HANDBOOK OF
HUMAN VIBRATION

M. J. GRIFFIN

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M. J. Griffin

Human Factors Research Unit,
Institute of Sound and Vibration Research,
The University,
Southampton, U.K.

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Preface

Whether hunting, or fighting, or sailing the seas, or chopping down trees, our ancestors were exposed to many forms of vibration. Today, the human body is exposed to vibration while travelling (by road, rail, air or sea), during leisure and domestic activities and in many occupations. Interest in human responses to vibration has grown: the mechanized sources of vibration have increased, the number of persons exposed has risen, the expectation of the quality of life is greater, the activities to be undertaken while being exposed to vibration have become more demanding, and the understanding of the generation, transmission and control of vibration has improved. Not least, however, understanding of the many human responses to vibration has advanced.

This book commences with an introduction to both vibration and possible human responses to vibration. Understanding of human responses to vibration is considered in two parts: whole-body vibration (Chapters 2 to 12) and hand-transmitted vibration (Chapters 13 to 19). The scope of each chapter, and the sections within each chapter, were primarily determined by the need for information in different areas rather than the volume of available information. This arose from the desire to understand human responses so that they could be 'modelled'. This book is not, therefore, an uncritical catalogue of all that has been reported, but an attempt to explain what is known. The extent to which this has been possible varies according to the state of knowledge in each area. Many chapters provide pictorial models of the relevant variables and their possible interactions. In a few cases, the models are very tentative: it is hoped that they will stimulate the research necessary to provide a better understanding. In some areas, work is still confined to the data-gathering stage and it is not possible to explain what is known. In the case of epidemiological studies, much of the available data are summarized in eight appendices in order to provide easy access to diverse information.

The study of human responses to vibration offers many challenges and presents many rewards. A major challenge arises from the extremely diverse multi-disciplinary nature of the subject. Human vibration involves physics, psychology, mathematics, physiology, engineering, medicine, and statistics, but little progress will be achieved while cocooned within the limitations of any single discipline. There can be few matters of everyday concern which place such varied demands on knowledge. The principal rewards may come either from any success in extending the boundaries of the understanding of these disciplines, or from combining the techniques of two or more disciplines.

The diversity of the subject can be a cause for consternation among those wishing for simple and useful information without a great depth of understanding. This book was written to provide a sufficient understanding of human vibration for both students of the subject and those addressing practical problems. In order to assist the potentially diverse readership, the book does not depend on an advanced knowledge of mathematics or a familiarity with jargon from the various disciplines. Where mathematics is employed it is either explained or is not essential to an adequate understanding of the material. A large multidisciplinary glossary of terms has been compiled to assist in the understanding of relevant technical and medical jargon. The information presented in the book should, therefore, be accessible to all persons interested in human vibration: medical doctors, engineers, lawyers, scientists, trade union officials and administrators.

While meeting with various groups in many countries in recent years I have been struck by the curiosity shown both by those with, and by those without, a problem related to human vibration. I hope this book provides answers to some of the many questions and directs the reader in an appropriate direction for further information. I have tried to encourage what, I hope, is a 'healthy' scepticism of some types of commonly offered information and to discourage the blind acceptance of what is written. The text, figures and tables in the book are not reproductions of what has frequently been presented in previous reviews; for example, most figures are either newly compiled or taken from recent scientific publications. While tables and graphs appear to present facts, the overriding message is that human responses change according to a complex set of circumstances.

Neither the application nor the republication of data is wise without understanding their origins and their limitations. For this reason, and because alternative data are frequently unavailable, many of the illustrations and conclusions are taken from studies conducted in my own laboratory. The prolonged genesis of this book has allowed its structure and associated philosophical approach to influence our research and generate data and conclusions contained within the book. This presented a dilemma because in several areas there are currently no truly comparable studies. I apologize for this self-indulgence and hope that others will challenge both the philosophy and the findings. Understanding of human responses to vibration continues to advance: if any of the information is re-offered elsewhere it should be accompanied by an appropriate re-interpretation in the light of the gradual unfolding of knowledge.

The writing of this book commenced in about 1980 and grew out of a report then being prepared for the Commission of the European Communities. Although the structure of the book was soon decided, it only gradually became apparent that the adequate treatment of the subject matter of each chapter required such lengthy considerations that some chapters became larger than some books. Nevertheless, the complexity and diversity of human responses is such that no chapter is complete and the offerings are mere shadows of reality.

It is hoped that readers will find something of interest and go on to learn more about human responses to vibration.

M. J. Griffin

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Acknowledgements

The information presented in this book has benefited from discussions with colleagues in many countries. It has been the author's particular good fortune to study human responses to vibration within the Human Factors Research Unit at the Institute of Sound and Vibration Research with undergraduates, research students, research assistants and research fellows having a diverse range of interests. By way of a small gesture to the considerable contribution they have made to the author's understanding of human responses to vibration, colleagues involved in relevant research are identified here in approximate order of their arrival in the Human Factors Research Unit: Rod McKay, Gray O'Hanlon, Colm MacAogain, Brian Rao, Christine Alexander, Les Fothergill, Ray Meddick, Nick Hawkins, Dave Fleming, Jackie Riddett, Chris Lewis, Eleri Whitham, Ken Parsons, Tom Furness, Colin Corbridge, Ann Dwyer, Neil Storey, Max Wells, Martin Cogger, Cam Macfarlane, Colin Norman, Tony Lawther, Merrick Moseley, Roger Weaver, Eric Abel, Tom Fairley, Ron McLeod, Silviane Villon, Harry Woodroof, Terry Simpson, Steve Libby, Geoff Walker, Eurico Calado, Martin Phelps, Gurmail Paddan, Robert Hayward, Henrietta Howarth (née Stuart), Chris Nelson, Tony Higgins, Janet Hoddinott, Colin Robertson, Kelvin Davies, Alison Messenger (née Cooper), Kate Carruthers, Neil Sherwood, Pierre Peruzzetto, Reza Honarmand, Richard So, David Brooker, Julian Eyre, David Clarke, Martin Brett, Richard Chapman and Andrew Harvey.

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This book would not have been possible without the support and forbearance of my family. I would like to thank my daughter, Joanna, for inspiring parts of Chapter 7, and my son, Andrew, for offering to write Chapter 21. My wife, Jackie, prepared the many drafts of the manuscript, offered constructive advice and provided unwavering support and encouragement.

Contents

1
Vibration and Human Responses

The shaking of the human body—a complex, active, intelligent, dynamic structure—should not be expected to have a single, simple, or easily predictable consequence. Vibration may be a nuisance or nauseating, exhilarating or excruciating, a source of pleasure or the cause of pain. Whether a motion causes annoyance, discomfort, interference with activities, impaired health or motion sickness depends on many factors—including the characteristics of the motion, the characteristics of the exposed person, the activities of the exposed person and other aspects of the environment. Attempts to summarize knowledge merely by recommending the avoidance of some vibration frequency, or by defining a single curve representing all responses to all frequencies, do not reflect a modern understanding of the effects of vibration on the body. The benefits of better information, and the satisfaction which comes from a greater understanding of human responses to vibration, are available to those willing to recognize the need for a less simplistic approach.

1.1 Introduction

This book explores the many diverse effects of vibration on the body. It attempts, primarily, to explain human responses and the way in which the various influential factors combine. With this background it is then possible to assess currently available standards, to recommend optimum means of applying the available information and to consider ways of minimizing undesirable effects of vibration.

Learning involves the formation of a concept, an image, or a model of the world. Decisions and actions reflect the state of knowledge contained within the model. Even the apparently simple act of deciding how to make a vibration measurement is always based upon some model, or concept, of the situation. The declaration of a model becomes essential when the subject matter allows different types or complexities of model. In many chapters of this book, therefore, models of the relation between vibration and its effects on the human body are suggested.

