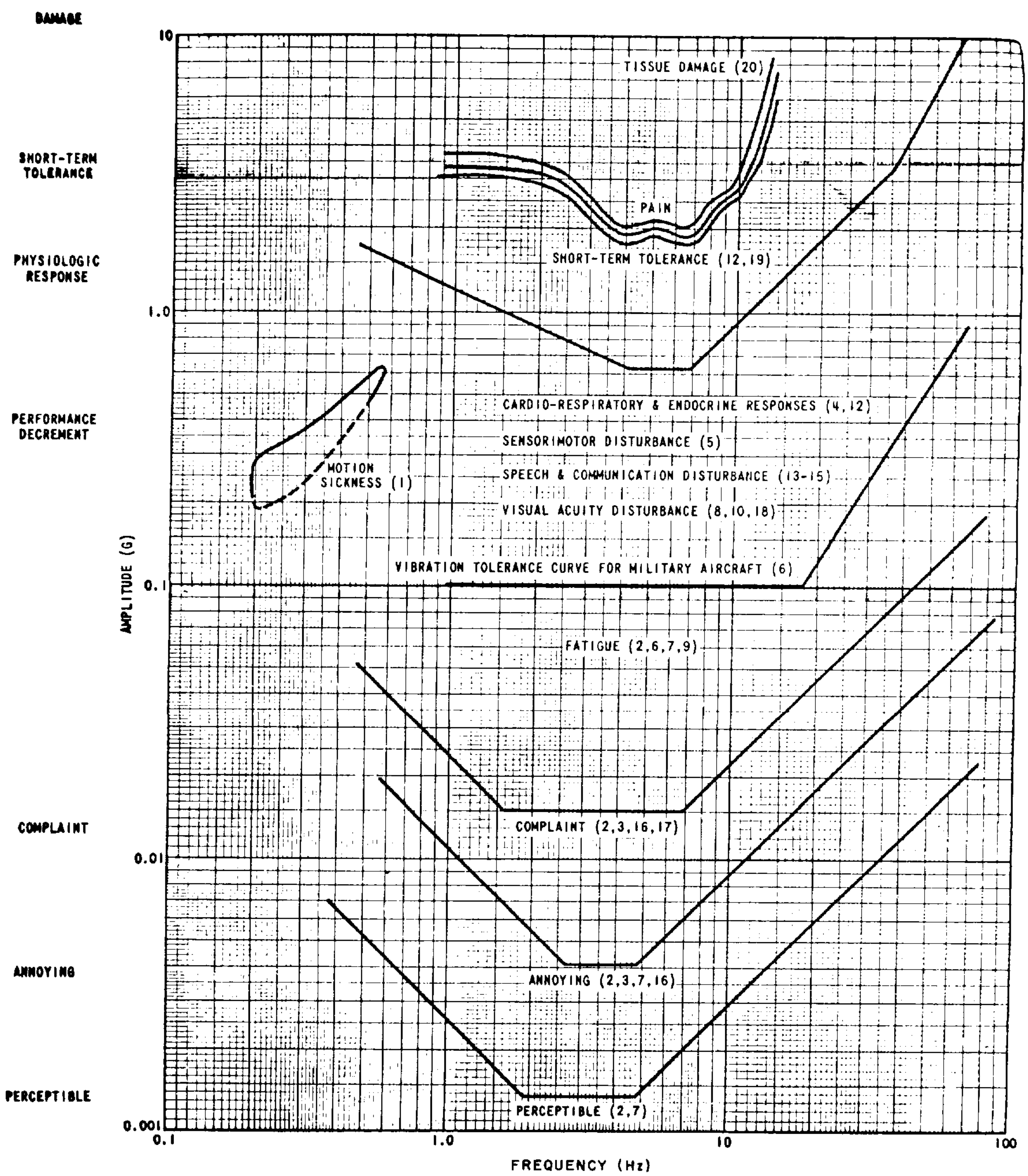


Figure 8-31 (continued)

b. Table of Experimental Conditions for Figure 8-31a

1. Seated subjects exposed for 20 min or less to vertical sinusoidal motion.

2. Standing and recumbent subjects exposed for short durations (5 min or less) to vertical and horizontal sinusoidal motion.

3. Standing, seated, and recumbent subjects exposed for short durations (< 20 min) to vertical sinusoidal vibration.

4. Recumbent subjects exposed for short durations to vertical sinusoidal motion.

5. Seated subjects exposed for 10-min periods to vertical sinusoidal motion.

6. Subjects seated in military aircraft exposed for periods of approx 1 hr to flight-induced vibration, primarily in the vertical direction.

7. Standing, seated, and recumbent subjects exposed for periods of 5-20 min to vertical or horizontal vibration.

8. Seated subjects exposed for short durations to vertical vibration.

9. Standing and seated subjects exposed for periods of 5 min or less to vertical sinusoidal vibration.

10. Seated subjects exposed for periods of approx 1 min to vertical sinusoidal vibration.

11. Standing and seated subjects exposed for short durations to vertical or horizontal sinusoidal motion (summary combination of limits).

12. Seated subjects exposed for periods of 1 min to vertical sinusoidal vibration.

13. Seated subjects exposed for short durations to vertical vibration.

14. Seated subjects exposed for short durations to vertical vibration.

15. Recumbent subjects exposed for short durations to vertical and horizontal vibration.

16. Standing subjects exposed for short durations (< 5 min) to vertical sinusoidal motion.

17. Airline passengers exposed for continuous periods of 100 min principally to vertical vibration.

18. Recumbent subjects exposed for periods of 1-2 min to vertical and horizontal vibration.

19. Recumbent subjects exposed to vertical and horizontal vibration at increasing amplitude up to the maximum voluntary tolerance.

20. Vibration limits (general summary).

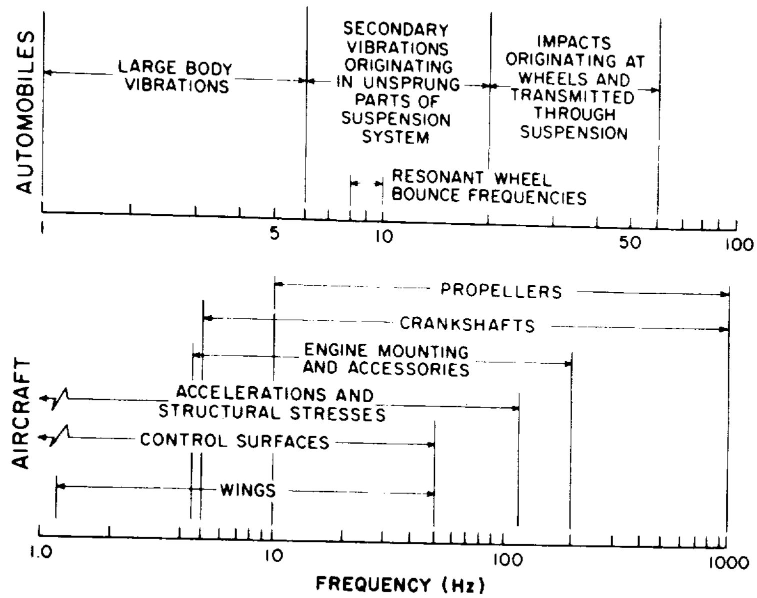


Figure 8-32

Vibration Frequencies Encountered in Aircraft and Automobiles

(After McFarland and Teichner[114])

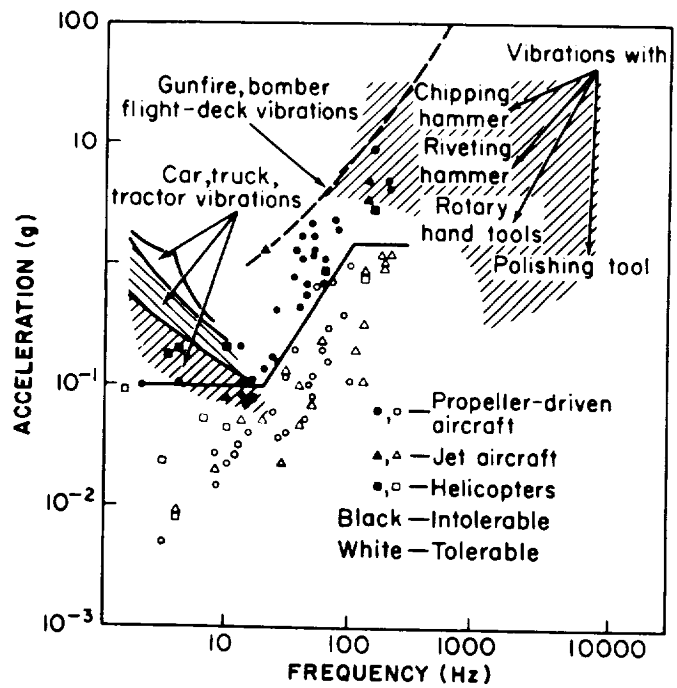


Figure 8-33

Vibration Environment for Various Transport Devices

(After Goldman and von Gierke[73])

Dangerous vibration levels in space vehicles will be restricted to the relatively short duration of takeoff and reentry. Review of past performance of astronauts during takeoff showed some difficulty in the visual area. (See Light, No. 2). No problems have arisen in the reentry phase of the profile, although it is possible that angular and linear buffeting patterns may be experienced during reentry emergencies in spacecraft or emergency capsules (120). The areas indicated for road vehicle vibration in Figure 8-33 are the range for the respective vibration maxima and do not represent spectral limits (41, 145). Most vehicles have very pronounced natural frequencies excited according to ground conditions. Very generally, rubber-tired tractors, as well as trucks, have the maximum of their vertical accelerations in the 2 to 6 Hz range; for large rubber-tired earth moving equipment the range is 1.5 to 3.5 Hz and for crawler type tractors it is near 5 Hz.

Tolerance thresholds to land vehicles producing random vibration over rough terrain have received recent review (142, 174). Data are also available on threshold to railroad vehicles and similar modes of mass commercial land and air transport (16, 109, 136, 159).

Excellent reviews have been made of tolerance to vibration on board ships at sea (11, 99). These relate tolerance criteria to ship configuration and state of the sea. Such data are of value in the design of tracking ship facilities for space operations.

Vibration levels observed on hands while operating various hand tools are also indicated in Figure 8-33. These levels are strongly dependent on tool design and type of operation. Most of the hand vibrations indicated are in the acceleration range at which chronic hand injuries may result (2, 58, 71).

The presence of gusts which buffet aircraft lead to random, single-shock pulses of repetitive nature (61, 135, 146). These are prominent in low altitude, terrain-following maneuvers where high wind shears are present. During search and rescue missions for returning spacecraft, these gusts are potential problems. A review of this problem is available with coverage of the gust response of many military aircraft (61). Figure 8-34 presents the most widely used summary of available information on human tolerance to aircraft gust response as a function of duration of exposure. These curves were based on considerable data for exposures up to approximately 10 minutes. From there on, the validity is based on relatively few points. A straight line extrapolation of the intolerance boundary indicates that the environment would become intolerable before one would experience performance decrement. These curves also show that vertical accelerations equal to 0.25 g (rms) hamper performance after several minutes. For durations of approximately one hour the performance boundary is 0.15 g (rms). For duration of three hours, a convenient estimate is approximately 0.1 g (rms).

Since atmospheric turbulence is random in nature, aircraft response should be considered in terms of the statistical probability of encountering various gust loads. Most of the current data on human buffet tolerance are extrapolated from short-time simulation studies and limited flight-test

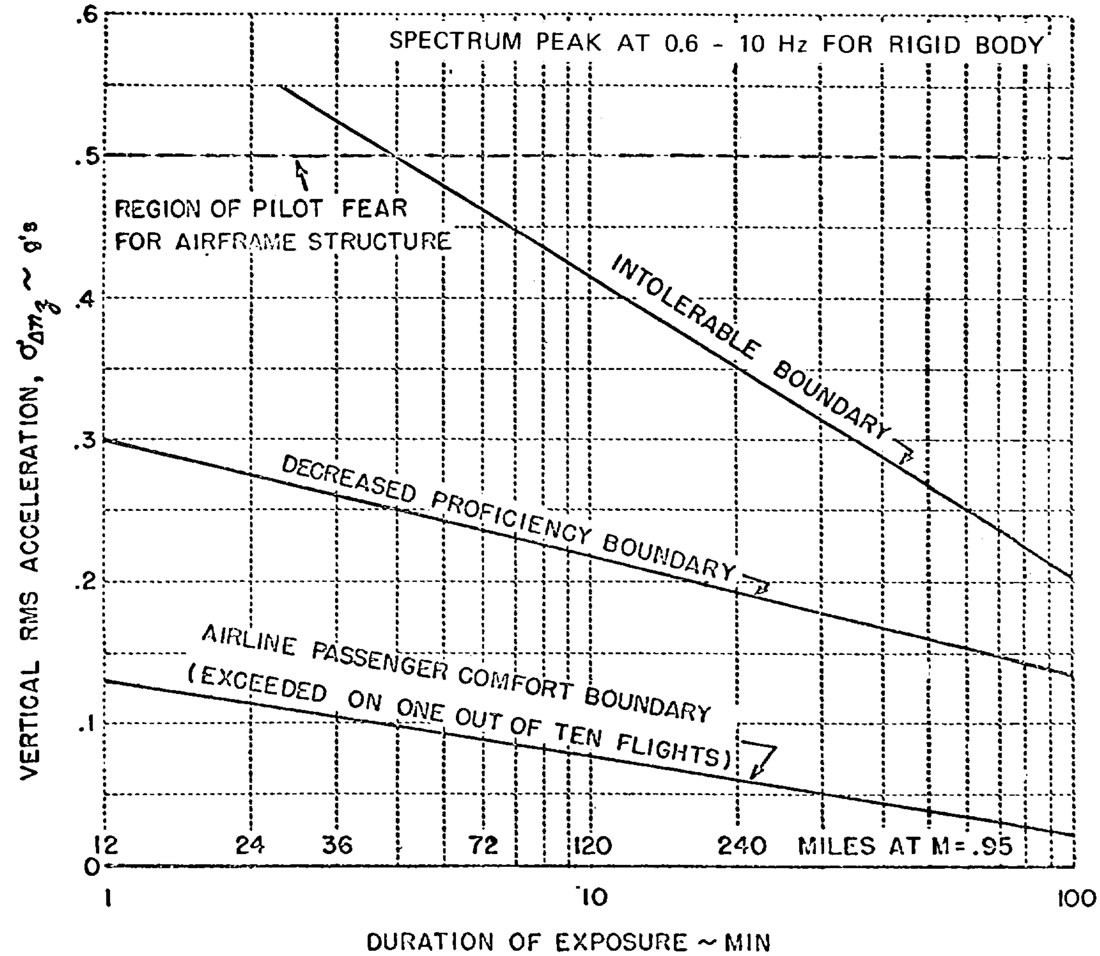


Figure 8-34

Time-Intensity Vibration Boundaries

(After Gell[61])

programs and must be extended to the durations proposed for future systems. (See Figure 8-50.)

For irregular, random vibrations the tolerance curves established for sinusoidal vibrations may serve as temporary guidelines for the time being, since little data exist. Single shock acceleration pulses as they occur as floor vibrations near drop forges or similar equipment were used in one study and some of the results are presented in Figure 8-35. The intolerable range in this series of experiments should probably be considered as conservative since experiments with sinusoidal vibrations by the same authors, which were included in the averages of Figure 8-30, gave relatively conservative tolerance levels (73).

Recent studies have shed some light on the relative importance of peak vs. rms acceleration in evaluation of tolerance in periodic low frequency vibration exposure (25). For various rms acceleration levels and frequency

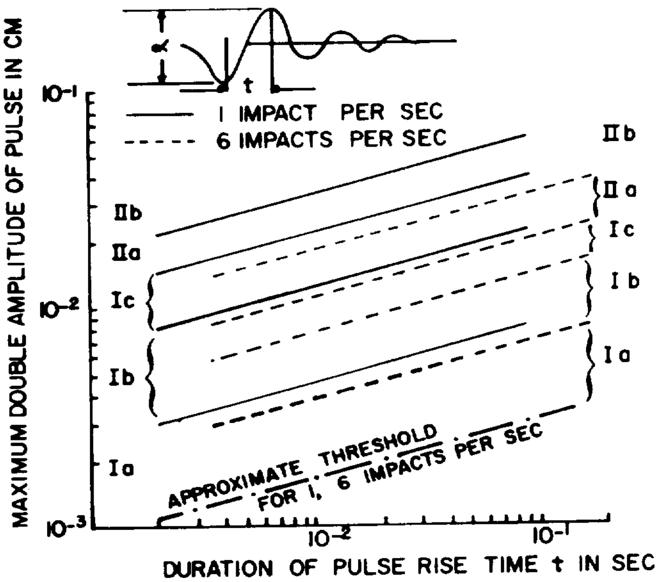


Figure 8-35

Tolerance of Human Subjects in the Standing or Supine Position to Repetitive Vertical Impact Pulses

These are representative of impacts from pile drivers heavy tools, heavy traffic, etc. Subjective reaction is plotted as a function of the maximum displacement of the initial pulse and its rise time. The numbers indicate the following reactions: Ia, threshold of perception; Ib, of easy perception; Ic, of strong perception, annoying; IIa, very unpleasant, potential danger for long exposures; IIb, extremely unpleasant, definitely dangerous. The decay process of the impact impulses was found to be of little practical significance.