Figure 1.1 shows a model of the entire book. It may be seen that Chapters 2

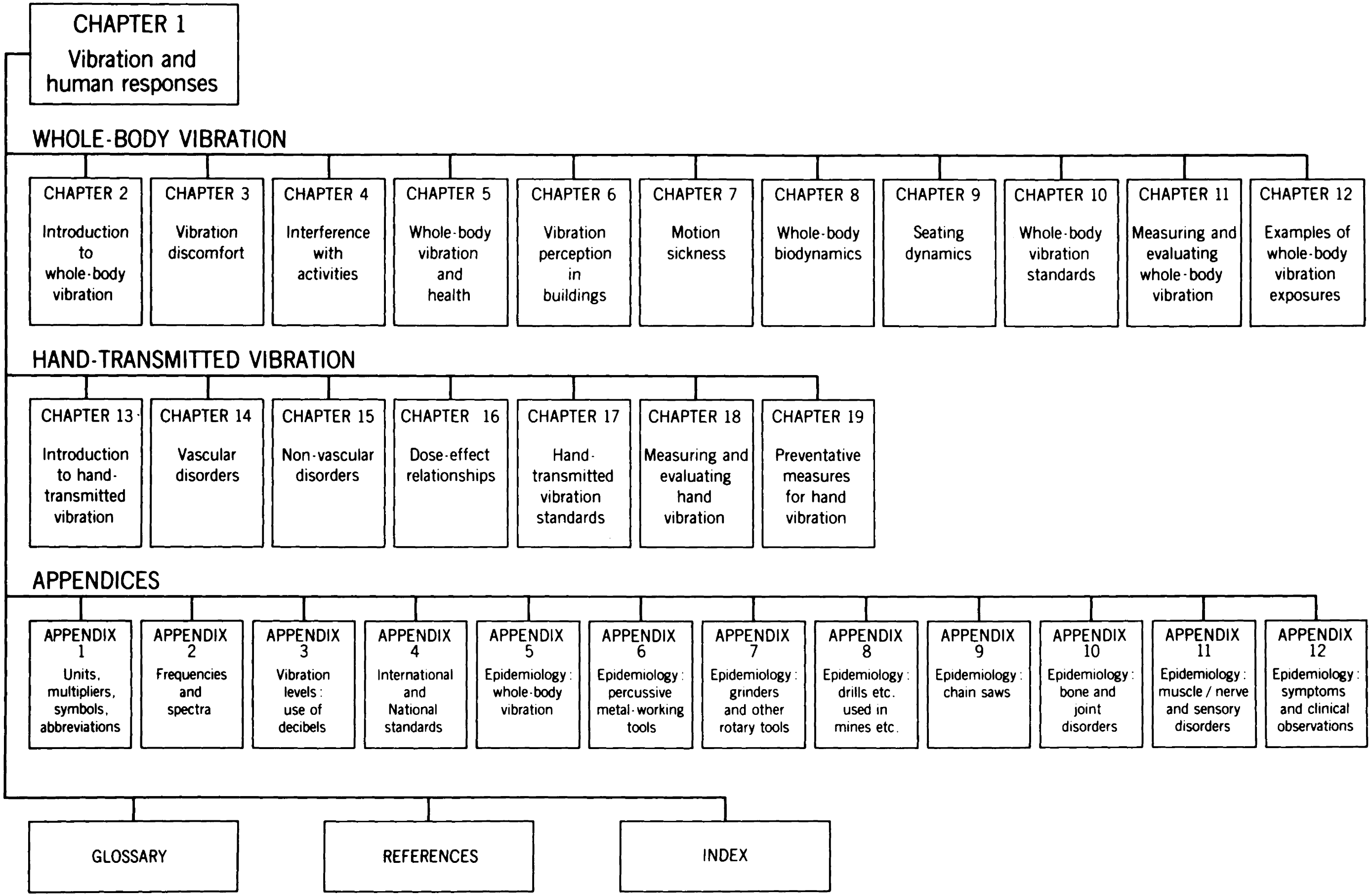

Fig. 1.1 Scheme to show the structure of the book.

to 12 concern human responses to whole-body vibration, while Chapters 13 to 19 concern hand-transmitted vibration. The units, symbols and abbreviations are defined in Appendix 1; Appendices 2 and 3 concern methods of expressing vibration frequency and level; Appendix 4 lists relevant standards; and Appendices 5 to 12 give a summary of epidemiological studies of vibration effects.

'Human vibration' is a multi-disciplinary subject involving knowledge from disciplines as diverse as engineering, ergonomics, mathematics, medicine, physics, physiology, psychology and statistics. Each area brings its own technical terms which may not always be understood by those from another field. For example, few readers will be familiar with the technical use of all the six terms 'abscissa', 'acrocyanosis', 'admittance', 'aliasing', 'ampulla' and 'antagonistic effect', yet some use of such words is necessary when describing the full range of human responses to vibration.

The Glossary at the end of this book has been prepared to assist the understanding and use of relevant technical terms. The entries in the Glossary include those specialist terms used in chapters of this book and others which will be encountered when reading the various references. Although some mathematical expressions are used throughout the text it is the intention that all chapters should be understandable to persons who do not have mathematical expertise.

This first chapter provides a general background in vibration evaluation, introduces the types of human response and outlines methods of determining human responses to vibration.

1.2 Categorization of vibration

1.2.1 Types of vibration

Vibration is oscillatory motion. By definition, the motion is not constant but alternately greater and less than some average value. The extent of the oscillation determines the magnitude of the vibration and the repetition rate of the cycles of oscillation determines the frequency of the vibration. The nature of a future oscillation may be predictable from knowledge of previous oscillations (i.e. a deterministic motion) or may be characterized only as having some statistical properties (i.e. a stochastic motion, commonly called a random motion). Both deterministic and stochastic vibration may be further subdivided as shown in Fig. 1.2.

Only with sinusoidal vibration is it possible to study the response to a single frequency of motion. Many laboratory experimental studies of human response to vibration have therefore attempted to investigate the reaction to pure sinusoidal vibration. In practice, imperfections in vibration generators have usually resulted in the presentation of distorted sinusoids (i.e. complex periodic or multi-sinusoidal motions) containing a mixture of harmonically

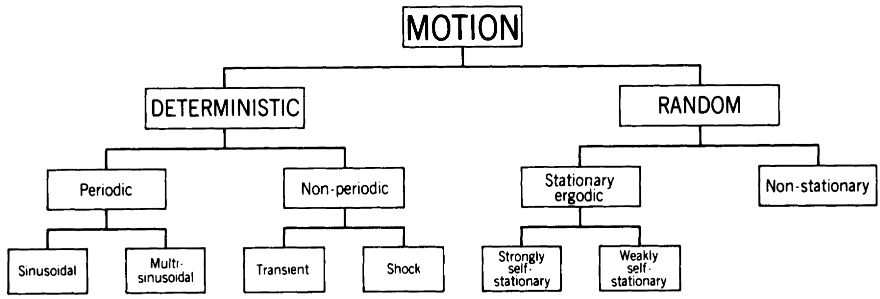

Fig. 1.2 Categorization of types of oscillatory motion.

related frequencies. There have been few experimental studies of response to deterministic non-periodic (i.e. transient and shock) motion.

Vibration exposures encountered during work, travel and leisure are often described as random. For a 'stationary' random vibration a sample averaged over a sufficiently long period is independent of the period of time over which the sample was taken. Some experimental studies with sinusoidal and stationary random vibration have investigated whether human response to random vibration can be predicted from a knowledge of response to sinusoidal motion. A knowledge of the outcome of such studies is necessary before the results of sinusoidal studies can be applied to random vibration environments.

Methods proposed for the evaluation of human vibration exposures have usually assumed that the motion is stationary and that a representative average value can be used to indicate the severity of the motion over the full period of exposure. In practice, of course, the vibration conditions often change from moment to moment. Restricting the evaluation of vibration to periods when the motion is stationary may exclude the periods of greatest interest. The recognition of this problem and the definition of a simple solution forms one of the themes of this book.

A rigid body may oscillate so that all its parts undergo the same motion. This will occur if the motion is translational. If a rigid body rotates, not all its parts undergo the same motion. Both translational and rotational vibration influence human responses. In this book the terms 'translation' and 'rotation' are used in preference to 'linear' (or, preferably, 'rectilinear') and 'angular' which are sometimes used elsewhere.

1.2.2 Vibration magnitude

1.2.2.1 Displacement, velocity or acceleration

There are many possible means by which the magnitude of an oscillatory motion can be measured. With a large-amplitude low-frequency motion it is possible to see the *displacement* between the maximum (i.e. peak) movement in one direction and the peak movement in the opposite direction (i.e. the *peak-to-peak displacement*). In practice, this distance can be difficult to measure and, with high-frequency motions, the vibration can be severe even when the displacement is too small to be detected by the eye.