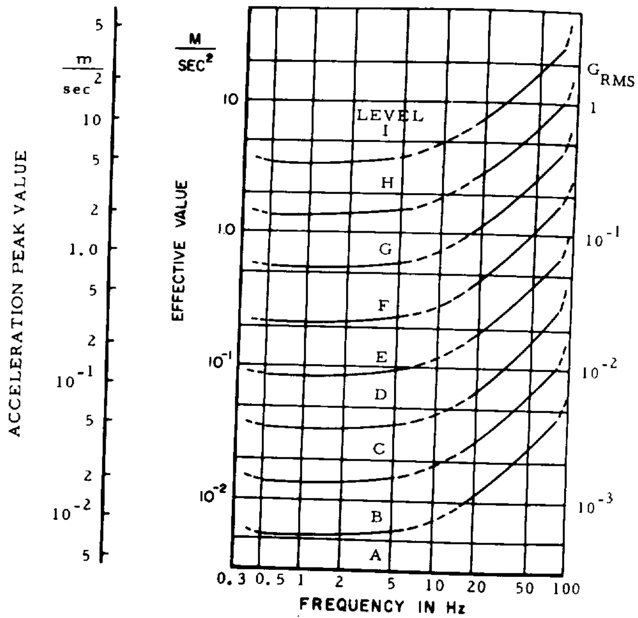
(After Goldman and von Gierke[73], adapted from Reiher and Meister[147])

contents, pairs of periodic vibration exposures having the same rms but different peak accelerations were evaluated using both a subjective severity rating and a measure of vibration induced hand motion. The higher peak acceleration of the various pairs having the same rms values was subjectively rated more severe in 32 of 40 observations. However, when attempting to hold the hand in a fixed position during vibration, the induced deviations from the null point, expressed either as average or peak-to-peak errors appeared to depend more on rms acceleration and frequency than on the small differences in peak acceleration studied here.

Efforts are underway to arrive at international agreement on vibration levels acceptable to man under various conditions (65, 93). The goal is to arrive at standard methods for rating environments with respect to human exposure (65, 93). The attributes, hazardous, acceptable and comfortable are not absolute qualities, but are dependent on innumerable biological, psychological, sociological, economic and technological variables. Most rating systems contain at least three criteria: thresholds of perception, unpleasantness, and tolerance. However, only perception can be recognized as a real threshold, whereas unpleasantness and tolerance are more or less subjective judgments and as such are certainly strongly dependent on motivation, the test structure, and the task being performed.

Many approaches have been attempted. The most applicable one is that of the German Engineering Society which gives 10 zones of equal perceptibility and tolerability. These are shown in Figure 8-36. The German standard (128) goes into considerably more detail with respect to evaluation of complex frequency spectra and direction of vibrations. It is hoped that an American standard similar to whatever will evolve as an international standard can be proposed. Soviet standards for industrial vibration exposure are available(190).

Unfortunately, time of exposure is not adequately covered by these standards. The time dependence of various responses to vibration, such as the curves for "fatigue times" and comfort limits, are illustrated in Figure 8-34



Perceived Intensity K	Level	Description of the Perception	Tolerance of Exposure
0.1	A	Not perceptible	Threshold of perception
		Barely perceptible	
0.25	B	. . . .	Living in dwellings with short or without interruptions*
0.63	C	Perceptible	Living in dwellings with prolonged interruptions*
1.6	D	Very perceptible	Physical labor without interruption*
4.0	E	Strongly perceptible	Physical labor with short interruptions*
10.0	F	Very strongly perceptible . . .	Rather long trips in trains and trucks.
25.0	G	Differentiated judgment . . . . no longer possible	Physical labor with prolonged interruptions**
63.0	H	. . . .	Driving in self-propelled working machines.
	I	. . . .	Trips in trains and trucks for a short time.

* The interruptions refer to the application of the vibration. "Short" in this context means that continuous oscillations are interrupted by occasional pauses of approximately 10 minutes in length. The relation of pauses to time of vibration should not exceed 0.1.

** "Prolonged" in this context means that the length of the pauses is at least one hour and that the relation of pauses to time of oscillation lies between 0.1 and 1.0.

The curves of equal perceived intensity (K-values) classify ranges (levels of A to I) of equal perception and tolerability.

Figure 8-36

German Standard for the Classification of Vibration Exposures

(After von Gierke[65], adapted from VDI[175]) and 8-37a. The acceptability vs. time curves of Figure 8-37a are for longitudinal (Z-axis) sinusoidal vibrations for a sitting subject. For lateral vibrations the equivalent tolerance or comfort levels are usually reported as being lower than for vertical vibrations by a factor 0.7 to 0.5. Similarly the corresponding root mean square (rms) value for random-type, broad-band vibrations appear lower than the same rating for the rms value of sine waves by a factor of approximately 0.6. With respect to these corrections, differences of opinion are not marked (65). Considering the limited data on which these curves are based, it is conceivable that one time-correction function would be satisfactory for all levels of vibration.

Figure 8-37b is a recent proposal by the ISO/TC 108 Working Group 7 for whole-body vibration in the range of 1 to 90 Hz related to the fatigue-decreased proficiency (f.d.p.) criteria (77, 78). The safe exposure limits have been temporarily set at 6 dB above corresponding f.d.p. limits. These draft limits apply to healthy people exposed to whole-body vibration while seated or standing in vehicles or industrial work places. It can be seen from Figure 8-37b that the acceptable level declines with increasing duration of exposure. Noise limits for hearing conservation are similarly related to time and it may be taken as a general rule that in occupational situations the required effectiveness of silencing or vibration control increases with the duration of exposure of personnel at risk. Tentative weighting forces, listed in Figure 8-37b, have been proposed for use in adapting the limits in the event of vibration acting transversely (i.e., athwart the body rather than vertically along the spinal axis), or when the criterion, instead of being working efficiency, is either the preservation of comfort or occupational health. Weighting factors for use when the oscillatory motion is complex or discontinuous are under consideration.

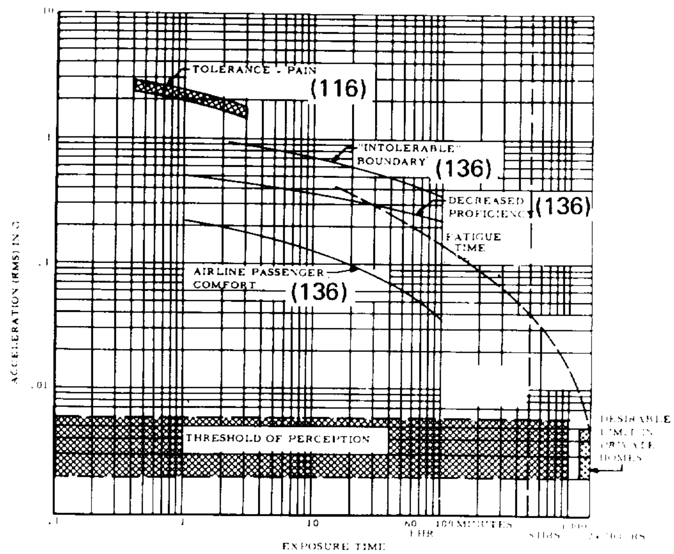
Attempts have been recently made to correlate tolerance with power input. This is of specific value during random vibration. Pages 8-22 to 8-32 cover the theory of absorbed power determinations. Figures 8-38a to d describe constant power graphs for vertical, ($\pm G_Z$) fore and aft, ($\pm G_X$) side to side, ($\pm G_Y$) vibration, and the vibratory response of the feet. The acceleration-frequency relationships are achieved by holding power constant and solving for the acceleration at each frequency. These graphs can then be interpreted as constant-comfort graphs for acceleration versus frequency. The dash line in Figure 8-38a is a constant power graph that includes both the seat and the feet input.

It is apparent from the functions described previously and from Equation 11 that absorbed power can be expressed, at a single frequency, as a product of a constant, K_i, and acceleration squared, A^2. Consequently, it is possible to provide a table that supplies this constant along with effective mass G (jw) and phase angle ϕ, so that one can determine power, acceleration, or force at any frequency through very simple calculations. Tables 8-38c to h provide these constants for four vibration inputs and are used in the examples given in References (105, 141).

The information in Figure 8-38b includes both feet for a man in a seated position. This analysis assumes the vibration is the same for both feet.

Figure 8-37

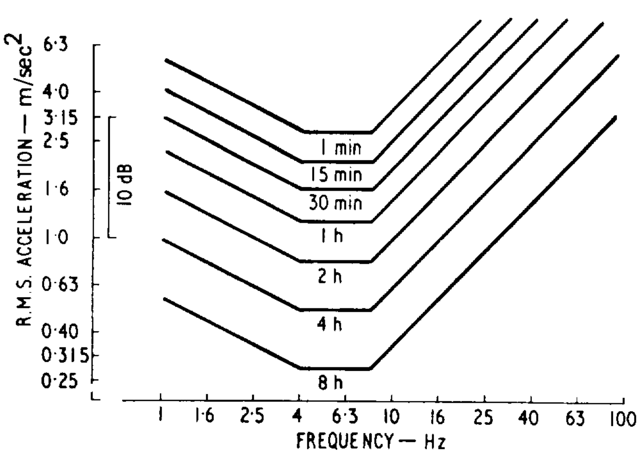
Vibration Limits as a Function of Exposure Time



The curves are valid for sinusoidal vibrations of approximately 1 Hz

a. Longitudinal Vibrations

(After von Gierke[71], based on references 24, 131, 134, 136, and 137)



Proposed weighting factors for adaptation of the limits.

Transverse (horizontal) vibration	subtract 3 dB
Reduced comfort boundaries .	subtract 10 dB
Safe exposure limits . . .	add 6 dB

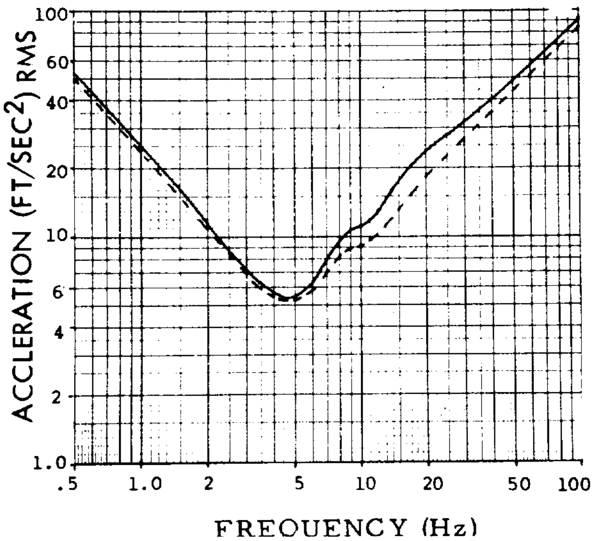
b. Proposed "Fatigue-Decreased Proficiency" Limits for Vertical Vibration in the Range 1 to 90 Hz; Weighting Factors Are Given in Table

(After Guignard[79], from ISO/TC108[93])

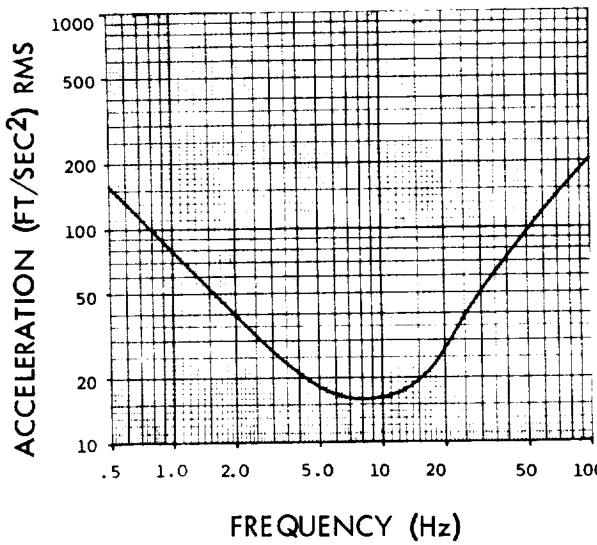
Figure 8-38

Constant Power Graphs for Comfort of Seated Man Undergoing Vibration and Table of Constants

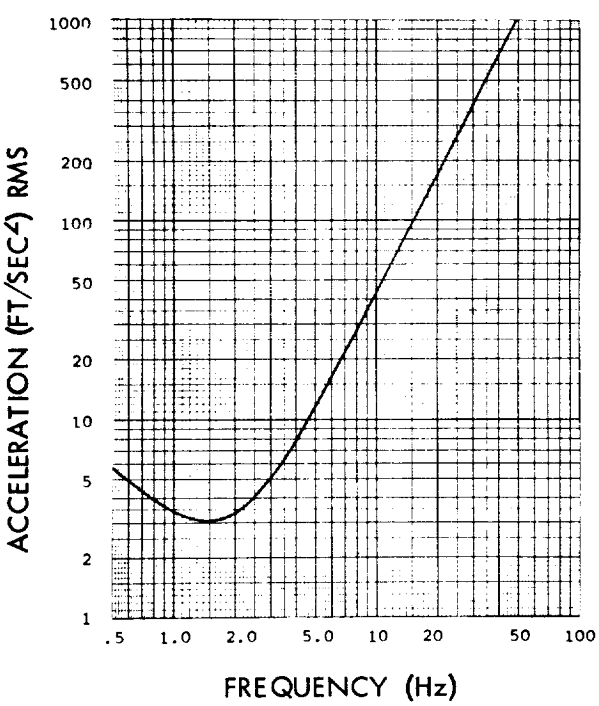
(After Lee and Pradko[105])



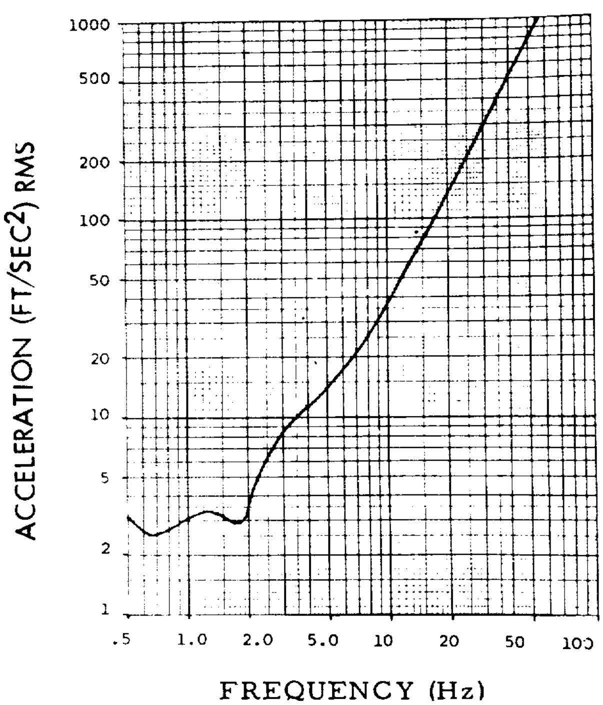
a. ± G_z Vibration
—— seat input only
- - - seat and feet input



b. ± G_z Vibration
(input from feet)



c. ± G_x Vibration



d. ± G_y Vibration

Figure 8-38 (continued)

e. Absorbed Power Constants: $\pm G_z$

$P = \sum_{i=0}^{N} K_{iv} A_i^2$ — Acc., Φ, Force

Frequency (Hertz)	K_{iv} $\left(\frac{\text{Watts}}{(\text{Ft/Sec}^2)^2}\right)$	$\lvert G(jw) \rvert$ (Slugs)	Φ Phase Angle (Radians)
0.00	.000000	4.3537	.000000
0.10	.000082	4.3557	.000009
0.20	.000330	4.3616	.000070
0.30	.000747	4.3716	.000237
0.40	.001338	4.3855	.000566
0.50	.002113	4.4035	.001111
0.60	.003080	4.4255	.001935
0.70	.004253	4.4517	.003099
0.80	.005645	4.4820	.004669
0.90	.007272	4.5166	.006714
1.00	.009149	4.5553	.009307
1.10	.011296	4.5983	.012522
1.20	.013731	4.6455	.016435
1.30	.016471	4.6969	.021125
1.40	.019535	4.7524	.026669
1.50	.022941	4.8118	.033143
1.60	.026705	4.8751	.040622
1.70	.030840	4.9419	.049177
1.80	.035359	5.0121	.058874
1.90	.040269	5.0853	.06977
2.00	.045576	5.1612	.08193
2.25	.060561	5.3595	.11808
2.50	.077843	5.5635	.16280
2.75	.097002	5.7629	.21616
3.00	.117336	5.9463	.27786
3.25	.137876	6.1018	.34721
3.50	.157454	6.2175	.42322
3.75	.174830	6.2833	.50463
4.00	.188845	6.2914	.58997
4.25	.198576	6.2372	.67765
4.50	.203469	6.1197	.76601
4.75	.203404	5.9417	.85332
5.00	.198689	5.7092	.93785
5.25	.189988	5.4309	1.01790
5.50	.178206	5.1176	1.09174
5.75	.164358	4.7812	1.15769
6.00	.149444	4.4340	1.21404
6.25	.134362	4.0880	1.25915
6.50	.119843	3.7550	1.2915
6.75	.106430	3.4454	1.3098
7.00	.094481	3.1687	1.3137
7.25	.084182	2.9321	1.3035
7.50	.075581	2.7408	1.2811
7.75	.068618	2.5965	1.2500
8.00	.063152	2.4973	1.2151
8.25	.058994	2.4378	1.1813
8.50	.055923	2.4100	1.1528
8.75	.053709	2.4046	1.1328
9.00	.052125	2.4124	1.1222
9.25	.050964	2.4255	1.1211
9.50	.050041	2.4375	1.1283
9.75	.049205	2.4436	1.1426
10.00	.048340	2.4408	1.1623
10.50	.046233	2.4026	1.2117
11.00	.043455	2.3218	1.2661
11.50	.040109	2.2077	1.3175
12.00	.036470	2.0734	1.3607

f. Absorbed Power Constants $\pm G_z$ (Foot Response)

$P = \sum_{i=0}^{N} K_{if} A_i^2$ — Acc., Φ, Force

Frequency (Hertz)	K_{if} $\frac{\text{Watts}}{(\text{Ft/Sec}^2)^2}$	$\lvert G(jw) \rvert$ (Slugs)	Φ Phase Angle (Radians)
0.00	.000000	1.1820	.000000
0.10	.000009	1.1822	.000004
0.20	.000029	1.1829	.000030
0.30	.000087	1.1840	.000103
0.40	.000155	1.1856	.000243
0.50	.000243	1.1877	.000473
0.60	.000349	1.1901	.000816
0.70	.000475	1.1930	.001293
0.80	.000621	1.1964	.001923
0.90	.000785	1.2001	.002729
1.00	.000969	1.2043	.003729
1.10	.001172	1.2088	.004942
1.20	.001394	1.2137	.006385
1.30	.001635	1.2190	.008077
1.40	.001894	1.2247	.010032
1.50	.002172	1.2307	.012265
1.60	.002468	1.2370	.014791
1.70	.002782	1.2437	.017621
1.80	.003114	1.2506	.020767
1.90	.003462	1.2578	.024239
2.00	.003828	1.2652	.028045
2.25	.004813	1.2847	.039068
2.50	.005890	1.3052	.052299
2.75	.007047	1.3263	.067759
3.00	.008270	1.3476	.085416
3.25	.009542	1.3687	.105185
3.50	.010843	1.3891	.126935
3.75	.012153	1.4085	.150494
4.00	.013451	1.4266	.175659
4.25	.014716	1.4431	.202203
4.50	.015929	1.4576	.229885
4.75	.017073	1.4701	.258464
5.00	.018133	1.4806	.287704
5.25	.019100	1.4882	.317383
5.50	.019967	1.4951	.347303
5.75	.020731	1.4993	.377291
6.00	.021391	1.5016	.407202
6.25	.021951	1.5023	.436924
6.50	.022416	1.5014	.466369
6.75	.022791	1.4993	.495483
7.00	.023086	1.4959	.524231
7.25	.023307	1.4916	.552601
7.50	.023462	1.4865	.580601
7.75	.023561	1.4806	.608250
8.00	.023609	1.4742	.635580
8.25	.023613	1.4673	.662630
8.50	.023579	1.4599	.689444
8.75	.023512	1.4522	.716067
9.00	.023416	1.4442	.742546
9.25	.023294	1.4358	.768927
9.50	.023149	1.4271	.795251
9.75	.022984	1.4181	.821557
10.00	.022799	1.4088	.847875
10.50	.022374	1.3889	.900654
11.00	.021880	1.3674	.953720
11.50	.021316	1.3438	1.007090
12.00	.020683	1.3178	1.060673

Figure 8-38 (continued)

g. Absorbed Power Constants: $\pm G_x$

$P = \sum_{i=0}^{N} K_{if} A_i^2$ — Acc. / Force

Frequency (Hertz)	$K_{if} \cdot a$ $\left(\frac{Watts}{(Ft/Sec^2)^2}\right)$	|G(jw)| (Slugs)	Φ Phase Angle (Radians)
0.00	.000000	4.3532	.000000
0.10	.007986	4.3848	.000844
0.20	.031531	4.4763	.006528
0.30	.069418	4.6188	.020894
0.40	.119689	4.7995	.046237
0.50	.179748	5.0039	.83320
0.60	.246496	5.2171	.131737
0.70	.316507	5.4257	.190360
0.80	.386231	5.6176	.257704
0.90	.452216	5.7832	.332167
1.00	.511349	5.9148	.412159
1.10	.561072	6.0071	.496171
1.20	.599565	6.0573	.582807
1.30	.625846	6.0647	.670801
1.40	.639787	6.0306	.759027
1.50	.642028	5.9580	.846508
1.60	.633817	5.8513	.932423
1.70	.616810	5.7157	1.016109
1.80	.592853	5.5567	1.097054
1.90	.563802	5.3798	1.11749
2.00	.531380	5.1902	1.24936
2.25	.444761	4.6900	1.42020
2.50	.361943	4.1928	1.56942
2.75	.290275	3.7293	1.69887
3.00	.231488	3.3130	1.81097
3.25	.184614	2.9465	1.90839
3.50	.147747	2.6272	1.99340
3.75	.118894	2.3505	2.06800
4.00	.096307	2.1109	2.13385
4.25	.078565	1.9030	2.19232
4.50	.064556	1.7224	2.24452
4.75	.053425	1.5649	2.29138
5.00	.044521	1.4269	2.33366
5.25	.037349	1.3057	2.37192
5.50	.031533	1.1987	2.40686
5.75	.026783	1.1040	2.43874
6.00	.022879	1.0197	2.46799
6.25	.019650	0.9445	2.49491
6.50	.016963	.87707	2.51977
6.75	.014714	.81649	2.54280
7.00	.012821	.76187	2.56418
7.25	.011220	.71245	2.58410
7.50	.009859	.66761	2.60269
7.75	.008696	.62682	2.62008
8.00	.007698	.58960	2.63639
8.25	.006838	.55556	2.65171
8.50	.006094	.52465	2.66613
8.75	.005448	.49567	2.67972
9.00	.004885	.46926	2.69256
9.25	.004392	.44488	2.70470
9.50	.003959	.42234	2.71621
9.75	.003578	.40145	2.72713
10.00	.003242	.38206	2.73749
10.50	.002679	.34725	2.75675
11.00	.002233	.31695	2.77426
11.50	.001876	.29044	2.79024
12.00	.001587	.26710	2.80489

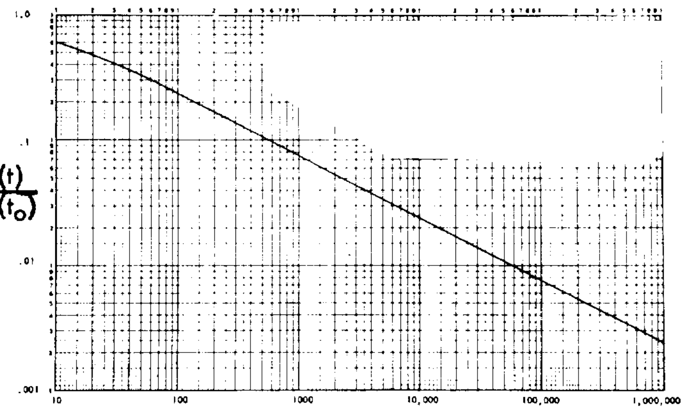
h. Absorbed Power Constants: $\pm G_y$

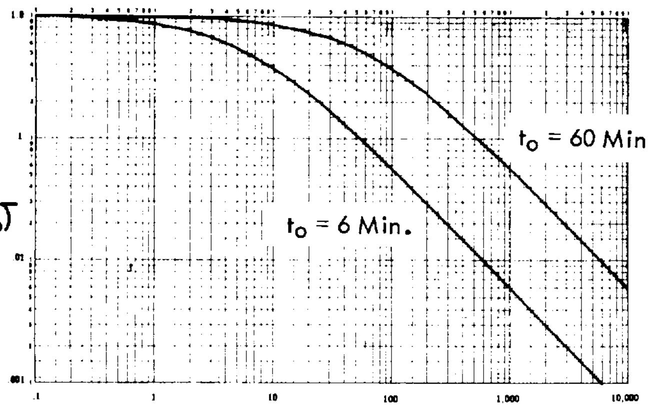
$P = \sum_{i=0}^{N} K_{is} A_i^2$ — Acc. / Force

Frequency (Hertz)	K_{is} $\frac{Watts}{(Ft/Sec^2)^2}$	|G(jw)| (Slugs)	Φ Phase Angle (Radians)
0.00	.000000	4.3530	.000000
0.10	.012617	4.41226	.001325
0.20	.056579	4.59712	.011406
0.30	.152512	4.92206	.043086
0.40	.336090	5.37203	.116218
0.50	.618917	5.79730	.249935
0.60	.875526	5.86860	.427688
0.70	.929853	5.48783	.581862
0.80	.834987	4.98867	.669312
0.90	.718723	4.62680	.704698
1.00	.630460	4.44417	.717277
1.10	.575382	4.41090	.727329
1.20	.549073	4.49642	.746387
1.30	.547652	4.68182	.781883
1.40	.568966	4.95442	.840497
1.50	.610599	5.29472	.929863
1.60	.664520	5.65275	1.058335
1.70	.708175	5.91674	1.230978
1.80	.703578	5.91849	1.440331
1.90	.628075	5.5513	1.65955
2.00	.508018	4.9033	1.85402
2.25	.260384	3.2238	2.14049
2.50	.152064	2.1955	2.21043
2.75	.105940	1.6455	2.17949
3.00	.082866	1.3463	2.11488
3.25	.069233	1.1759	2.05159
3.50	.059955	1.0715	2.00434
3.75	.052919	1.0006	1.97603
4.00	.047168	0.9466	1.96438
4.25	.042241	0.9012	1.96568
4.50	.037906	0.8602	1.97640
4.75	.034040	0.8216	1.99367
5.00	.030573	0.7846	2.01533
5.25	.027458	0.7488	2.03975
5.50	.024660	0.7142	2.06579
5.75	.022152	0.6808	2.09262
6.00	.019906	0.6487	2.11967
6.25	.017899	0.6180	2.14652
6.50	.016107	.58865	2.17290
6.75	.014509	.56073	2.19863
7.00	.013084	.53423	2.22360
7.25	.011813	.50912	2.24773
7.50	.010681	.48537	2.27099
7.75	.009669	.46293	2.29337
8.00	.008768	.44175	2.31487
8.25	.007961	.42177	2.33551
8.50	.007240	.40292	2.35531
8.75	.006594	.38515	2.37430
9.00	.006155	.36839	2.39251
9.25	.005496	.35258	2.40998
9.50	.005028	.33767	2.42674
9.75	.004608	.32360	2.44282
10.00	.004228	.31032	2.45826
10.50	.003576	.28591	2.48733
11.00	.003042	.26409	2.51419
11.50	.002601	.24453	2.53905
12.00	.002235	.22696	2.56212

Figure 8-38 (continued)

i. Normalized Acceleration Factors for Constant Time-Dependent Power (See text) t_o = 6 min.





j. Normalized Power Factors for Constant Time-Dependent Power (See text)

Where this is not the case the numerical constant K_0 for the feet must be divided by 2 and the transfer function used for each foot. Similar tables in Reference (141) provide for frequencies up to 100 Hz for pitch and roll vibrations.

As would be expected from the previous discussion, the physical surroundings in which the vibration occurs have a strong influence on what is an acceptable or unacceptable vibration power. For example, an upper acceptable absorbed power for automobile ride may be 0.2-0.3 W. If one were to ride in an automobile about this level, the opinion would very likely be that the ride is rough and the vehicle uncomfortable. On the other hand, the upper acceptable limit for off-road vehicles may be 6-10 W, and if one were to experience a ride in the 0.5-1.0 W range, the opinion would likely be that the ride is very comfortable. The measurement of the absorbed power for each application allows comparison on an absolute scale.

For vibrations of short duration, absorbed power can be used as a measurement of vibration severity, but frequently it is desired to determine a vibration comfort level for a longer period of time. The amount of available information for the effect of long time vibration is very sparse. (See Figure 8-37.) One can easily deduce why the amount of information is very limited. There are several parameters that affect the comfort level. These parameters are frequency, amplitude, environment, and a certain amount of fatigue or discomfort with the passage of time, even when there is no vibration present.

Since absorbed power accurately measures vibration severity for short term vibration, it can be deduced that for long term vibration, a term can be added to this power that may be similar to energy absorbed.

If this is done, an empirical expression for power becomes

$$P_T = P + \frac{1}{t_0} \int_0^t P dt \tag{12}$$

where P_T = Long term absorbed power

P = Average power

t_0 = Time scale factor, approximate onset of fatigue

Power need not remain constant, but if it does, Equation 12 takes the form

$$P_T = P + P \frac{t}{t_0} \tag{13}$$

Substituting KA^2 for power, (See Equation 8)

$$P_T = KA^2 \left[1 + \frac{t}{t_0} \right] \tag{14}$$

An acceleration-time relationship is given by

$$A(t) = \sqrt{\frac{P_T}{K(1 + (t/t_0))}} \tag{15}$$

At $t = 0$, $P_T = P_{av}$. Therefore, setting $P_T/K = A^2(t_0)$, which is the short-term acceleration, gives

$$A(t) = \frac{A(t_0)}{\sqrt{1 + (t/t_0)}} \tag{16}$$

This equation describes degradation of acceleration for constant comfort when time is considered. If one divides both sides of Equation 16 by $A(t_0)$

$$\frac{A(t)}{A(t_0)} = \frac{1}{\sqrt{1 + (t/t_0)}} \tag{17}$$

Figure 8-38i is a graph of Equation 17 with t_0 = 6 minutes.

If both sides of Equation 17 are squared, the equation is then absorbed power or comfort:

$$\frac{P(t)}{P(t_0)} = \frac{1}{1 + (t/t_0)} \qquad (18)$$

This equation is graphed in Figure 8-38j with t_0 = 6 minutes and 60 minutes.

PERFORMANCE DURING VIBRATION

The effects on performance may be considered as direct mechanical interferences with performance, or indirect effects resulting from physiological alterations. Some of the types of performance which are significantly affected by vibration include (80, 114, 188).

a. Visual tasks including effects on visual acuity and eye movements. Direct effects are primarily mechanical (resonance) for certain g-vector and frequency combinations; indirect include pain for other g-vector/frequency combinations.

b. Vigilance, concentration, and reaction time.

c. Simple motor tasks such as operation of switches.

d. Speech.

e. Complex motor tasks such as tracking.

Figures 8-39a and b review the general trends in psychophysical and performance tolerance under vibration in the longitudinal axis of a seated subject. Figure 8-31a and b also cover performance thresholds of an even more general nature. These figures and tables may be used as a general guide to the type of data available from experimental study.