The magnitude of the oscillation may alternatively be defined by the *velocity*, which is more directly related to the energy involved in the movement. The peak-to-peak velocity is the difference between the maximum velocity in one direction and the maximum velocity in the opposite direction. Although there are various good reasons for quantifying the vibration severity in terms of velocity, instrumentation for measuring the *acceleration* of the oscillation is, at present, generally more convenient. Many standards therefore advocate that the severity of human vibration exposures should be expressed in terms of the vibration acceleration rather than the velocity or the displacement.

The preferred S.I. unit for quantifying acceleration magnitude is metres per second per second. This unit is commonly abbreviated to m/s^2 or $m\,s^{-2}$; $m\,s^{-2}$ is the most commonly used abbreviation and is used throughout this book. Methods of converting to other units are presented in Section 1.2.4. The preferred S.I. multipliers (pico, milli, mega, etc.) are defined in Appendix 1.

1.2.2.2 Peak, average or dose measures

The acceleration magnitude of a vibration could be expressed in terms of the *peak-to-peak* acceleration or the *peak* acceleration. Since with complex motions this may result in the severity of the vibration being determined by one unrepresentative peak, it is often preferred to express severity in terms of an average measure. The measure in greatest use in engineering is the *root-mean-square* (r.m.s.) value. This is the square root of the average value of the square of the acceleration record (see Section 11.3.7.3 and the Glossary). For a simple harmonic (i.e. sinusoidal) motion of peak magnitude A the peak-to-peak magnitude is $2A$ and the r.m.s. magnitude is $A/\sqrt{2}$ (i.e. $\sim 0.707A$). Failure to specify whether the peak-to-peak, peak or r.m.s. value is being used therefore allows an uncertainty of up to 2.828 to 1. For non-sinusoidal motion the error can be much greater (see Fig. 1.3).

Root-mean-square acceleration (i.e. $m\,s^{-2}$ r.m.s.) is generally adopted as the preferred method of quantifying the severity of human vibration exposures. The preference is not based on any fundamental reasoning that r.m.s. measures of acceleration should predict any human response more accurately than peak-to-peak, peak or any other measure. The prime justification is the convenience of measurement and analysis and the harmonization with some other areas of engineering.

Root-mean-square acceleration is not universally accepted and peak velocity is preferred by many. It is easily shown that there exist motions which have similar r.m.s. magnitudes of acceleration but give different responses (see later chapters). However, when quantifying the magnitude of reasonably behaved motions (e.g. periodic deterministic motions and stationary random motions)

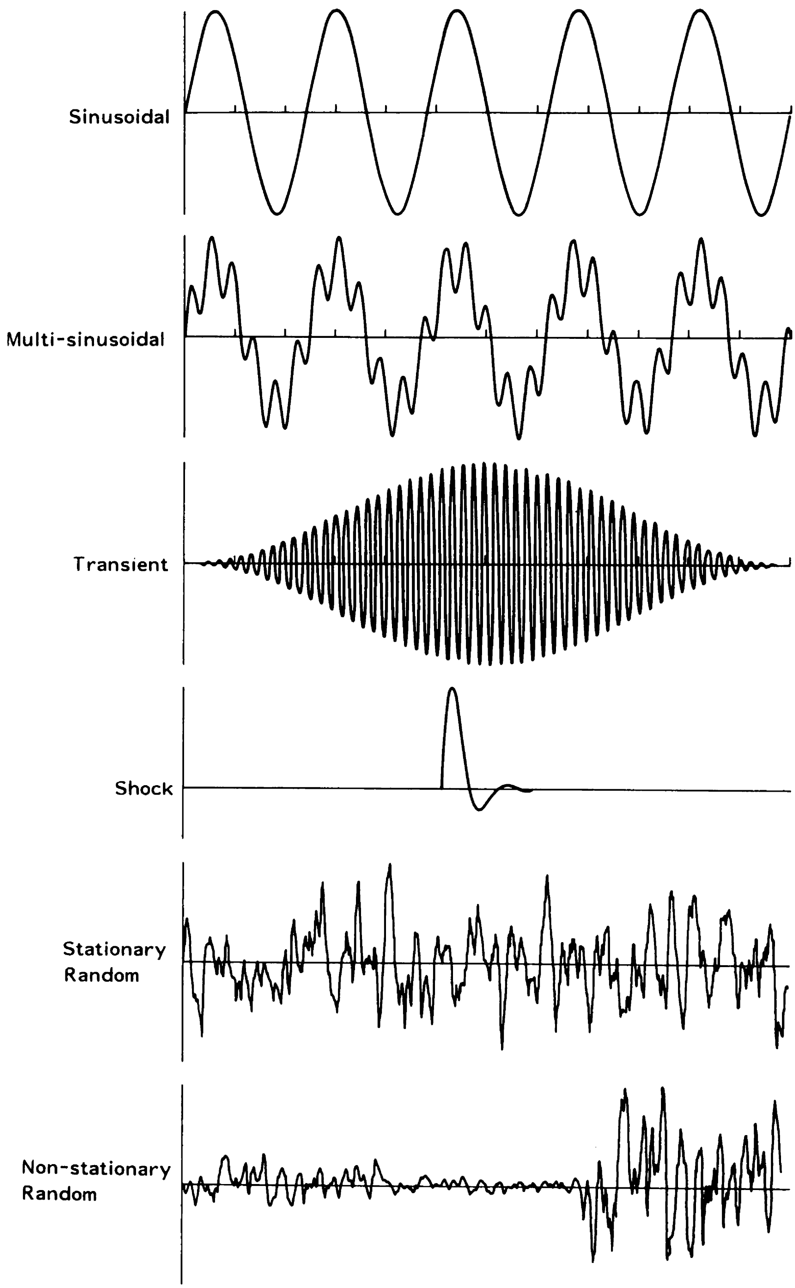

Fig. 1.3 Examples of waveforms of different types of oscillatory motion.

it is found that peak-to-peak, peak, r.m.s., and other similar measures often show the same general trends, although having different numerical values. The somewhat arbitrary, though convenient, choice of r.m.s. acceleration aids communication by unifying methods of measurement. Root-mean-square measures are obviously as reasonable as other alternatives so long as they and the alternatives yield similar conclusions.

Peak, r.m.s and other methods of quantifying vibration magnitudes can yield different conclusions in a range of common, though not easily specified, conditions. This generally occurs if any of the measures gives a significantly different value when determined over only part of the vibration exposure. Motions containing occasional shocks, those consisting of intermittent periods of vibration and all other non-stationary vibration conditions fall into this category.

Neither peak nor average measures reflect the importance of the duration of the motion event: the peak value is determined by the magnitude at one instant while the r.m.s. magnitude can either increase or decrease with increasing duration. If all motions were 'well-behaved' it might be possible to summarize human response to vibration by a simple curve in which the 'acceptable' magnitude of r.m.s. acceleration depended on the period of exposure. However, for real-world exposures in which the vibration characteristics vary greatly from moment to moment, the period over which the r.m.s. magnitude should be determined is not always apparent and the r.m.s. value can sometimes be shown to be an inappropriate measure. For such motions a cumulative measure (sometimes called a 'dose') is more reliable. For whole-body vibration the *vibration dose value* provides a convenient measure of the total severity and this has been found to correlate well with some responses to vibration. The vibration dose value can be applied to either a single shock, a mixture of shocks and vibration, or a full-day exposure to vibration of various types (see Sections 3.5, 5.7.1 and 6.4.13 and Glossary). A similar measure (using a different time dependency) is used to obtain *energy-equivalent* magnitudes of hand-transmitted vibration (see Section 17.6.2).

A simple measure sometimes used to indicate the conditions where r.m.s. and peak values are not appropriate is the ratio of the peak value to the r.m.s. value of the vibration:

$$\text{Crest factor} = \frac{\text{peak acceleration}}{\text{r.m.s. acceleration}}$$

The crest factor is usually calculated from the acceleration after it has been frequency weighted according to human sensitivity to different frequencies. For sinusoidal vibration the crest factor is $\sqrt{2}$ (i.e. ~ 1.414). Typical vibration in a vehicle on a good road may have a crest factor in the approximate range 3–6, but this will increase if the measurement period includes any shock motions (which will mainly increase the peak value) or if the vehicle stops (which will reduce the r.m.s. value). It is well recognized that when the crest factor is high the root-mean-square acceleration is a less useful measure of the vibration severity. The use of the crest factor implies that for low crest factor motions human response is reasonably indicated by the r.m.s. value while for high crest factor motions it is mainly determined by the peak value. A single measure applicable over all crest factors should therefore asymptotically approach the characteristics of these two measures with extreme crest factors (the vibration dose value and root-mean-quad measures discussed in subsequent chapters tend to have this property).