Visual Effects

Visual impairment is a major psychophysical defect expected from vibration in a spacecraft (158). Unfortunately, most studies have been performed during G_z vibration in the seated position. This will be assumed in the text unless otherwise stated.

Visual Acuity

Vibration of either the viewer or the object can blur vision over certain frequency and acceleration ranges and is usually attributed to movement of the retinal image at a speed too great to be followed by the eye (80, 167). In general, there is no clear-cut evidence that decrement in acuity is either purely frequency dependent or amplitude dependent. The evidence is conflicting because the same methods for measuring visual acuity or the same conditions of vibration have not always been held constant during the tests. Some,

Figure 8-39

Psychomotor Performance During Longitudinal Vibration

(After Linder[107]. References available in original document.)

a.

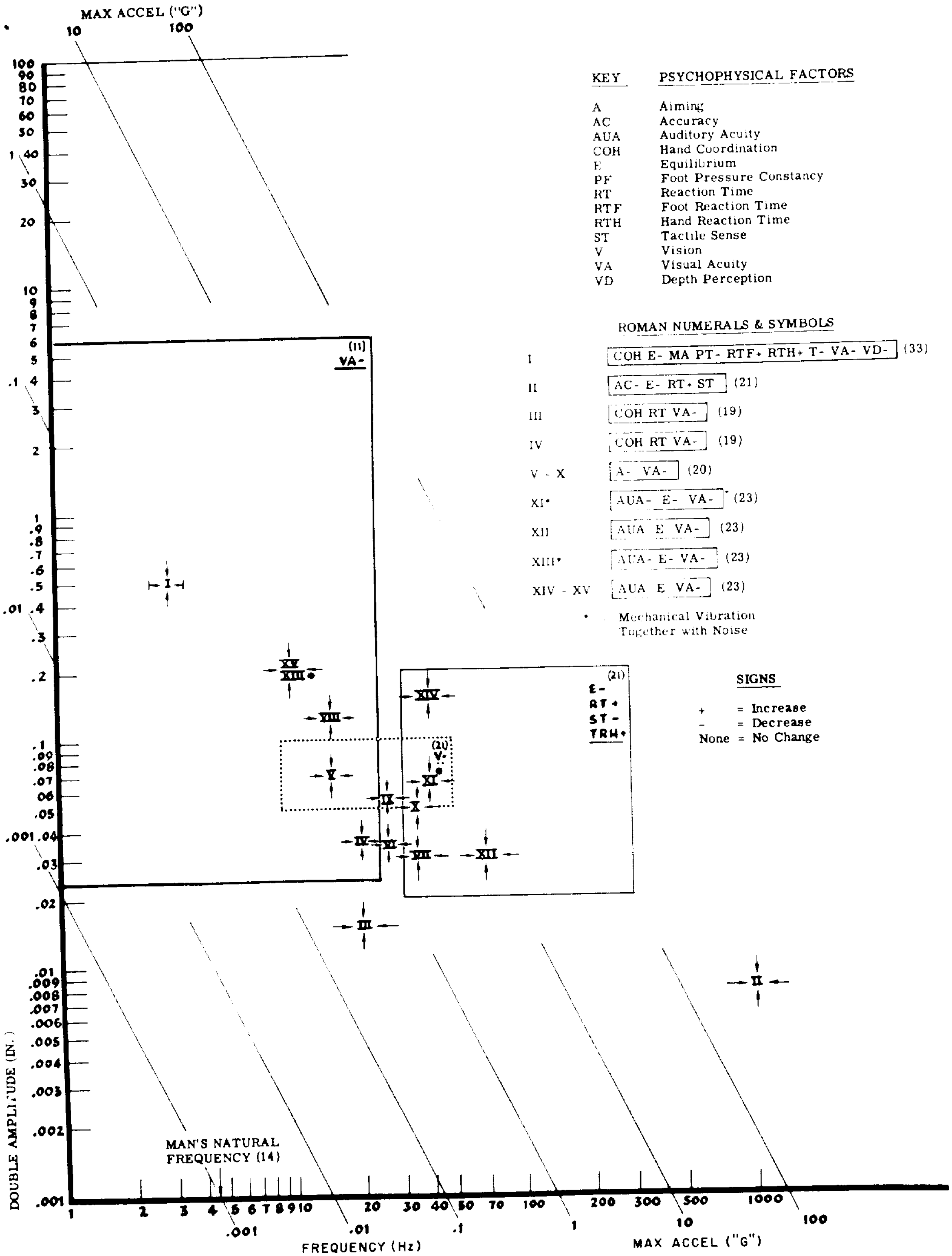
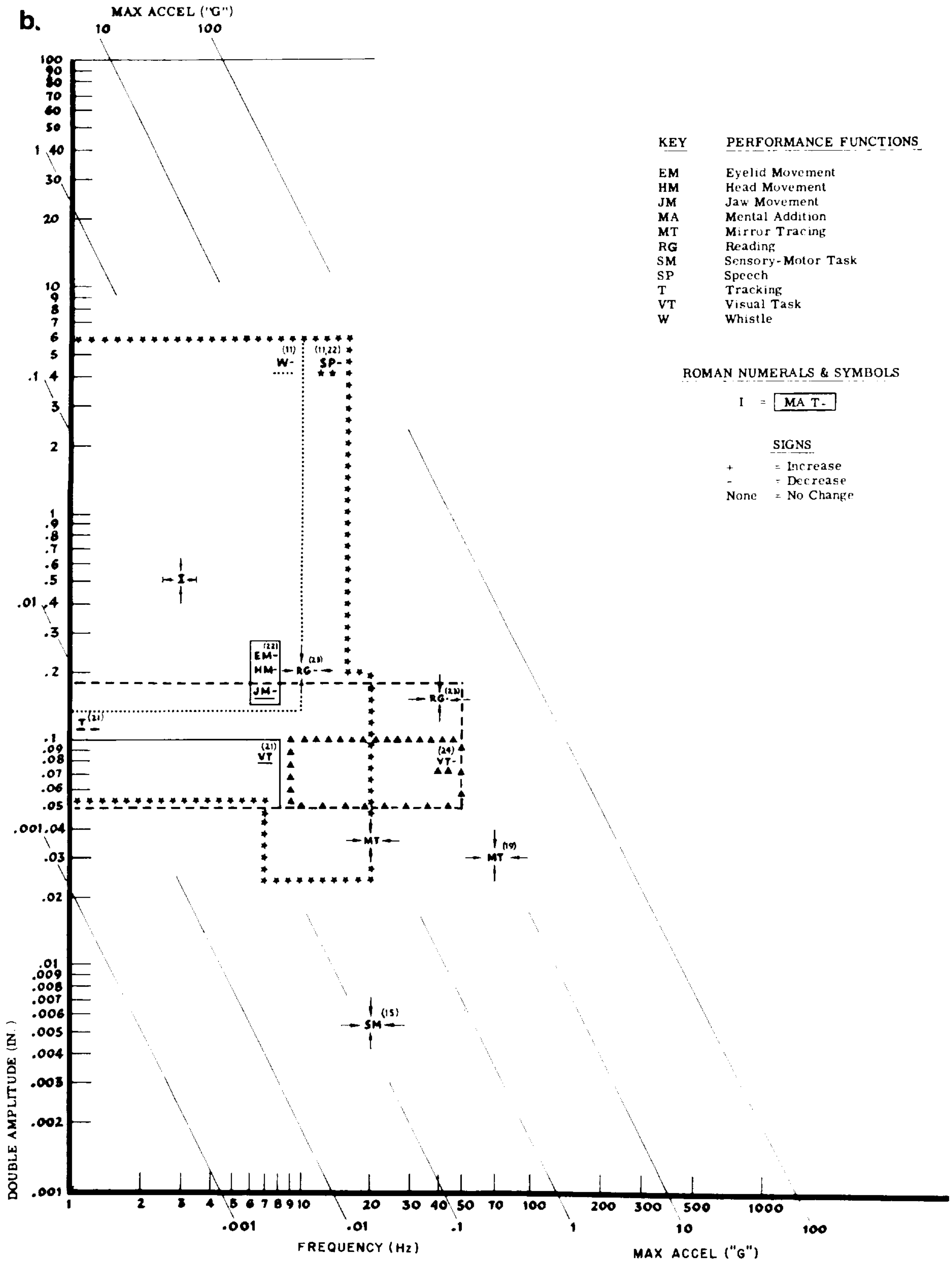


Figure 8-39 (continued)

b.



for example, have applied a constant displacement-amplitude at all frequencies others have reduced amplitude at the higher frequencies (110, 125).

The tests of visual acuity under vibration have included the use of: a) Landolt C (38, 44, 154), b) variable coarseness gratings, such as the Clason acuity meter (111), c) the separation of diverging lines (31), and the reading of printed numbers of letters to study the legibility of test material vibrated with the observer stationary (34, 36, 45, 79, 98, 125).

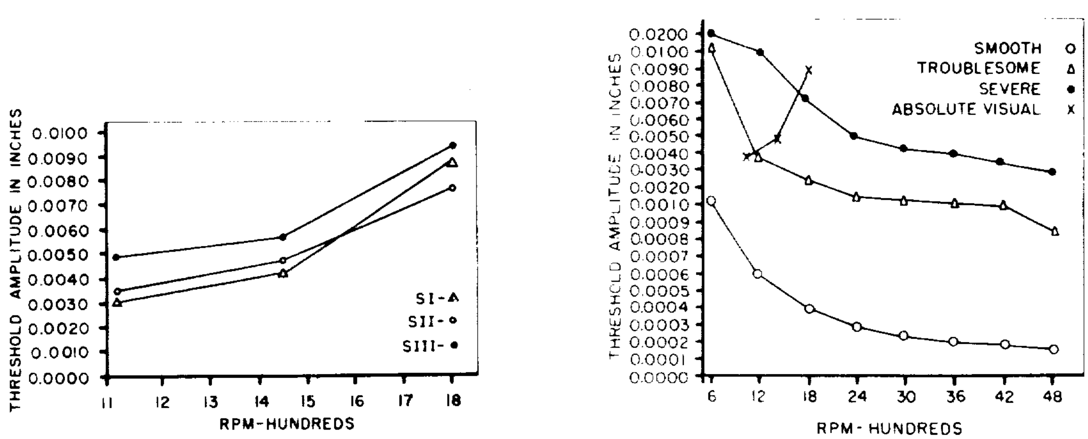
The sensitivity to vibration in the visual field is a factor of interest (34, 169, 189). The results of a determination of the minimum amplitudes of vibration in the visual field which are just perceptible at various frequencies are shown in Figure 8-40a. Stimuli were printed materials in six- and eight-point type viewed at a reading distance of 14 inches under 13.0 and 23.5 ft-L. The amplitude threshold increased with frequency, and the average amplitude threshold is in the neighborhood of 0.0056 inch. The threshold increased with decreasing brightness, but the type size variable was not found to affect the threshold through the range tested. The visual threshold to total body vibration as related to subjective threshold of vibration in the visual field is noted in Figure 8-40b.

Visual acuity is degraded during vertical sinusoidal vibration at frequencies above 15 Hz, particularly in the frequency bands of 25 to 40 Hz and 60 to 90 Hz, and in a third band for some subjects at 50 to 55 Hz (31). Within a limited range, the decrement in acuity increases with increasing amplitude of vibration reaching the head. This is interpreted as the result of mechanical

Figure 8-40

Thresholds of Perceptibility of Vibration in the Visual Field for $\pm G_z$ (Seated Subjects)

(After Wulfeck[189])



a. Amplitude Threshold at Three Frequencies for Three Subjects (First Order Interaction: Frequency X Subjects) (See text)

b. Amplitude Thresholds to Vibration

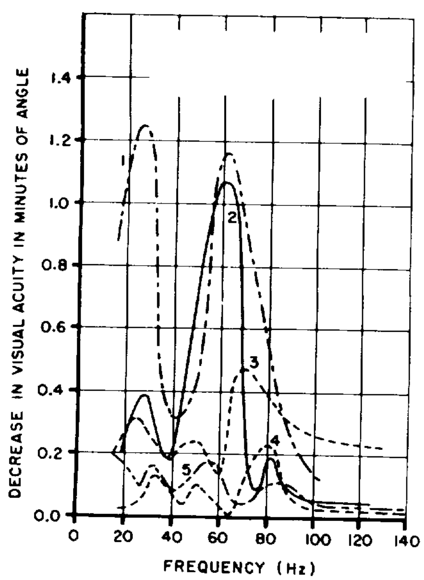
These curves compare subjective response to total body vibration with the amplitude required for detection of vibration in the visual field. (X) body resonances. The decrement in the 60 to 90 Hz band is caused by resonance of the eyeball or its adnexa within the orbit. Also the reduction in acuity in the range of 20 to 40 Hz is attributed to passive movement of the eyes produced by resonance of the soft tissues of the face and scalp (37).

Figure 8-41a shows binocular visual acuity at various frequencies of head vibration for five subjects. At particular frequencies there appear to be resonance points at which acuity was most affected. The first point might be due to difficulty in fixating the vibrating test object. The remaining peaks may be due to the effects of complex sympathetic vibrations produced at resonance in the musculature of the eye, compounded with the fundamental vibration of the test object. The results are clear in indicating that vibration of the body and test object impairs visual efficiency. The results do not, however, permit an evaluation of the effects of vibration in the visual field as opposed to those of vibration impressed directly upon the body. The subject-to-subject variability is clear.

Visual acuity has also been shown to be degraded by vertical, whole-body vibration at acceleration-amplitudes between 0.1 and 0.75 g in the frequency range from 4 to 40 Hz (36, 38, 104, 111, 125). The effect of whole-body vibration on the ability of humans to read digits of an aircraft mileage indicator

Figure 8-41

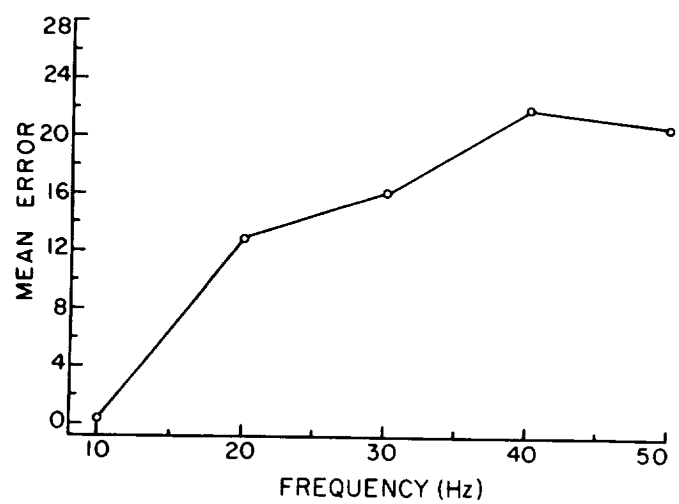
Effect of Whole-Body Exposure to ± G_z Vibration (Seated) to Visual Performance



a. Person to Person Variability

The curves show that during 2 hrs. of exposure to vibration visual acuity decreases, particularly at two distinct ranges of frequency. The five curves are for different subjects.

(After Wulfeck[189], adapted from MacFarland[113])



b. Increase in Errors of Reading of Dial Digits with Forcing Frequency During Vibration at Constant Displacement-Amplitude of 0.05 Inches

(After Mozell and White[125])

is shown in Figure 8-41b (125). Vertical sinusoidal frequencies between 8 and 50 Hz with displacements of 0.05, 0.1 and 0.16 in. double amplitude were used but only those of 0.05 is recorded in the figure.

Orientation of test materials with respect to the direction of vibration also have been shown to influence acuity. Using the Ronchi type of test-objects, it has been found that visual performance decreased when the lines of the grating were placed athwart the direction of vibration (111, 161). This is interpreted as being the result of the blurring of the margins between the lines of the grating and the intervening spaces, whereas this does not occur when the vibration is parallel with the lines of the grating.