1.2.3 Vibration frequency

A periodic motion repeats itself identically in a time interval called its *period*. The *frequency* of the motion is given by the reciprocal of the period and can therefore be expressed as the number of cycles of motion per second. The measure of frequency, in cycles per second (c.p.s.), is currently named after the German physicist Heinrich Hertz (1857–94), the S.I unit for frequency is the *hertz* (Hz) not cycles per second (or cycles per minute). It is often convenient to refer to the *angular frequency*, ω, which is expressed in radians per second. A complete cycle (i.e. 360° corresponds to 2π radians so that, if the frequency is f Hz, the angular frequency is $2\pi f$ (i.e.$\omega = 2\pi f$) rad s^{-1}.

Simple harmonic motion occurs when there is a sinusoidal oscillation at a single frequency. This is the simplest type of motion since it contains only one frequency. Most commonly encountered motions contain vibration at more than one frequency. In some cases the various frequencies are harmonics, i.e. integer multiples of the lowest (i.e. *fundamental*) frequency. Often, human exposures to vibration involve some motion occurring throughout a range of frequencies.

Since human response can be highly dependent on the frequency of vibration it is very often necessary to indicate the frequency content of vibration. Frequency can be determined by various methods, including the use of electronic filters and computers (see Chapter 11). The frequency is described (in a table or graph) by a *spectrum* which shows how some measure of the vibration magnitude varies over a range of frequencies (see Appendix 2). In the past it has been common to determine the vibration magnitude in either *octave* or *third-octave* bands. Thus the spectrum can be given by, say, the r.m.s. acceleration occurring in octave bands centred on 1 Hz (i.e. the band from 0.707 Hz to 1.414 Hz), 2 Hz (1.414–2.828 Hz), 4 Hz (2.828–5.656 Hz), 8 Hz (5.656–11.314 Hz), etc. As the response of the body can vary within these rather broad bands it is more satisfactory to use third-octave bands centred on 1 Hz (i.e. the band from 0.891 to 1.122 Hz), 1.25 Hz (1.114–1.403 Hz), 1.6 Hz (1.425–1.796 Hz), etc. Third-octave band analysis may sometimes have a sufficiently fine resolution and it produces a manageable number of values (e.g. 23 values for a 0.5–80 Hz spectrum often used for whole-body vibration; 24 values for a 6.3–1250 Hz spectrum used for hand-transmitted vibration). However, there are situations where a finer resolution is required. Much modern analysis equipment is more directly suited to determining frequency content using *constant-bandwidth* analyses (e.g. a 0.1, 0.5 or 1.0 Hz bandwidth at all frequencies) rather than *proportional-bandwidth* analysis in which the bandwidth increases in proportion to frequency, as with octave and third-octave bands. Vibration spectra are therefore sometimes presented in terms of octaves or third octaves and sometimes as constant-bandwidth spectra, e.g. spectral densities (see Section 11.3.8, Appendix 2 and Glossary).

There need be little problem in interpreting vibration spectra presented by the different methods. However, great confusion arises if frequency-dependent vibration limits are specified for a specific bandwidth. It is not possible to convert these limits to another bandwidth without making assumptions about the spectrum of motion to be evaluated. For example, with a pure 4 Hz sinusoidal motion, both octave and third-octave filters centred on 4 Hz give similar values and a similar limit would be appropriate. If the motion is broad band (or contains discrete frequencies at, say, 3.15 and 5.0 Hz) the 4 Hz octave band filter would indicate a higher value than the third-octave band filter and a different limit would appear to be necessary. Human response to vibration does not depend on the filters used in analysis equipment! It is therefore highly desirable that vibration limits are formulated so that all reasonable proportional-bandwidth and constant-bandwidth analysis procedures give similar results.

1.2.4 Conversion between alternative units of measurement

Although it is generally preferred to quantify the average vibration magnitude in $m\,s^{-2}$ r.m.s. and the frequency in Hz, there is often a need to convert to other measures. Non-SI units of distance (foot, inch, micron, etc.) found in many older publications are defined in the Glossary. The currently used units and those with special applications (e.g. vibration dose value, VAL, PAL, etc.) are defined in the Glossary and other chapters. Some publications express vibration acceleration in terms of '*g*', the acceleration due to gravity, which is 1 g standardized as 9.80665 $m\,s^{-2}$ (32.1740 $ft\,s^{-2}$).

There have been several attempts to introduce a logarithmic scale of vibration severity in which the magnitude of vibration is expressed in decibels. There appear to be few advantages but several disadvantages in using a logarithmic unit for quantifying human exposure to vibration. International Standard 1683 (International Organization for Standardization, 1983b) mentions reference levels of $10^{-6}\,m\,s^{-2}$, $10^{-9}\,m\,s^{-1}$ and 10^{-6} N for acceleration, velocity and force respectively, but others are in use (see Appendix 3). If the reference level given in International Standard 1683 is used, the acceleration level, L_a is expressed (in decibels) by $L_a = 20 \log_{10} (a/a_0)$, where a is the measured acceleration ($m\,s^{-2}$ r.m.s.) and a_0 is the reference level of $10^{-6}\,m\,s^{-2}$.

A logarithmic scale is in common current use for the assessment of sound, partially because of the wide range of sound pressures that occur and partially because of the convenience offered by a logarithmic relation between sound pressure and the sensation of loudness. With whole-body vibration there is merely a 1000 : 1 range between perception thresholds and pain thresholds (see Chapters 5 and 6) and vibration discomfort increases in almost linear proportion to the vibration magnitude. Decibels may give persons with a background in the measurement of sound an illusion of understanding the measurement of vibration magnitude. However, the expression of vibration magnitudes in terms of decibels adds a further and unnecessary unit which may impede a good fundamental understanding of the subject.

The most commonly needed conversions are those between the acceleration, velocity and displacement and between peak, peak-to-peak and r.m.s. measures. These conversions depend on the waveform of the motion. It may be seen from Fig. 1.4 that, for a sinusoidal motion, at maximum displacement the velocity is zero and the acceleration is at a minimum; when the displacement is zero the velocity is at its maximum and there is zero acceleration. For such a sinusoidal motion (i.e. a single-frequency periodic function as shown in Fig. 1.4) it is simple to convert between displacement, velocity and acceleration if the frequency is known. At time t, the instantaneous displacement x, is given by

$$x(t) = X \sin (2\pi ft + \varphi)$$

where X is the peak displacement of the motion, f is the frequency (in Hz) and φ is the phase angle of the oscillation. If the displacement is zero at time $t = 0$, then $\varphi = 0$ and $x(t) = X \sin 2\pi ft$.

The instantaneous velocity of the same motion is given by the rate of change of displacement

$$v(t) = \frac{\mathrm{d}x}{\mathrm{d}t} = 2\pi fX \cos 2\pi ft$$

$$= V \cos 2\pi ft$$

where V $(= 2\pi fX)$ is the peak velocity of the motion. The instantaneous acceleration of this motion is given by the rate of change of the velocity

$$a(t) = \frac{\mathrm{d}v}{\mathrm{d}t} = -(2\pi f)^2 X \sin 2\pi ft$$

$$= -A \sin 2\pi ft$$

where A $[= (2\pi f)^2 X = 2\pi fV]$ is the peak acceleration of the motion.

Jerk is obtained by a further stage of differentiation, with the peak jerk being equal to $(2\pi f)^3 X$, $(2\pi f)^2 V$ or $2\pi fA$.

Therefore, if the motion is sinusoidal, it is simple to convert between measures of displacement, velocity, acceleration and jerk using the relationships derived above (see Table 1.1). The conversions apply irrespective of whether the peak, peak-to-peak or r.m.s. value is used. Similarly, it is possible to convert between peak, peak-to-peak and r.m.s. values using the same procedure, irrespective of whether the displacement, velocity or acceleration is used (see Table 1.2).

The conversion tables (Tables 1.1 and 1.2) may be used to determine the

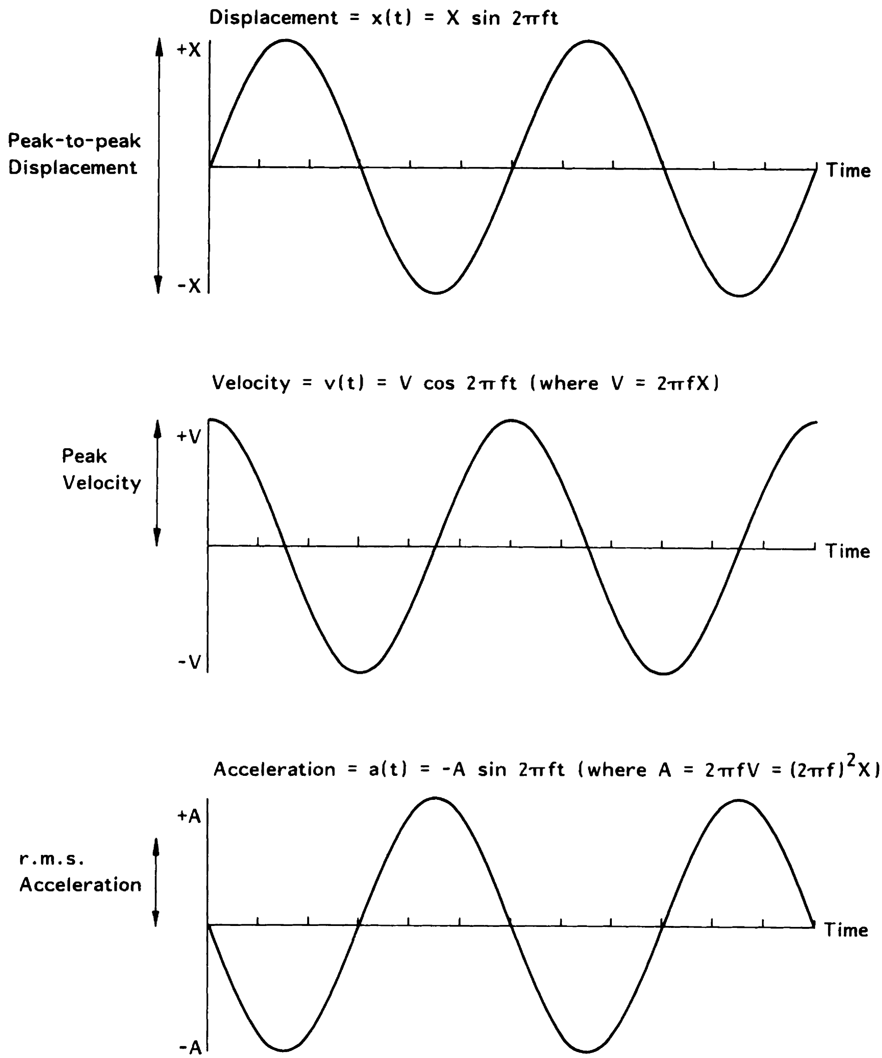

Fig. 1.4 Displacement, velocity and acceleration waveforms for a sinusoidal motion. The peak-to-peak, peak and root-mean-square (r.m.s.) magnitudes of sinusoidal motion are also shown.

displacements and velocities associated with some acceleration limits considered in later chapters. The same tables are also often used to estimate the approximate displacements corresponding to complex acceleration spectra; in this case the mathematical relationships do not apply and, therefore, although with experience useful approximate values can be obtained, they will never be accurate.

Some researchers have claimed to have discovered that human response is determined solely by either the displacement, velocity, acceleration or jerk of

Table 1.1 Conversion between peak displacement, X, peak velocity, V, and peak acceleration, A, for sinusoidal motion of frequency, f (in Hz)

	Displacement, X	Velocity, V	Acceleration, A
Displacement, X	$X = X$	$X = \frac{V}{2\pi f}$	$X = \frac{A}{(2\pi f)^2}$
Velocity, V	$V = 2\pi f X$	$V = V$	$V = \frac{A}{2\pi f}$
Acceleration, A	$A = (2\pi f)^2 X$	$A = 2\pi f V$	$A = A$

Table 1.2 Conversion between peak, peak-to-peak and root-mean-square. (Conversions only apply to sinusoidal motion)

	Peak	Peak-to-peak	r.m.s
Peak	Peak = peak	Peak = $\frac{\text{peak-to-peak}}{2}$	Peak = $\sqrt{2}$ r.m.s.
Peak-to-peak	Peak-to-peak = 2 peak	Peak-to-peak = peak-to-peak	Peak-to-peak = $2\sqrt{2}$ r.m.s.
r.m.s.	r.m.s. = $\frac{\text{Peak}}{\sqrt{2}}$	r.m.s. = $\frac{\text{Peak-to-peak}}{2\sqrt{2}}$	r.m.s. = r.m.s.

oscillatory motion. Each of these units varies differently with changing frequency. For example, Fig. 1.5(a) shows that if the frequency is increased, the acceleration will decrease in proportion to frequency (by − 6 dB per octave) if the jerk is held constant, will increase in proportion to frequency (by + 6 dB per octave) if the velocity is held constant and will increase in proportion to the square of the frequency (by + 12 dB per octave) if the displacement is unchanged with increasing frequency. The apparent conflict between the claims that response depends on each of these four diverse units is resolved if each of the claims is restricted to a narrow range of frequencies [see Fig. 1.5(b)].

It is now generally accepted that most human responses depend on vibration frequency in a complex manner and are not simply dependent on any single physical measure. However, it is sometimes convenient to represent the approximate frequency dependence by straight lines: slopes with multiples of 6 dB per octave, such as those in Fig. 1.5(b), are then useful. The frequency dependence of human response may be allowed for by frequency weightings which approximate towards these straight lines. Only if the vibration frequencies associated with an environment are restricted to a narrow range is it reasonable to assume that the vibration can be evaluated without a frequency weighting.

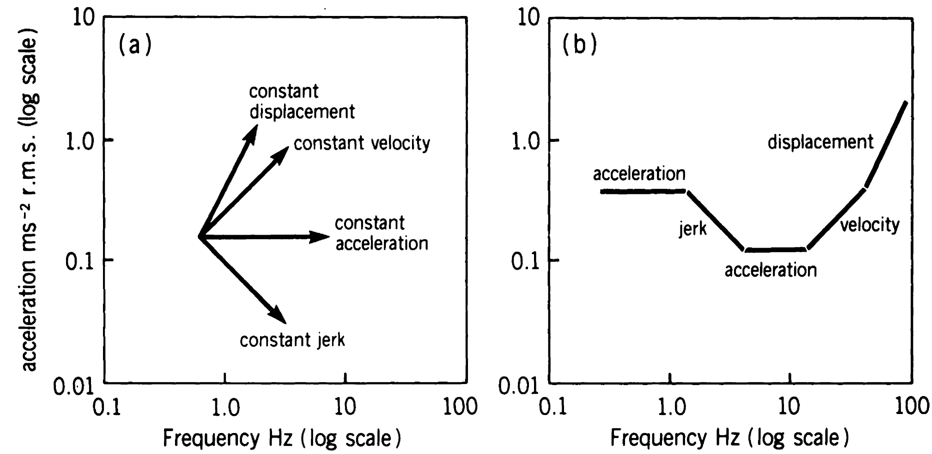

Fig. 1.5 Simple representations of the effects of vibration frequency: (a) change in acceleration associated with constant jerk, acceleration, velocity and displacement; (b) formation of a single contour showing the magnitudes of vibration at different frequencies which might cause similar effects.

1.2.5 Vibration duration

The duration of some vibration exposures may be determined by using a clock or stop-watch. However, duration is also covertly incorporated within all methods of measuring the magnitude (and frequency) of vibration. There are many possible ways of measuring vibration magnitude and they may all give different values for the same motion. This was clearly the case when comparing peak and r.m.s. measures of vibration magnitude (see Section 1.2.4). In addition, there are an infinite number of possible r.m.s. measures according to the period of time over which the r.m.s. value is determined. Furthermore, depending upon the available instrumentation, some prefer not to give equal importance to all intervals (i.e. rectangular averaging) but attach more importance to recent values (i.e. exponential averaging). In both cases the values obtained depend on the measurement period, but, while rectangular averaging may be used over long periods, exponential averaging usually incorporates a 'time constant' which is often in the region of 1 s.

Again, human response to a vibration does not vary according to which time constants are built into the meter used to measure vibration. Rectangular averaging and exponential averaging are engineering methods adopted for practical convenience. When comparing some types of motion it is possible to obtain broadly similar conclusions with a wide range of averaging methods and any attempt to harmonize methods might reasonably conclude that the selection of a procedure should be based more on convenience than accuracy. However, with some other motions (e.g. those which are non-ergodic, non-stationary or non-periodic) the different methods can yield different conclusions. The selection of a method of summing or averaging motions should be based on evidence of how human response varies with duration; a method adopted solely on the basis of temporary practical convenience may prove unsuitable.