Increase in the level of illumination reduces the amount of impairment of visual acuity (34, 36, 38). The visual acuity decrements produced by vibration can be compensated for by increased luminance of the displays (34). Figure 8-42 indicates that as luminance increases from 0.046 ft-L to 15.0 ft-l

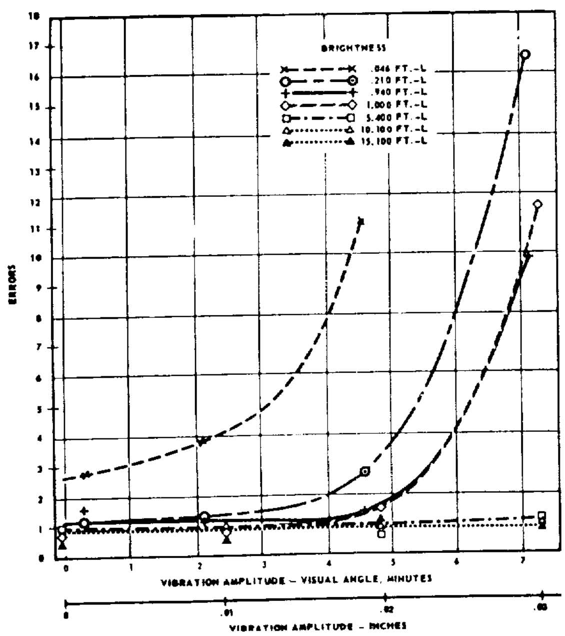


Figure 8-42

Effect of Vibration Amplitude (1050 cpm) on Reading Accuracy for Various Luminances

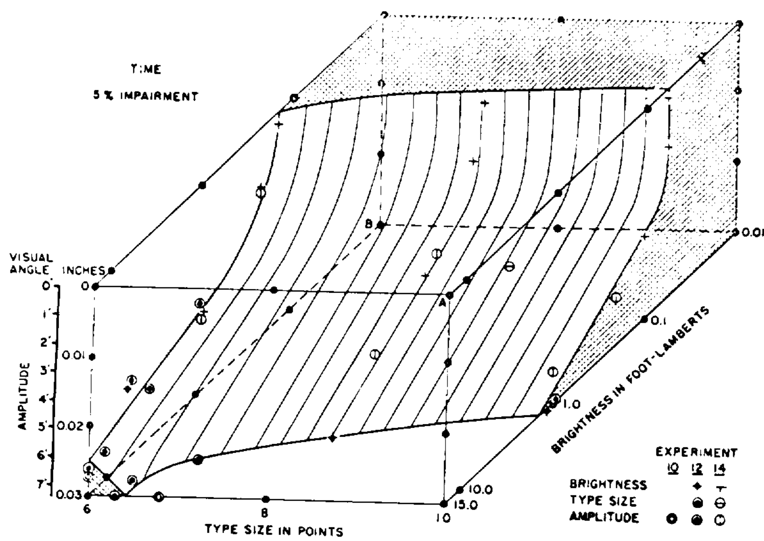
(After Urmer and Jones[173], adapted from Crook et al[34])

performance is significantly improved, although the difference in errors between luminances of 5.4 ft-L and 15.10 ft-L is not marked. The subjects performed simple mental arithmetic on printed numbers (34). The effect on the subjects' speed and accuracy has been measured as vibration was varied in frequency, amplitude and form, and as the printed material was varied in brightness, contrast and type size. Of these variables, amplitude of vibration, brightness and type size seem to be the most critical. The results of experiments on these variables are summarized in Figures 8-43a and b, for a mid-frequency value of 1050 cpm. The three variables interact to produce given decrements in speed and accuracy of performance. The authors conclude that:

Figure 8-43

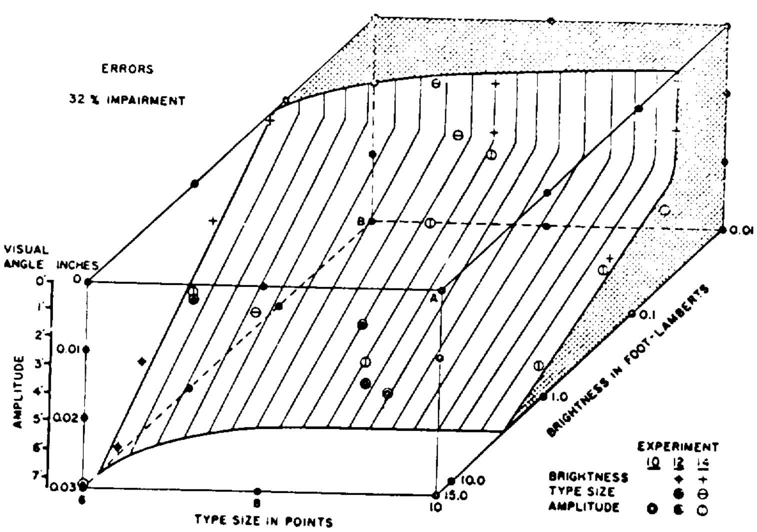
Effects of Amplitude, Brightness, and Type Size on Visual Performance During Vibration

(After Crook et al[34])



a. Combinations of Amplitude, Brightness, and Type Size Producing a Constant Impairment in Time Scores

In the solid figure, corner A represents the most favorable conditions, B the least favorable. The curved surface is the boundary at which time is increased 5% as conditions become less favorable. Based on results from 12 subjects each.



b. Combinations of Amplitude, Brightness, and Type Size Producing a Constant Impairment in Error Scores

In the solid figure, corner A represents the most favorable conditions, B the least favorable. The curved surface is the boundary at which errors are increased 32% as conditions become less favorable. Based on results from 12 subjects each.

- On a numeral-reading task involving simple mental arithmetic, performance is not significantly impaired by decrease of brightness to 0.05 ft-L, decrease of type size to 6-point or below, or increase of amplitude of visual vibration produced by rotating prisms at 1050 cycles per minute to 0.02 inch, if only one factor is varied at a time.
- Two of these values, in combination, impair time scores from 0 to 40 percent and error scores from 0 to 190 percent. All three, in combination, impair time and error scores 130 and 1100 percent, respectively.
- Certainly for brightness, and possibly for type size, the range within which performance is not affected is broader than for reading of verbal material.
- Performance as a function of any one variable, especially when all other conditions are favorable, tends to improve rapidly to a critical value and then levels off sharply.
- Impairment caused by the visual vibration introduced by means of prisms is considerably less than would be caused by vibration of the head at the same amplitude, to judge from previous work on the relation of head vibration to acuity.
- Because of this factor and the possible interaction of various other unfavorable conditions, the results of these experiments should be considered as indicating the minimum impairments that would probably be produced in the most similar practical situation.
- The effect of head vibration can be assumed to be greater than that of exclusively visual vibration, for the same amplitude of relative vibratory movement. In some operational situations the visual vibration might be the more troublesome, because vibration of the viewing surfaces would cause excessive amplitudes of relative movement. For this reason separate estimates of the two factors would be desirable in practical application.
- As far as relative vibratory movement alone is concerned, under daylight or high levels of artificial illumination, the reading of printed numerical materials at 14 inches would not be affected by vibration amplitudes up to 0.02 inch nor of dial numerals by amplitudes up to 0.04 inch. Under night illumination designed to protect dark adaptation the tolerances would be much less. A drop in brightness to 0.046 ft-L, for example, puts a premium on printed numerals above 8-point in size, and brings the critical amplitude down to perhaps 0.01 inch for the larger type sizes; in the case of dials at the same brightness, the corresponding critical numeral size would be about 5/32 inch and the critical amplitude 0.02 inch; for 1/8 inch dial numerals a brightness drop to 0.2 ft-L would bring critical amplitude to 0.02 inch.

These data, the data on visual thresholds to vibration, and the data on discomfort thresholds can be used to establish some general principles for avoiding or compensating for the effects of vibration in the visual field on visual performance. Maybe the most significant of these is that if brightness can be kept above 0.1 ft-L, type size above 8-point, and vibration of material in the visual field less than that which would be judged "severe" (0.0200 inch) anywhere in the frequency range of total body $\pm G_z$ vibration, there would be no impairment of legibility due to vibration.

Eye movements in response to sinusoidal oscillation of either a subject with stationary test material or a vibrating test object with a stationary subject have been studied (54, 82, 83, 98, 134, 163, 170). Figure 8-44 shows the movement of the eyes during sinusoidal vibration. The ability of the human eye to follow a sinusoidal relative movement of a target begins to break down at 1 to 2 Hz and is practically lost by 4 Hz. Figures 8-44, 8-45 and 8-46 show this effect.

Experiments have recently been carried out in which the effects upon visual performance of whole-body vibration have been compared with the effects of vibrating the visual object itself (37). At 6 Hz, using similar angular displacements, vibration of the visual object was found to result in higher impairment of vision than vibration of the human subject. At 14, 19, and 27 Hz the converse was found to be the case; results which support previous theories of resonance of eyeball or facial tissue to account for the sensitivity of visual performance to whole-body vibration at these higher frequencies (34).

Effects on Visual Tasks

Figure 8-51a summarizes the threshold factors in degradation of visual tasks (see discussion). Several complex visual tasks have been studied in detail. In Figure 8-47, subjects were given two separate tasks to perform (scanning and placing) in the seated position while being vibrated in the frequency range in which significant body resonances occur (81). Vibration frequencies ranged from 2.4 to 9.5 Hz. "Scanning" required the subject to scan blocks of type script letters "c" and to count randomly placed anomalous letters "o". "Placing" required the subject to pick four markers off the periphery of a 16 inch diameter disc in front of him and to place them precisely on spots, providing 1/32 inch clearance, one inch from the center of the disc. Errors and time to complete task are given in Figure 8-47 which presents only the mean time to completion (in seconds) rather than errors since very few errors were made under any conditions. Correlation with velocity and amplitude of head and eye movements is noted.

Data on visual acuity of different digit heights at periodic, vertical, low-frequency vibration are available (104, 127). Data are also available on random vibration effects in aircraft flight during gusty conditions with emphasis on letter-height factors (92).

Control of the axis of vibration and reduction of the vibration transmitted to the head reduces impairment of visual acuity (36, 38). This is particularly significant in the design of head restraints (164, 165). (See below.) Subjects were studied in the adjustable couch described in Figure 8-24a.

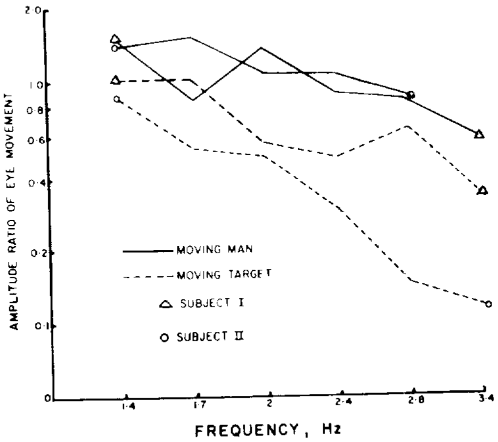


Figure 8-44

Frequency Response of the Oculomotor System Fixating a Stationary Target During Whole-Body Vibration (peak-to-peak displacement 5 mm) Giving Relative Angular Displacement of Target at 0.08 Degree of Arc

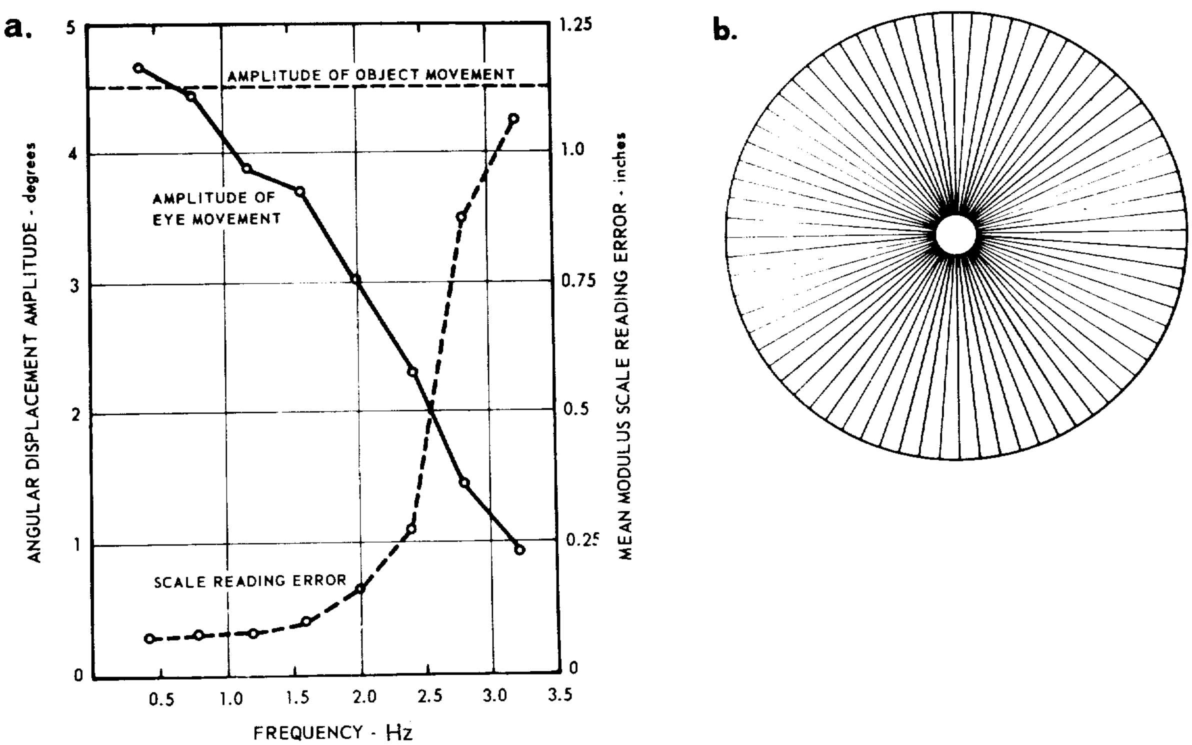
Note that the amplitude ratio of eye movement shows a greater decline with frequency when the target is vibrated than when the subject is vibrated with respect to to a stationary target (continuous lines).

(After Guignard and Irving[83])

Figure 8-45

The Effect of Vibration of Target on Visual Performance

(After White[186], adapted from Jones and Drazin[98])



The diagrams show scale reading error and eye movements when viewing vibrating targets, a radial line disk, (b), and a horizontal scale, (a). The subject's head was fixed, and he was asked to follow the motions of the disk and scale at the frequencies shown, the excursion of .the targets being 4.5 min of arc. The subject's eyes moved with the target at frequencies below 0.5 Hz, but less and less as the frequency increased. Distortion of the radial lines also increased with frequency. Errors in reading the position of markers on the horizontal scale also increased as the frequency increased.

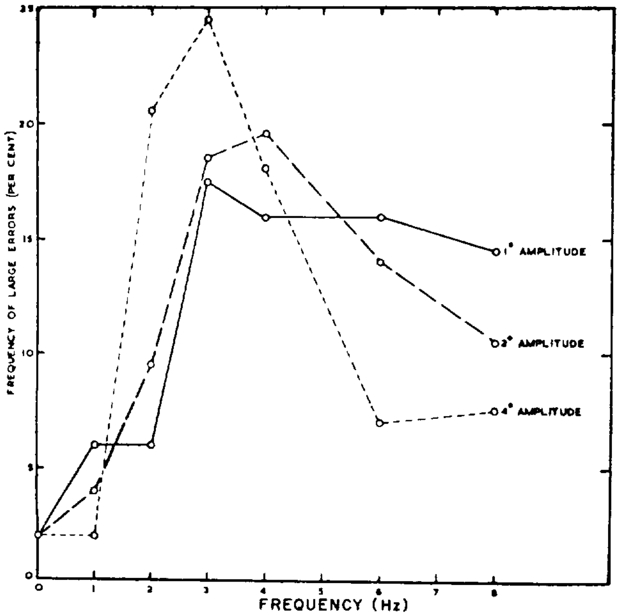


Figure 8-46

Variation of Large Dial Reading Errors (greater than 0.5 scale division) with Frequency and Amplitude of Sinusoidal Dial Vibration

(After Drazin [45])

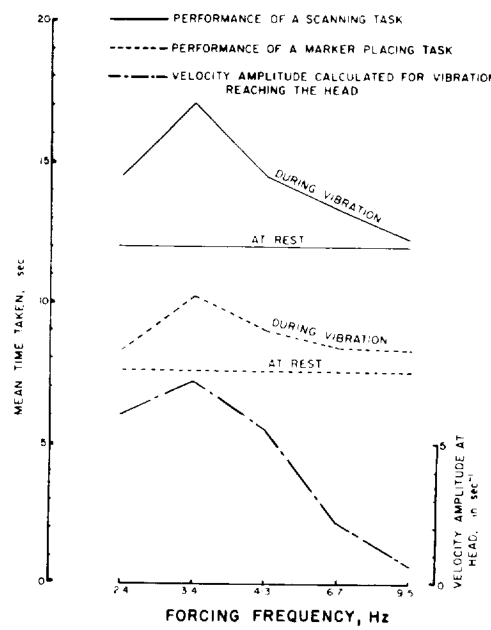


Figure 8-47

Effects of Vertical Sinusoidal Whole-Body Vibration on Performance.