It appears that there is a need to know how response to vibration varies with duration. More immediately, there is a need to know where the different methods of averaging vibration yield different conclusions and which of the methods are inconsistent with available information on human response. These problems are addressed in subsequent chapters.

1.2.6 Co-ordinate systems

When sitting on a stationary seat some experimental, self-induced shaking of ones' own body can demonstrate that up-and-down vibration causes different effects from side-to-side vibration. The definition of the direction of any vibration is therefore of some importance. Such shaking also demonstrates that with either direction of motion the magnitude of the vibration is different at different parts of the body. The response of the body therefore depends on both the direction of the vibration and the position in the body which is excited. These two variables can be quantified by reference to co-ordinate systems in which directions are defined by orthogonal *axes* having convenient *origins*.

There are two types of biodynamic co-ordinate systems: anatomical and basicentric. *Anatomical co-ordinate systems* are defined relative to identifiable anatomical features and are currently mostly used in laboratory research into vibration effects. *Basicentric co-ordinate systems* are defined relative to surfaces which come into contact with the body and are more easily suited to the assessment of environmental vibration. The two types of systems have similar means of identifying the directions of movement, but differ in their origins.

Biodynamic co-ordinate systems are usually right-handed, the positive direction of the x-, y-, and z-axes being given by the directions of the first finger, second finger and thumb of the right hand. For a seated or standing person the positive directions are frontwards, to the left and upwards, respectively.

Co-ordinate systems used for whole-body vibration are described in Section 2.4, while those used for hand-transmitted vibration are described in Section 13.3. It will be seen that the axes are referenced as x, y and z for translational vibration and r_x, r_y and r_z for rotational vibration. Subscripts are sometimes used to denote the origin of the co-ordinate system (e.g. x_s for the x axis at the seat or x_h for the x axis at the hand). Terms such as roll, shunt, sway, etc., are in common use but do not always distinguish between the axes of the body and the axes of the environment in which the motion is occurring (see Section 2.4).

1.3 Effects of vibration

Whole-body vibration is capable of producing a wide variety of different effects. It can generate a range of subjective sensations which can be quantified in many different ways. Both simple and complex activities can be disturbed by vibration affecting the various components of a task, from the input of information to the body (e.g. vision) through to the output of information from the body (e.g. hand control). Physiological parameters may be disturbed by vibration with either transitory effects or permanent changes. Vibration also causes a range of physical movements of parts of the body which may be quantified by objective methods and simulated in mathematical equations or with anthropodynamic dummies. Table 1.3 gives examples of some parameters which may be studied.

Table 1.3 Some parameters studied in the context of human response to vibration

Subjective	*Activity*
Absolute thresholds	Vision
Subjective equality	Hearing
Subjective order	Touch
Equality of intervals	Proprioception
Equality of ratios	Vestibular function
Rating of stimuli	Psychomotor performance
Cross modality judgements	Cognitive performance
Differential thresholds	Vigilance
Physiological	*Biodynamic*
Skeletal	Body impedance
Muscle	Hand impedance
Nerve	Body transmissibility
Cardiovascular	Head movements
Respiratory	Hand movements
Central nervous system	Organ movements
Endocrine/metabolic	Energy absorbed

1.3.1 Criteria

It is common practise to group the effects of stressors under three main headings: (a) interference with comfort; (b) interference with activities; and (c) interference with health. These groups of response broadly define three principal *criteria*. A criterion states the effect of interest and it is changes in this chosen effect that allow the vibration to be judged. A *limit* may be set such that there is a low (i.e. acceptable) probability of occurrence of the effect defined by the criterion. In consequence, limits tend to be defined by numbers whereas criteria are sets of words which define both the reasons for, and the scope of, the limits.

The three broadly defined criteria provide a useful starting point to considering the effects of vibration and also allow convenient analogies to be made with other stresses (e.g. for noise: loudness, speech-interference and hearing-damage risk). However, these criteria are far too imprecise to allow the formulation of useful vibration limits. For this purpose it is necessary to define how much discomfort, what type of activity, how much disturbance and what type and degree of injury is experienced. Discomfort, activity and health limits for a luxury car may be different from those for a military tank; it is a common observation that train vibration may interfere with writing activities when it has little effect on reading; injury to one part of the body may be considered more serious than injury to another part. Clearly there is scope for a subdivision of these three criteria into more precise fields. However, a proper subdivision leads to great complexity and a confusing proliferation of different vibration criteria and limits.

Fortunately, the adoption of meaningless criteria or the use of a different criterion for each application are not the only alternatives. In some areas there is sufficient knowledge to specify criteria sufficiently precisely to allow the definition of meaningful limits. In other areas there may still be a need for a scale of severity but limitations to knowledge may necessitate that the scale has limited properties and may be based on reason and analogy rather than direct evidence. One of the primary purposes of such a scale may be to encourage the gathering of data needed to formulate improved criteria or more accurate limits. A scale of severity of this type may not allow the definition of a limit which, if exceeded, is known to produce certain effects. This type of scale is best considered to be a uniform measurement procedure to which limits may be attached if sufficient evidence becomes available.

1.3.2 Limits

Vibration limits should not be considered to be the first and most important requirement. The first necessity is the formulation of the criterion. The second requirement is the definition of the measurement procedure. If these initial steps are defined precisely, uniform vibration measurements can be made and the definition of useful vibration limits may be possible. The criterion and measurement method are prerequisites to the setting of a limit.

A limit will, by implication, restrict the activities of some persons. Clearly, only certain persons can be empowered to restrict the activities of others, for example, governments, law courts and employers. A body (or individual) should only issue a limit for the group of persons for which it is responsible. In deciding upon a limit there is usually an implied acceptance of an allowable risk. Indeed, the process may involve balancing the various 'costs' of a low limit against the probability of annoyance, impaired activities or injury with a high limit. A decision upon a limit therefore requires knowledge of what adverse effect may occur and how the severity and probability of this effect will increase as the limit is increased. The limit can then be promulgated with the declared intention that it will protect a certain percentage of exposed persons from a certain degree of adverse reaction.

1.3.3 Good vibration

Most study has concentrated upon the unwanted effects of vibration on the body, but vibration is not always to be avoided. It is a means of expressing friendship by shaking hands, and it may be pleasant, such as with the rocking of a baby, a rocking chair or a swing. It can be a source of excitement at the fairground, on surf-boards or in motorcross racing. It may provide feedback on the state of the moving parts in aircraft and vehicles and so warn of failures. It is used by physiotherapists to help clear the lungs of their patients and has been advocated as a means of improving joint mobility among both athletes and those suffering from rheumatoid arthritis. Vibration has been used to treat the stumps of amputated limbs, to improve the dialysis of patients with renal failure, to promote the return of good limb function to patients with limbs in plaster and it is used in the rehabilitation of paraplegics. Vibration may also be used for diagnostic purposes, e.g. to assess the tactile senses and neural pathways at high frequencies or to observe the performance of the vestibular system at low frequencies. Changes in the dynamic response of limbs determined with vibration or shock excitation have been used to monitor the healing of fractures and it has been suggested that the vibration generated by joints may help to diagnose joint disorders.

1.4 Methods of human vibration research

1.4.1 Objectives

The study of human response to vibration is concerned with establishing relationships between various effects (e.g. impaired comfort, activities or health) and their causes (e.g. vibration conditions, other environmental conditions, or subject characteristics). With an endless range of potential effects and, frequently, very complex causal conditions, it cannot be hoped that knowledge will become complete, but that it will merely become sufficient to assist in the solution of problems.

The complexity of the cause–effect relationship is such that two distinct methods of laboratory research have emerged: either the systematic study of each variable in turn or the simulation of the 'real' conditions and the study of their effects on the 'real' tasks. While both approaches may use satisfactory scientific methods, the systematic approach is more likely to advance knowledge of cause–effect relationships, explain why effects occur, and lay down the basic knowledge needed for solving problems. However, systematic research will never lead to a perfect solution to the complete human response to vibration 'equation'. For a particular set of conditions a precise solution might only be available by simulating the conditions, observing the effects they produce and studying how changing the conditions alters the effects. This approach is often limited by the difficulty (cost, complexity and, ultimately, the impossibility) of simulating environments in the laboratory.