Average times taken to complete accurately the scanning of printed material (continuous lines) and the placing of markers on a board (finely hatched lines), plotted against frequency of vibration. The horizontal lines indicate the control times taken in the absence of vibration. The lowermost curve (coarsely hatched line) shows the calculated velocity-amplitude of vibration reaching the subjects head. (See text)

(After Guignard and Irving[81])

Performance at 6, 11, and 15 Hz was compared at various levels of acceleration with and without use of a helmet restraint. Results indicate that performance of an easy dial reading task was relatively unaffected, but a more difficult dial test incurred performance decrease as the g-load was increased from 0.3 to 2.4 g. Helmet restraint and frequency factors depended on axis of vibration. Helmet restriction improved performance at all frequencies when vibration was in the X axis; improved performance at 6 Hz but degraded it at 11 Hz and 15 Hz in the Y axis; and had no effect in the Z axis. At $1G_x \pm 1.1 G_x$, use of an X-axis piston-spring damper isolation system resulted in less errors than use of an X-axis rigid system at 6 and 11 Hz (164). At 15 Hz, at this vibration intensity, both the pure piston and pure spring systems were effective in the X-axis. A Z-axis restrainthad an effect only at 15 Hz. Free movement of head was better than Z-axis restraint at this frequency. More work is needed on the relative eye movement during restraint in this form of vibration exposure, with special emphasis on cross-axis motions and combinations including roll movements before optimum restraints are possible.

The effects of in-flight vibration on visual function of astronauts of the Mercury and Gemini programs are covered in Light, (No. 2).

Vigilance, Concentration and Reaction Time During Vibration

These functions have been tested by many investigators during low frequency, whole-body vibration but there is no unequivocal evidence that they are directly impaired (31, 91, 104, 111, 154, 161). Choice reaction time with either transverse or longitudinal motion usually shows no relationship to frequency or intensity of motion. No difference from the pre-vibration control level was noted during vibration. However, reaction time significantly increases (subjects slow down) following exposure to transverse vibration (91, 155). This may or may not be due to drop in motivation. It has been suggested that if situations are such that hasty decisions are required of vehicle occupants after a vertical or transverse vibration experience, it can be expected that they will respond slower than normal, and even slower than during such vibration (91). Although it is widely believed that environmental vibration contributes to the lowering of performance by fatigue, the specific mechanisms by which it does so are unknown.

Simple Motor Performance

Measurements of simple motor performance during whole-body vibration have yielded varied results depending more upon the nature of the tests than upon the quality of the environmental stress. In general, those tests which call for maintained intensity rather than precision of volitional activity, for example, strength of grip or speed of tapping, reveal little or no decrement in performance during low frequency vibration (111). On the other hand, tests which call for precise muscular coordination, and positional control of the limbs and extremities, do show adverse effects. The reduction of manual and bodily steadiness has already been mentioned. Large-amplitude vibration or jostling of the body interferes mechanically with fine muscular actions. The performance of tasks involving precise muscular action, such as controlled depression of an accelerator pedal, accurate placing of markers on a screen, throwing switches on a console or using hand-held navigational aids, has been shown to be degraded most by vibration at low frequencies in the region of the major body resonances (81, 91, 154). This is explained by the vibratory excitation of large and rapid differential movements between the operating limb and the point of contact with the task. Fine movements of the hand and wrist, such as in writing, or in turning control knobs on electronic apparatus, in which there is only light pressure of application of the hand to the task, are easily disturbed by vibration. Tasks in which the control may be firmly gripped and provides a greater resistance to operation are less likely to be severely hindered.

Speech, which can be regarded as a special form of coordinated postural activity, can be seriously disturbed by heavy vibration and jolting of the body. This can add to the difficulties of communication by aircrew in flight. Interference with speech by continuous vibration is caused by modulation of the flow of air through the respiratory passages and by vibratory deformation of the organs of speech. The degree of interference is related to the periodicity and intensity of vibration, the dynamic properties of the buccal, cervical and thoraco-abdominal structures involved in speech, and the time-course and duration of the spoken syllables. The disturbance of speech during whole-body vibration is worst at forcing frequencies between about 3 and 15 Hz. Within this band, intelligible speech becomes very difficult at acceleration-amplitudes exceeding 0.5 g (80, 166).

Performance of Complex Tasks.

Whole-body sinusoidal vibration at acceleration-amplitudes exceeding 0.1 g in the frequency range 1 to 30 Hz can produce significant increases in the error scores in compensatory tracking tasks (17, 55, 59, 75, 91, 125, 138, 154). There is considerable divergence between the conclusions reached by different workers, particularly on the relative importance of intensity and frequency of vibration in producing the performance decrement. Some of this conflict of opinion arises from differences in method. Not all investigators have used constant amplitudes of vibration over the frequency band studied; in some experiments the man and the display were vibrated together, while in others the man was vibrated but not the display; and there has been no standardization of either the nature of the display or the type of control used.

It is generally agreed that error scores in tracking tasks rise with increasing frequency at a constant displacement-amplitude, and with increasing amplitude at a given frequency of vibration. It is easy to conclude from this that performance during whole-body vibration depends largely upon the intensity (acceleration-amplitude) of the vibration. However, other factors also contribute. There is a dearth of reliable information about the frequency-dependence of the decrement in performance during continuous vibration. Performance at a task involving the adjustment of knobs on a console vibrated with the man is particularly impaired by resonance of the shoulder-girdle at frequencies around 4 Hz (138).

Transverse vibration or sway (Figure 8-48) lowers most performance more significantly than does vertical vibration (91). The frequency of 1.5 Hz is considered to be a particularly disturbing frequency of vibration in this plane. Fore-and-aft vibration (surge) at 0.15 g may impair tracking performance. Figure 8-48b shows that performance over comparatively long periods of vibration (30 min) deteriorated with the passage of time during continuous steady-state vibration. Tracking ability was also found to be worse during the immediate post-vibration period than during the preliminary control test. While part of the decrement in performance during vibration can be explained as simple mechanical interference with the task; other factors, including the motivation of the subject during prolonged periods of working under environmental stress, must also operate.

A systematic study of tracking performance during vibration at frequencies from 2 to 12 Hz and amplitudes from 0.0625 to 0.25 in., showed that the decrement in performance is a function of amplitude and a fractional exponent of frequency (59). (See Figure 8-49). The error score was reported to be approximately proportional to $A\sqrt{f}$, where A is the displacement-amplitude of vibration and f is the forcing frequency. However, a generalization that tracking error scores are proportional to displacement amplitude times the sq. rt. of frequency may be an erroneous concept in view of what is known concerning the relationships between body resonance phenomena and tracking performance (63). The presentation of data at constant displacement amplitudes and varying frequencies obscures the fact that there is tremendous variation in the resultant acceleration levels and could lead to obfuscation and misinterpretation of frequency effects. No theory has been presented to support this relationship. Tracking ability when the man and the display are vibrated together were compared with that when the man alone was vibrated relative to a static display. The latter condition created greater difficulty for the subjects and increased the error scores.

The direction of the tracking task relative to the direction of vibration appears to be a factor in performance. A comparative study has been made of the effects of whole-body vertical vibration at frequencies of 5, 7, and 11 Hz from 25-35 percent of the human tolerance levels (defined by amplitude levels within each frequency in Reference (26) on performance of tasks representative of those encountered in aerospace flight (12). Within the limits of the vibration conditions studied, it was found that while the most pronounced decrements occur in vertical tracking, decrements in horizontal tracking, especially at 5 Hz were quite large. Vertical tracking errors ranged from 34 to 70 percent greater under vibration than under vibration-free conditions in the first experiment, although there was some adaptation on the part of the subjects since the magnitude of the vertical tracking performance decrement was lower in each treatment cell. However, the smallest vertical tracking decrement observed was still about 23 percent. Horizontal tracking decrements ranged from 10 to 48 percent with very little change between experiments. The magnitude of the tracking performance decrements was related to the magnitude of integrated absolute G_z (output) measured at the sternum. More procedural errors were committed under vibration than under static conditions. This degree of degradation is likely to reach unsatisfactory levels of decrement in an operational situation. This reach has been extended to include a study of the effects of tracking performance at vertical peak acceleration values of 25%, 20%, 15%, and 10% of the one-minute tolerance level at 5 Hz (86). (See the squares in Figure 8-51b). It was determined that a statistically significant decrement at 5 Hz began at 0.20 g or 20% of the one-minute tolerance level. No significant decrement in performance occurred at 15% and 10% tolerance. Another significant effect in this experiment was that due to trails. The performance of the subjects improved through each 5-trial testing period. Trials were three minutes in length and five trials were presented during 20 minutes of continuous vibration. It would be tempting to postulate that the disruptive effects of vibration, of the g levels used in this experiment, are temporary, and the subject adapts to them. There was a trend (not significant) for greater adaptation to take place for the two higher amplitudes than for the two lower ones.

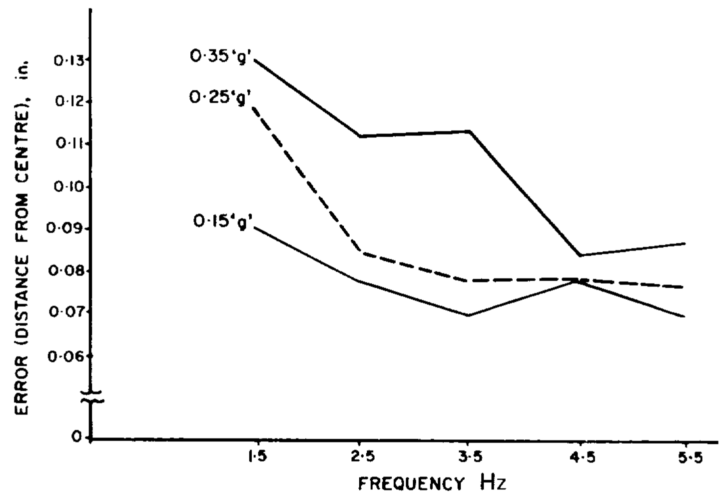
Figure 8-48

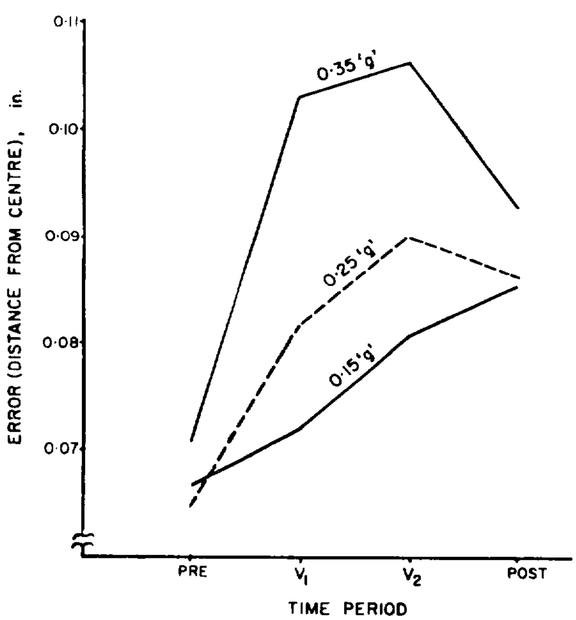
Effect of G Load, Frequency, and Duration on a Compensatory Tracking Task

(After Hornick et al[91])

a. Performance of a Compensatory Tracking Task as a Function of Frequency and Intensity of Transverse Whole-Body Vibration (acceleration-amplitude is the parameter).

Note that the error scores are greatest at 1.5 Hz and increase with increasing acceleration-amplitude.





b. Performance of a Compensatory Tracking Task as a Function of Intensity and Time Period for Transverse Whole-Body Vibration (acceleration-amplitude is the parameter).

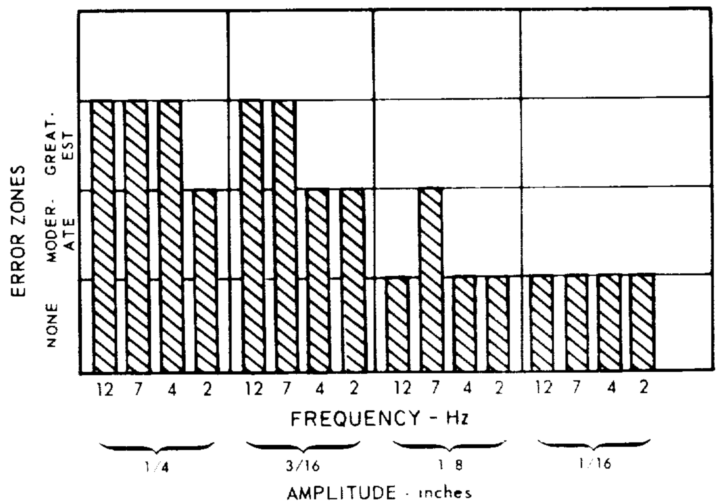
Note that performance worsens (error scores increase) during the second half of a 30-min. period of vibration and that some deterioration, compared with the control period, is present immediately after vibration has ceased.

Figure 8-49

Tracking Performance During Vertical Sinusoidal Vibration While Unrestrained

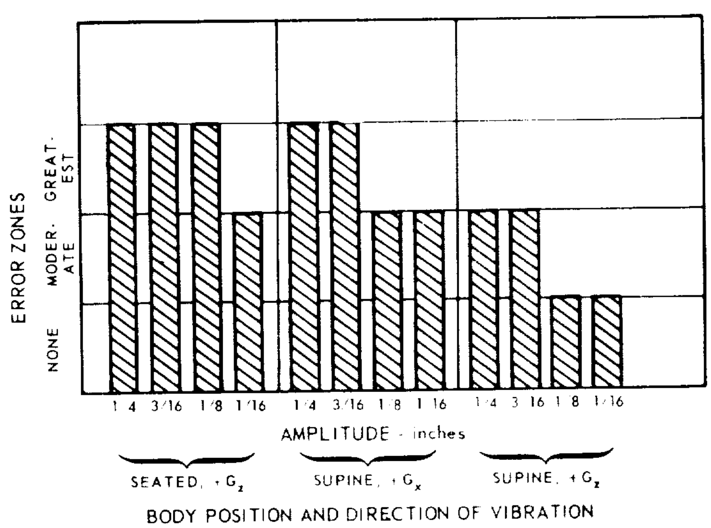
(After Webb[178], adapted from Fraser et al[59])

a.



The averaged effects of both amplitude and frequency of sinusoidal vibrations on error in a tracking task are shown for four subjects who were entirely unrestrained. Maximum accelerations were 3.63 G.

b.



The effects of the direction of vibration and of amplitude are shown for the same experimental situation as in a.

Recent comparisons have been made of the effect of whole-body vertical vibration on tracking performance with compensatory wheel, column, and foot systems (20) in 4 subjects at frequencies ranging from 1 through 27 Hz. A good correlation was found between general subjective experience and tracking performance. Maximum effects were noted in the 10-20 Hz range. Within the limits of this experiment and over the entire range of vibration frequency and intensity, increased force requirements in foot tracking produced the lowest degree of error but are increasingly affected by vibration. Thus, if precision is of utmost importance and the environment is to contain little vibration, higher force values (150 lbs.) are recommended; whereas, if vibration is to be present and consistency in performance is the objective, lower values (50 lbs.) appear most appropriate. Foot pressure constancy is most severely affected at 1.5 and 2.5 Hz at 43 lb./inches during transverse, and at 3.5 Hz during longitudinal vibration (91). Error increases with intensity. There is no trend of error over time, and recovery is virtually complete following exposure. The frequency dependence may vary with pressure.

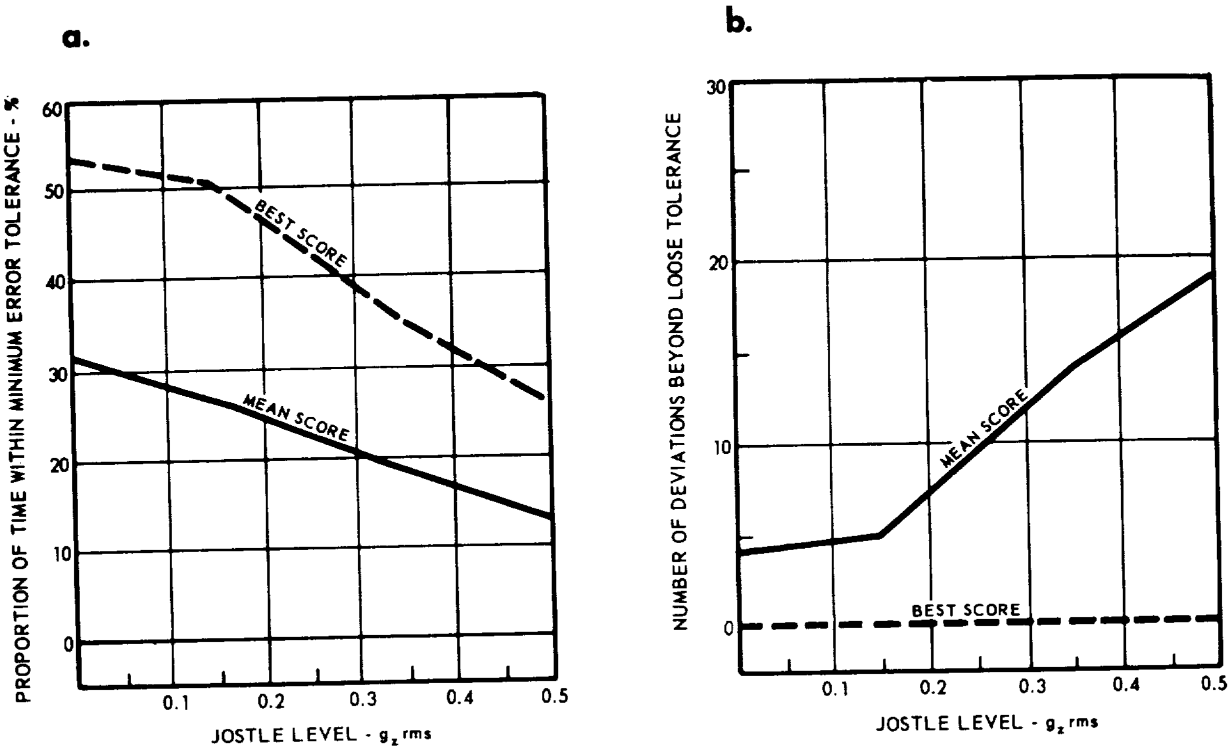
The effects of random vibrations or jostle on control tasks are seen in Figure 8-50. The difference between sinusoidal, random-amplitude and random amplitude-and-frequency vibration has received study (20, 25, 138). A comparison has been made of tracking ability during sinusoidal, narrow-band and wide-band random vertical vibration, produced by a dynamic flight simulator (20). The three types of vibration were equated in terms of their rms displacement-amplitude. The random vibration represented flight through turbulence having characteristic modes of vibration at 0.75 and 2.5 Hz and had a power spectral density representation with peaks at about 0.01 g^2/Hz at 1 and 2.5 Hz. Sinusoidal vibration was applied at 0.75 and 2.5 Hz, which were also the nominal frequencies of the narrow-band random vibrations used. The report revealed no clear-cut difference in tracking performance during sinusoidal and random vibrations of the same rms intensity. Under the conditions of the trial, significant differences were found only when the design of the display was important in relation to the direction of vibration. A marked decrement in performance was measured during steady-state vibration at 2.5 Hz and 0.54 in. amplitude when the task involved vertical tracking with a control-display feedback delay. The time-constant of the feedback delay was 2 sec, which is representative of an aircraft control system.

In another set of experiments an attempt was made to study human subjects under whole-body vertical vibration to compare effects on performance of 5 Hz sinusoidal, 5 Hz random amplitude, and 4-12 Hz random vibration equated on the basis of power, and determine acceleration levels at which significant performance decrements are found for each type of vibration (183). The complex experimental task required two-dimensional compensatory tracking, visual monitoring, and auditory monitoring during 20-minute vibration exposures at levels equated to 5, 15, 25, and 30 percent of the 1-minute human tolerance values for 5 Hz sinusoidal vibration. Performance decrements under vibration were restricted to tracking, the most demanding component of the task complex. Tracking performance deteriorated with increasing acceleration levels of each type of vibration. Overall performance differences associated with the different types of vibration equated on the basis of power were not significant. A number of task and procedural variables,

Figure 8-50

Tracking Performance During Vertical Jostle

(After Webb[178], adapted from Clark[22])



These two figures illustrate the increasing difficulty of performing a demanding control task as random vertical vibrations ("jostle") increased in magnitude. Pilots were held by a Navy torso restraint device in the North American Aviation "G-seat," which was then programmed to move in the $\pm G_Z$ direction with an electrical white noise input, and jostle levels of: 0.15 G_z rms (root mean square) described by the pilots as similar to flying through mild turbulence; 0.35 G_z rms, described as severe turbulence; and 0.50 G_z rms, in which the largest jolts were classed as one-of-a-kind in a real flight. Power density spectra peaked near 1 Hz. A panel-mounted accelerometer showed maximum and minimum accelerations of 0 to 2.5 G_Z for 0.15 G_z rms; -1.2 to 4.0 G_Z for 0.35 G_z rms; and -2.5 to 5.0 G_Z for 0.5 G_z rms. The demanding control task was to track in pitch, shown on a 5-inch oscilloscope screen, and hold roll to 0. Fourteen highly motivated and skilled Navy pilots made 70 runs; they tolerated the random vibrations well, although they had to brace themselves against the larger seat movements to avoid slapping of the head or body against the structure. Longer runs – 15 to 30 minutes at 0.35 G_z rms – produced muscular fatigue.

Chart a shows what tracking error occurred as the jostle levels increased; the minimum tolerance for error was set to be 1/12 of the task amplitude. Chart b shows that as jostle increased, more and more tracking deviations appeared beyond the loose tolerance level of 5/6 of the task amplitude.

including task difficulty, work-rest cycle, and prior experience appear to be important determinants of performance capabilities and fatigue effects found in vibration studies, indicating a need for further investigation of these variables. For various pairs of periodic vibration exposure having the same rms but different peak accelerations, subjective severity ratings seem to depend on differences in peak acceleration but motor functions such as holding hand and arm in fixed position depend on rms values. The evidence presented above indicates that differences in bandwidth and spectral density characteristics of vibration conditions equated on the basis of power (mean square acceleration) are of far less importance in determining performance capabilities than other experimental variables. Inasmuch as the vibration conditions tested cover a significant portion of the 1-20 Hz range in which the more significant effects of vibration are found, further study should be undertaken to test the generality of this finding. If performance equivalence of power values is found to hold within a number of frequency bands spanning the 1-20 Hz range, the way will be open to utilize data derived from tests with simple sinusoidal vibration in predicting performance under more complex spectra.

A major difficulty of research in this area still centers on selection of performance tests representative of operational tasks for which difficulty levels and operator loading can be specified. If unitary activities such as tracking or visual monitoring are tested in isolation, measurement problems are simplified, but task difficulty must be increased in order to achieve adequate sensitivity to stress effects. An alternative is to employ complex tasks which require time-sharing of attention among several activities. The use of tasks of this type, which simulate more closely operational situations, will be facilitated if some effort is devoted to establishing the difficulty level of the total task complex and each of its component activities. One approach which merits consideration is the use of secondary task scores to measure operator workload. Techniques are available for deriving quantitative estimates of operator loading in a complex task by measuring ability to perform an auxiliary task concurrently (49, 101, 102).

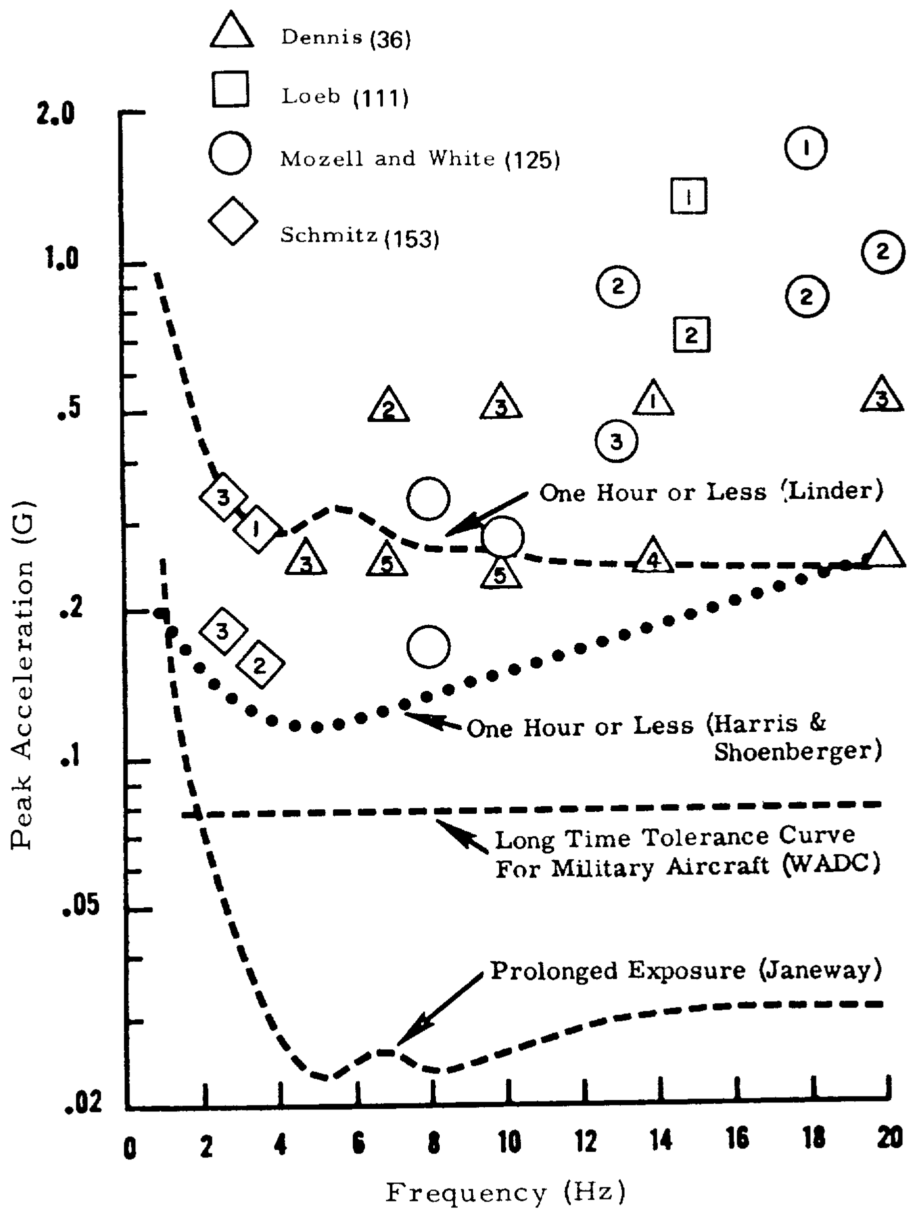
An interesting comparison has been made between the long-time tolerance limits proposed and the result of visual acuity tests and tracking performance as shown in Figures 8-51a and b. The curves offer an excellent opportunity for display of the effect which experimental variables may have on the setting of performance thresholds. The following discussion is taken from this review (87).

In Figure 8-51a, the geometric symbols refer to the studies of particular authors and their locations on the figure indicate the levels of vibration at which visual acuity was tested. The numbers inside the symbols show the relative level of decrement obtained within any one study. Number 1 denotes the greatest decrement with successive numbers indicating decreasing decrement. The absence of a number means that no decrement was obtained. There is nothing to indicate that visual acuity will be adversely affected at the levels of the two long-term exposure curves at the bottom of the figure. Of course, no data are presented at these levels. However, it seems extremely unlikely that visual acuity would be significantly affected at these low g values. (See also Figure 8-23a.)

Figure 8-51

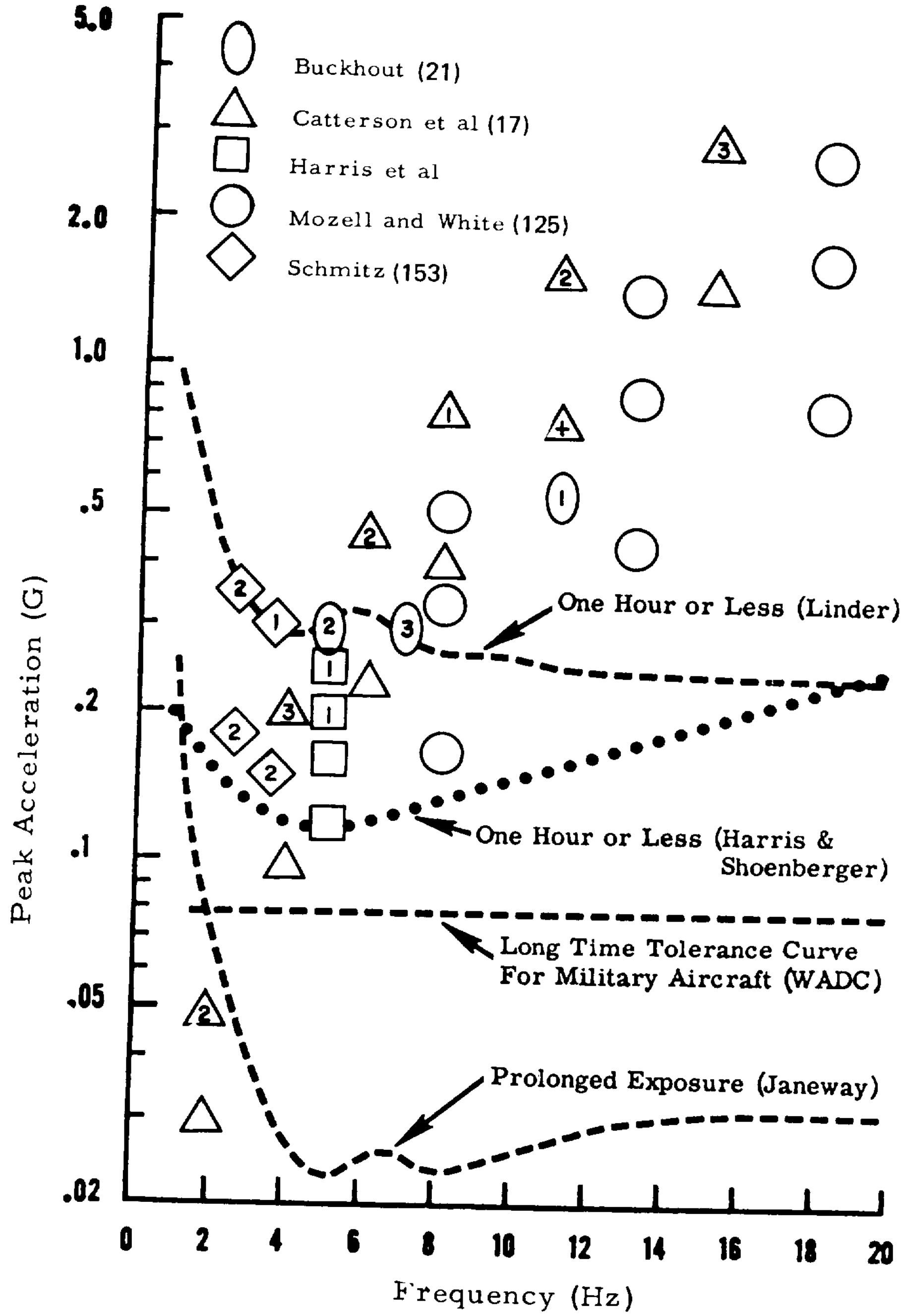
Performance During Vibration in Relation to Long-Time Recommended Limits

(Adapted from Harris and Schoenberger [87])



a. Performance on Visual Acuity Tasks (See text)

Figure 8-51 (continued)



b. Performance on Tracking Tasks (See text)

The upper curve (one hour recommended limit) has numerous data points surrounding it; some showing decrements and some showing no decrements in visual acuity. Of particular interest are the data presented by Dennis because they follow the recommended one hour exposure curve rather closely. The greatest decrement occurred at the 0.25 g level at 5 Hz, with less decrement occurring at 14 Hz, still less decrement at 10 Hz and at 7 Hz, and finally none at all at 20 Hz. Thus these data look pretty good in relation to a body resonance hypothesis and would suggest an alteration of the curve more in line with body resonance. However, the situation is complicated by the data points indicated by the circles (Mozell and White). At 8 and 10 Hz at g values higher than used by Dennis, no decrement in visual acuity was obtained. There are data by Schmitz at lower frequencies of 2.5 Hz and 3.5 Hz indicating a decrement in visual acuity at the level of the curve. These data are also in line with body resonance in that a greater decrement in visual acuity was obtained at the frequency value closer to body resonance, that is, a greater decrement was obtained at 3.5 Hz than at 2.5 Hz.