Much of the basic information presented in the following chapters was obtained by the systematic study of human response under laboratory conditions. Some sceptics will scorn the implication that the results of fundamental laboratory research can be applied to real problems, but this often arises from confused thinking. Those involved in systematic research design their experiments to be highly controlled *because* they are well aware that many extraneous factors can influence their findings. They are therefore unlikely to assume that the results of their research apply to all situations. They are also more aware than most that a successful application of their findings in either a laboratory simulation or in a field experiment can be a highly attractive, but wholly insubstantial, addition to the information already amassed by systematic study.

In addition to laboratory research, there is much need for field studies of vibration, its effects and the cause–effect relation. Some studies are best conducted in the laboratory because, for example, they may involve the determination of the relative effects of a large number of different types of vibration: this cannot easily be arranged in the field. Other studies are more appropriate to field environments, especially if they involve assessment of the absolute acceptability of the conditions. The two methods of investigation tend to be highly complementary with laboratory research indicating the likely relative importance of various factors (different vibration frequencies, directions, seating, posture, etc.) and field study assessing a few alternative methods or determining a dose–effect relationship. The alternative measurement methods may be largely determined in the laboratory while the quantitative relation between cause and effect and any consequent vibration limit may be determined from field data.

1.4.2 Vibration generation

Laboratory experimentation requires vibrators with which to expose experimental subjects to motion. Many types of vibrator are possible with platforms being driven by hydraulic, electromagnetic, pneumatic or mechanical power or electric motors. The performance required of a laboratory vibrator is highly dependent on the type of vibration which is to be investigated. The exposure of a subject to high frequency building vibration may require little force and small displacements which can be achieved with small vibrators; the general investigation of response to vibration at frequencies in excess of about 2–3 Hz may require a vibrator with a peak-to-peak displacement of only 50 or 100 mm; the study of response to lower frequencies requires larger machinery capable of $\geqslant 1$ m of movement. The performance of a vibrator may be conveniently expressed by a single graph showing the displacement, velocity and acceleration limits (see Fig. 1.6).

If a laboratory vibrator is to be used to determine cause–effect relationships

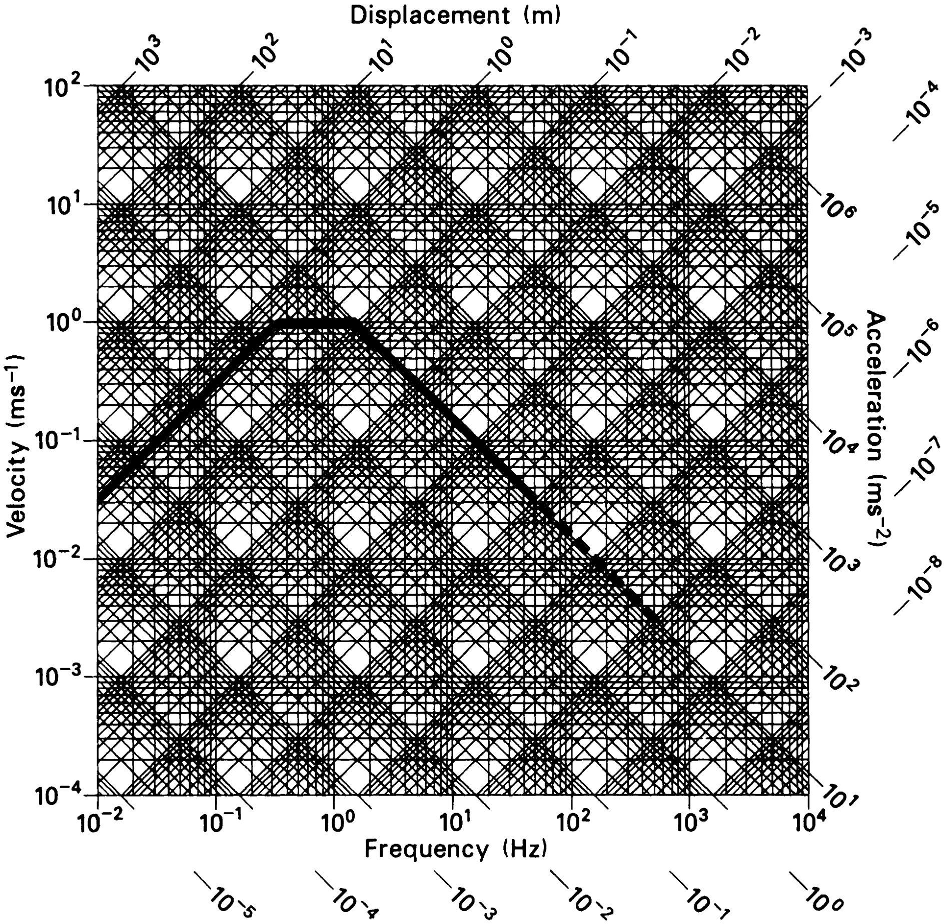

Fig. 1.6 Simple graphical presentation of the performance of a vibrator having a maximum stroke of ± 0.5 m, a maximum velocity of ± 1 m s^{-1} and a maximum acceleration of ± 10 m s^{-2}. (In practice the useful performance of a vibrator depends on other factors including the load and the acceptable distortion. The boundary shows the upper limit to the performance but all lower magnitude vibration conditions may not be reproduced with adequate purity.)

it is necessary that the vibrator is capable of reproducing motion with high purity, otherwise the 'cause' is not easily quantifiable. The vibrator should not introduce unwanted motions in any direction. These aspects of a vibrator's performance are quantified by its distortion, cross-axis motions, non-linearity and background noise. While some vibrators reproduce motions faithfully, others introduce very considerable impurities. The effects of the impurities on human response depend on their frequency and direction as well as on their magnitude and, while in some cases a high level of distortion may have little effect on responses, a small impurity can often dominate human response. Many of the published research papers give little information on the characteristics of the motion experienced by subjects and there is a consequent uncertainty in the interpretation of the findings. Analysis of the quality of vibration reproduction must be considered prior to conducting any experiment and should be available for those wishing to interpret the experimental findings.

1.4.3 Safety

An even more important aspect of laboratory vibrator performance is the safety of the system during normal operation and during failure conditions. Vibrators capable of lifting and moving a subject at moderate magnitudes may also have the capability of imparting severe motions when incorrectly adjusted or when an excessive signal is sent to the system. Where necessary, electronic circuits should be used to stop the vibrator if either the instantaneous command signal or the vibrator motion (acceleration, velocity or displacement) exceed predetermined safety limits. In these situations the vibrator must be designed to come to a safe stop: an instantaneous halt during a high-velocity motion would be unsafe and it would not be safe to switch off the power and allow the platform and subject to either coast or drop. The limits of travel on a vibrator capable of large-amplitude high-velocity movements must be arranged so that should the platform be accidentally driven or fall to one end of its travel it will be retarded safely in buffers. Some guidance on the design of vibrators for human exposure is given in British Standards Institution Draft for Development DD23 (British Standards Institution, 1973) and BS 7085 (British Standards Institution, 1989) (see Sections 10.9.1 and 10.9.7).

Apart from the design of a vibrator which is mechanically and electrically safe there are other matters to consider before exposing experimental subjects to vibration. The risks inherent in the vibration exposure should be assessed and weighed against the benefits to be obtained from the study. The risk may depend on the health of the experimental subject: for severe exposures this may need to be determined by medical examination prior to the experiment and monitored throughout the experiment by medically qualified staff. For some exposures it may be sufficient to ascertain the health of a subject with the assistance of a list of medical contraindications to exposure shown to the subject. A list of such contraindications based on the guidance given in BS 7085 (British Standards Institution, 1989) is given in Table 1.4. Subjects should be aware of all safety precautions (e.g. how to stop the motion) and know that they are free to withdraw from the experiment at any time. The information gathered during the course of an experiment should be treated in confidence: the identity of subjects should not normally be apparent in publications showing individual data.