All of the remaining data points on the graph are above approximately 0.4 g and all indicate a decrement in visual acuity. Of interest again are the data obtained by Dennis at 0.5 g, since he held peak acceleration constant and varied the frequency. At 0.5 g the greatest decrement occurred at 14 Hz, the next at 7 Hz and the next and last ones at this g level are 10 and 20 Hz. An interesting comparison is that as much error occurred at 0.25g at 5 Hz as occurred at 0.5 g at the frequencies of 10 and 20 Hz. The contradiction between the Mozell and White data and the Dennis data can be easily explained. A comparison of the data of these investigators shows that Dennis used a much more difficult task for measuring visual acuity than did Mozell and White. Dennis found about 15% error in visual acuity during control conditions, and Mozell and White found essentially no error in visual acuity for the control conditions in their study.

In Figure 8-51b, tracking performance data obtained under many different conditions is presented for comparison with the recommended long-term tolerance curves. Perhaps the most striking aspect of this figure is the fact that Mozell and White found no decrements in tracking performance at any combination of frequency and peak acceleration used. Many of these data points of Mozell and White are at levels where other investigators found tracking ability adversely affected; and also, from the preceding figure, it can be seen that consistent losses in visual acuity occurred at much lower levels than those at which Mozell and White failed to find tracking performance decrement. In reality, the simplicity and grossness of the display and the simplicity and crudeness of the motor response account for this discrepancy (87, 125).

The subjects in the study by Catterson et al were not restrained, while the subjects of all of the other investigators represented on this figure were. Overall, the data of Catterson et al seem to correspond fairly well with body resonance except for the two data points at 2 Hz. At this frequency, 0.05 g produced a decrement in tracking performance where 0.03 g at the same frequency did not. While it is difficult to explain the difference in performance obtained between these small g levels, it is perhaps possible to understand why decrements could occur at such low values. The authors state, "there is objective evidence of a sedative and somnolent effect of vibration at 2 Hz (17). This could explain the decrement which occurred at 2 Hz and would suggest that it occurred for a very different reason than the decrements at other frequencies. However, one doesn't have to look far for another unusual finding in these data. Catterson et al found an improvement in performance at 11 Hz at approximately 0.7 g. Buckhout found a large performance decrement at the same frequency at approximately 0.5 g.

There does not seem to be any generalized information that can be gleaned from this figure except for some suggestive evidence that tracking performance is more likely to be affected around body resonance, 3-8 Hz; however, as with the visual acuity data presented in Figure 8-51a, inconsistency exists here also. Considering both the visual acuity and the tracking data, about the only thing one can say about Linder's recommended 1 hour tolerance curve is that the g values seem too high at the low frequency end of the curve. One might also say that the g values appear to be too low at the high frequency end of the curve. In view of the fact that these studies lasted less than 1 hour, it would seem advisable to err on the side of conservatism, and to suggest further that Linder's curve is too high throughout the frequency range. Harris and Schoenberger curves for exposure times up to 1 hour are presented as the dotted line in Figures 8-51a and b. It represents somewhat of a compromise between Linder's curve and the WADC curve. Although the acquisition of new data will undoubtedly necessitate changes in this curve, it is believed to be a more realistic estimate than the one presented by Linder. In the absence of data to indicate otherwise, one may also suggest the WADC curve as a design guideline for long-term exposure, in preference to Janeway's curve.

Performance under Combined Vibration and Linear G

The effect of combined linear and oscillatory acceleration of liftoff and reentry patterns on pilot attitude-control capabilities are of interest. One might expect different resonance spectra under zero gravity and g loading superimposing vibration at 11 Hz onto a steady linear acceleration on the tracking ability of a human pilot in a stability- and rate-augmented vehicle with dynamics typical of a large high-thrust rocket (43). The linear accelerations ranged from 1 to 3.5 g and the oscillatory stresses varied from 0 to ±3.0 g at 11 Hz. A random-appearing compensatory tracking problem was presented to the pilot in the pitch plane, although the pilot controlled both pitch and yaw. No attempt was made to simulate additional pilot tasks such as monitoring of critical launch vehicle and spacecraft performance and status displays which would be required in the real situation. Various damper-failure situations were investigated, and certain characteristics due to non-linearities of the autopilot were studied. Effects on the tracking efficiency of dividing the pilot's attention between pitch and yaw channels were also examined. Both performance measures and subjective opinion indicated substantial degradation in pilot tracking effectiveness above vibration levels of ±1.5 g at 11 Hz. The pilots were almost completely ineffective at ±3.0 g vibration.

Under vibration, the pilots reached the limit stops of the engine-servo rate and position often enough that a linear analysis of the pilot describing function was difficult. Pilot comments indicate that they could not perceive rate information from the visual display (rate of needle motion). It is therefore assumed that the pilots were unable to generate the lead time constant usually necessary in this type of tracking. The engine-servo rate and position limits were chosen to simulate a typical large high-thrust booster rocket. The problem often arises in a study of this type that the vehicle and control dynamics are not compatible with the "standard" task. However, the task was selected so that comparisons could be made with previous studies. The highest frequencies of the present task were somewhat too high for the airframe-autopilot combination used and it was suggested that increasing the engine-servo rate limit would permit the pilot to improve his performance. Limiting the rapidity with which the control system under the pilot's direction can act also prevents him from tracking rapidly. Hence, the portion of the input not filtered by the system, the remnant, would tend to increase the error. To determine the magnitude of this effect in the present study a series of runs were made for three values of servo rate limits under 1 g static conditions using one above-average pilot. The results indicate an improvement between 5^o/sec and 20^o/sec with a modest improvement up to 50^o/sec. A brief investigation of the pilot's ability to cope with sudden changes in the controlled element was made by simulating pitch damper failures. The period of temporary adaptation required was approximately 15 seconds at a 3.0 $+G_x$ linear acceleration and ±2.0 Gz vibration, while for a +1 G_z acceleration, it was 5 seconds.

Dial reading has been studied in the semi-supine position of Figure 8-24 as a function of the level of 11 Hz G_x vibration and the size of the dial, where a bias acceleration of 3.75 G_x was superimposed on the vibration (26). Dial reading errors were inversely related to the arc length of the interval between dials and directly related to the amplitude of vibration. There was approximately 50% distortion of the 11 Hz vibration acceleration, which markedly influences the interpretation of results and their comparison to measurements of visual decrements from 11 Hz vibrations with 1 G_x bias loads. In most general terms, however, the 3.85G_x bias, and/or the unidirectional force (i.e., the resultant acceleration was always greater than 0G) creates a subjectively more tolerable environment than with a 1 G bias. Vibrations of 3.85G_x ±3.0g_x were without serious subjective effects in exposures of 90 seconds duration. Gross comparisons of dial reading performance under the two conditions provide some indication that the greater bias acceleration is associated with less visual decrement, probably as a result of alteration in resonance peaks at the eye.

The increase in the tolerance seen from trial to trial during studies of performance is of interest from the point of view of training to vibration tolerance (86). Also of interest is the fact that when an intensity range is reached that produces significant increments in error, the standard deviation is much larger than would be expected from the increase in the size of the mean (32, 87). The major reason for the large increase in variability is that some individuals show a tremendous increase in error while other individuals in the same experiment show little or no increase in error. This result has been obtained even for experienced pilots (146). This fact suggests that one may select individuals for those missions with a greater potential for vibration hazard, such as those with boosters giving severe POGO effects. (See Light, No. 2.)

Performance on Launch Towers During Horizontal Oscillation

Preliminary attempt has been made to determine on-tower-limitations of the capabilities of standing workers performing servicing tasks in the arms of the tower about the Saturn V Vehicle at a firing site on Launch Complex 39 (157). It was determined that horizontal, linear, sinusoidal oscillation-frequencies of 0.33 Hz and 0.80 Hz were satisfactory samples of the wind conditions that could be expected (162). The corresponding amplitudes of ±6.3 inches and ±7 inches could be expected at the uppermost level. Three tasks were performed at each of the frequencies and amplitudes: a hand accuracy test for nut and bolt assembly; a hand-probe steadiness test; and a visual acuity test. No significant differences were found in the results of the tests at 0.33 Hz, but significant decrements of performance appeared at 0.80 Hz, especially in precision tasks which cannot be done readily at this frequency. There were significant differences between G_x and G_y axes in these tests. More time is needed for tasks that do not require precision, but at 0.80 Hz, an increase of time does not result in an increase of performance accuracy of precision tasks. Visual acuity is lessened at 0.80 Hz only when worker-subject is oscillated from shoulder-to-shoulder. It was recommended that performance-time at 0.80 Hz should be limited to compensate for increased human error from fatigue which is seen at this frequency.

PROTECTION AGAINST VIBRATION

Techniques for reducing the transmission of vibration to vehicle-mounted equipment apply equally to man. These include vibration isolation, the use of nodal positions, and attention to the immediate routes of entry of vibration into the body. Protection against vibrations is so far mainly achieved by vibration isolation, a method relatively effective, economical, and requiring little space at the higher frequencies (13, 41, 70, 73, 80, 85, 129).

Vibration of the support structures at frequencies near the resonant frequency of a mass-spring system is made worse by spring isolation. Damping must therefore be included but unfortunately, the greater the amount of damping, the less attenuation is achieved at higher frequencies. There is also conflict between the demands of an isolation system for continuous vibration (a low frequency suspension with light damping) and those of a system for discrete impacts (a stiff suspension with fairly heavy damping). This problem is not easily resolved and passenger vehicle suspension systems represent a practical compromise. Motor car and railway carriage suspension systems have been found empirically to give the best overall ride with a natural frequency of 1 to 1.5 Hz and damping between 0.5 and 0.7 of critical for viscous damping or its equivalent. Such a system may slightly augment vertical oscillations near the resonant frequency. Suspensions with resonant frequencies below 1 Hz give a smoother ride but tend to make passengers motion sick.

The human may be passively isolated by means of a suspension seat or similar device. As a rough rule, the loaded system should have a resonant frequency not exceeding one half of the lowest frequency from which it is desired to isolate the load. For man, in vertical excitation, the latter may be taken to be 3 to 4 Hz, so that the resonant frequency of an occupied suspension seat should lie between 1 and 2 Hz. The precise spring stiffness and damping appropriate to particular conditions are a problem for individual solution. Provision should be made for the independent varying of stiffness and damping to suit the individual user and the particular circumstances. More practicable, although limited, advantages can be gained by fitting non-linear springs of the "hard" type to suspension seats. The stiffness of such springs increases with deflexion, so that displacement of the load is reduced for heavier vibration. A combination of non-linear stiffness and suitable damping can be obtained in rubber suspensions, or in spring and damper systems embodying special features such as recruitment. Pneumatic springs and other active isolation devices, in which displacement of the load is opposed under servo control by power supplied to the system, may also have applications in suspension systems.

The vibration of instruments, making them difficult to read, is reduced by placing the instrument or instrument panel on anti-vibration mountings. The resonant frequency of the loaded mountings should not fall within the range which is critical for instrument legibility. Design for operation by wrist and finger movements, rather than by extended movements of the whole arm, will improve the vibration resistance of control systems.

Below 5 to 10 Hz the large space required to compensate amplitudes at tolerance limits often prohibits application of isolation methods in aerospace-craft. Improved body restraint and suppression of individual resonances is a promising approach in this frequency range. The effects of such protective restraints, enclosures and supports have only been investigated in a very preliminary way (118, 168). Some increase in tolerance appears possible, although some supports such as integrated impact protective devices in suits can keep subject from relaxing and produce a less favorable coupling with the vibration source. Mice have been protected from damage from 20 Hz vibration at 7 G (rms) by positive pressure breathing at 3.75 and 6.00 inches of H_2O, but no direct extrapolation of efficacy to man is possible (9).

Contoured and adjustable couches have been used in spacecraft. In experiments with these adjustable couches (reviewed in Figure 8-24 and Table 8-25) the role of restraints becomes obvious in the discussion which is recorded here (168).

A structure is needed which will more effectively couple the head to the vibration source, and provide better body-to-couch coupling by reducing dead space, minimizing restraint slackness and lessening the possibilities for body-couch phase shift. The adjustable couch was designed to answer these needs and does provide considerable improvement in body-to-couch coupling. However, it does not completely solve the coupling problem. Further, the more positive restraint and protection that it provides for the helmeted head is only partly successful in improving tolerance.

The problem of operational head restraint and protection is a particularly difficult one. During the departure and reentry phases of space flight, the sustained linear acceleration, or deceleration, and associated severe vibrations will make head protection very important. Despite adequate restraint the head may still be subjected to severe uncontrolled, and possible injurious buffeting under some circumstances. In the study of Figure 8-24, with the head helmeted and well coupled to the couch, the symptoms limiting tolerance at the low frequencies seem to have been minimized. However, the coupling appears to have accentuated head discomfort and caused lower tolerances at the higher frequencies, particularly in the X and Y axes. This is in contrast to exposures in the contoured couch when raising the unrestrained, unhelmeted head from the couch helped to isolate it from the vibration source, contributing to better tolerance levels at the higher frequencies. It is possible that, in the adjustable couch, the mass of the head may have been resonating with the helmet and elastic liner, magnifying the vibration input to the head and causing lower tolerances. However, a study on the subjective tolerance of the restrained head vibrated alone at frequencies between 10 and 30 Hz, helmeted and unhelmeted, revealed that use of the helmet did afford an advantage in isolation and protection of the head when compared with results obtained under the same conditions without a helmet (168).

The significance of the observed relationship between head restraint and frequency in the response of the head to vibration has been given some emphasis by the results of a series of dial reading performance studies recently completed utilizing the adjustable couch in essentially the same configuration as used in this study (165). (See above.) One of the questions asked in these studies concerned the influence of head restraint on dial reading accuracy. It was demonstrated that accuracy below 8 Hz was greater with the head restrained than if it were unrestrained. The opposite was the case above this frequency range. These results held true for the X and Y axes, but not for the Z axis. A broad generalization concerning the interrelationships of head restraint, frequency and tolerance is not warranted on the basis of this study. Given the results obtained with this particular system, however, it appears that a head restraint should provide close coupling to the vibration source at frequencies up to about 10 Hz, and should provide isolation from the source at frequencies between 10 and 20 Hz. (Preliminary test of this idea was covered in the section on dial reading, page 8-90.)

One can look at protection from an impedance point of view (128, 179). Vibration tolerance, in terms of velocity, is relatively lower at the higher frequencies as shown in Figure 8-24d and e. In fact, the tolerance curves are strikingly similar in form to the inverse ($1/|Z(\omega)|$) of the impedance magnitude. The velocity tolerance appears to be lowest where impedance is highest and vice versa (179). There are also perturbations in the tolerance curve corresponding to the critical frequencies. In comparison to the effect of other frequencies, the perturbation in the velocity tolerance curves due to resonant frequencies is not as impressive as it is in the acceleration tolerance curves.

Acting on these facts, one can approach the problem of protection system design (179). The basic problem is to minimize the amount of power exchange by the human with the environment (105, 140, 141, 142, 143, 171). In other words, the protection system should have a characteristic such that, when interposed between the human and the environment, it modifies the environment to minimize transmittal of energy at the frequencies where the impedance is absolutely or relatively highest. Therefore, on accepting the premise that the mechanical energy, per se, damages the human, one would try to design a protection system whose velocity transfer characteristics attenuates 7 and 12 Hz energy and high frequency energy while passing low frequency energy. In fact, the protection system velocity transfer function could be the reciprocal of the impedance magnitude. There is an aspect of protection system design which cannot be specified by the impedance method. This is the absolute level or the total energy or power which can be transmitted with safety. In other words, there is no specification on how much energy the protection system must dissipate within itself. Also, in the real-world situation, both impact and vibration must be considered in design of the ideal restraint system and the appropriate tradeoffs mode. (See Impact section in Acceleration, No. 7.)

The most recent work on vibration isolation for aerospace pilot protection under low-altitude, high-speed flight suggests that passive systems cannot provide the required degree of isolation while simultaneously limiting maximum displacement to desired values (13). An active hydraulic system employing acceleration and displacement feedback mechanisms has been proposed.

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