In view of the inherent safety problems with vibration exposures they should not be undertaken lightly. It is good practice to prohibit casual exposures and require the documentation of the magnitudes, frequencies and durations of all exposures. There is a need to consider the legal position if an accident should occur. The experimenter should confirm that he is adequately covered by his

Table 1.4 Persons with any of the following conditions might be considered unfit for experiments involving whole-body vibration: adapted from BS 7085 (British Standards Institution, 1989)

Active disease of respiratory system
including recent history of coughing-up blood or chest pain

Active disease of the gastro-intestinal tract
including internal or external hernia, peptic ulcer, recent gall-bladder disease, rectal prolapse, anal fissure, haemorrhoids or pilonidal sinus

Active disease of the genito-urinary system
including kidney stones, urinary incontinence or retention or difficulty in micturition

Active disease of the cardiovascular system
including hypertension requiring treatment, angina of effort, valvular disease of the heart, or haemophilia

Active disease or defect of the musculo-skeletal system
including degenerative or inflammatory disease of the spine, long bones, or major joints, or a history of repeated injury with minor trauma

Active or chronic disease or disorder of the nervous system
including eye and ear disorders and any disorder involving motor control, wasting of muscles, epilepsy or retinal detachment

Pregnancy
any woman known to be pregnant should not participate as a subject in a vibration experiment

Mental health
subjects must be of sound mind and understanding and not suffering from any mental disorder that would raise doubt as to whether their consent to participate in the experiment was true and informed

Recent trauma and surgical procedures
persons under medical supervision following surgery or traumatic lesions (e.g. fractures) should not participate in vibration experiments

Prosthesis
persons with internal or external prosthetic devices should not normally participate in vibration experiments (although dentures need not exclude participation in experiments with low magnitudes of vibration)

organization or an insurance policy so that any justified claim for damages can be met.

Experimental exposures to vibration in field environments may also be associated with safety problems. There appear to be few risks when many vehicles are driven by experienced persons in the normal manner for short experimental purposes. The need to consider safety increases when exposures are of long duration, occur at excessive speed, arise from travel over rough surfaces or otherwise involve high magnitudes of vibration.

For both laboratory and field conditions there is guidance available on the vibration conditions which might require special consideration of adverse health effects (see Sections 5.8 and 5.9).

1.4.4 Subject variability

If the responses of all persons to vibration were the same on all occasions, knowledge of these responses and their associated mechanisms would now be virtually complete. There would be no need to conduct studies on large numbers of subjects and there would be far greater agreement between the results of different investigators. In fact, there can be large differences between the responses of individuals (*inter-subject variability*) and also large differences in the responses of an individual on different occasions (*intra-subject variability*). The existence of these two sources of variability devalues the personal opinions of the vibration by any single individual and makes it essential that conclusions are based on a sound statistical treatment of the responses of many individuals. This requires 'experimental designs' which allow the use of 'statistics' to test 'hypotheses'. Only in this way can a set of scattered results lead to a conclusion which has a known probability of being valid.

Research publications present conclusions based on statistical tests of the differences between two or more sets of data. The significance of a difference may be expressed as, for example, $p < 0.05$ indicating that there is less than 5% chance that the two sets of data are similar: often this, or a lower level of probability, will lead to the conclusion that there is a real difference. The mathematical procedure used to determine the level of significance depends on the experimental design. Statistical tests (which may be parametric or non-parametric) include analysis of variance, chi-square, t-tests, Wilcoxon matched-pairs signed ranks, etc. (see Glossary). A mathematical relation between two or more variables may be obtained by regression.

1.4.4.1 Inter-subject variability

Everyday observations of different individuals reveals that there are large physical differences between members of any chosen population. Some of these differences affect the dynamic responses of their bodies, and the consequent variability in vibration transmission should be expected to result in differences in the type and extent of any impairment in comfort, activities or health. In later chapters it will be seen that, while body size and mass can influence body response, it is changes in body posture which often have the largest influence. The age and gender of an individual may have an effect because of varying biodynamic responses or differing sensitivities, experience or attitudes (including expectations); the health and fitness of a subject are most likely to become important at either extreme magnitudes of vibration or in conditions of poor health; previous exposures to the vibration or some other aspect of the environment may have a large influence on the subjective assessment of vibration and are likely to be used as a basis for such judgements; prior training on a task with or without vibration may influence performance in vibration conditions; and the attitude and motivation of an

Table 1.5 Some sources of inter- and intra-subject variability

Inter-subject variability	*Intra-subject variability*
Body dynamics	Body dynamics
Body dimensions	Body posture
Body masses	Age
Body posture	Health
Age	Experience and training
Gender	Attitude and motivation
Health	Sensitivity and susceptibility
Experience and training	
Attitude and motivation	
Sensitivity and susceptibility	

individual may change due to exposure to vibration and many other causes and may be expected to have an influence on both subjective judgements and task performance.

No matter how well other sources of variability are controlled there will always remain individual differences in both sensitivity and susceptibility to vibration: a motion which is felt by one subject may be imperceptible to another, and vibration which injures one individual may have no detectable adverse effect on some other individual. Some of the many possible sources of inter- and intra-subject variability, are listed in Table 1.5.

1.4.4.2 Intra-subject variability

The differences that occur within individuals are due to changes in their response over time, either from one moment to the next or over a much longer period. All the variables which alter the response of a single individual also give rise to differences between individuals. Again, variations in body posture have very large effects which can easily be demonstrated in many vibration environments. The influence of experience and training can be especially important and this may give rise to problems with the design of experiments. If subjects experience more than one condition (e.g. several different vibration exposures) their judgements and responses in one condition may be influenced by what they experienced before. The possibility of 'carry-over' effects with such 'repeated-measures' experimental designs has led to the suggestion that results from all such experiments should be treated with great caution. However, the need to consider a large number of sources of variability has naturally resulted in most vibration experiments being of the 'repeated-measures' type. While it would be impractical to amass the required information from studies in which subjects received only a single condition, the potential influence of prior conditions requires careful attention in any experiment.

1.4.5 Experimental techniques

The principles involved in the study of human response to vibration are similar to those used in the study of human responses to other environmental conditions. There are effects which are *specific* to vibration and there are others which are *non-specific* and might occur with other stresses. Even with many of the specific effects there is much valuable information and many useful techniques available from other areas of science (acoustics, electronics, mathematics, mechanical engineering, physiology, psychology, etc.). In consequence, many of the experimental procedures are either borrowed or developed from methods used elsewhere.

This is not the place for a treatise on the wide range of experimental techniques available to scientists. In subsequent chapters reference is made to a variety of studies using different procedures. Readers involved in research should consult original papers so as to consider the merits of methods used by different investigators. Those embarking on a new area of research will, no doubt, attempt to familiarize themselves with the principles of their proposed techniques as used in allied fields of science before applying them to vibration. It is clear that many of the reported conclusions are greatly influenced by the experimental techniques which have been employed. Results are as much a consequence of the technique as they are a reflection of human response, so that the interpretation of experimental findings requires comprehension of the methods and some judgement of their relevance to the problem at hand.

One requirement of useful experimental findings is that they should be repeatable. It should be possible for another experimenter in another laboratory to conduct a similar study and obtain similar results. With the large number of experimental variables this is not easily achieved. For example, the vagaries of the transmission of vibration from seats to the body and the influence of body posture create practical difficulties in exposing subjects to identical vibration conditions in different laboratories. Some standardization of seats, postures, etc., would increase agreement but the adoption of a standard seating condition (e.g. hard, flat seat) requires agreement that the results of the standard test are applicable to other conditions. Researchers are often rightly reluctant to be constrained by standards and may be expected to adopt reference conditions only when they are either compatible with, or advantageous to, their experimental objectives.

A major reason for apparent disagreement between the results from different studies is that the experiments being compared have been conducted for different purposes. Many of the published studies have not been designed to test hypotheses but have been conducted to measure what happened under a specific situation. Such 'measurement' studies can be necessary and they are sometimes easy to conceive, but they can often prove difficult to interpret and their results may contribute little to a general understanding of human vibration.

1.4.6 The reporting of findings

The full and careful reporting of research studies is vital to the subsequent interpretation and application of the findings. The complexity of the conditions which contribute to human response to vibration has frequently resulted in publications failing to provide sufficient information. Some suggestions for information to be considered when writing experimental reports are offered in Tables 2.3 and 13.2. The variables tabulated may also be considered when comparing the findings from different studies.

In the following sections of this book no details of individual experiments are given; original reports should be consulted for this purpose. The results of laboratory and field studies are used either to present a general consensus of opinion or to compare and contrast different findings. Wherever possible, the discussion is based on the results of experiments in which the testing of specific hypotheses has laid down firm conclusions. It has not been possible to compare results from all relevant experiments but, where comparisons are not made, the cited references will often provide sufficient further information. Wherever possible, the results illustrated in the text are those for which the experimental conditions are known and the findings can be, or have been, confirmed by other observations. A comparison of the illustrated results with earlier studies will often be found in the publications from which the principal figures have been extracted.

1.5 Summary

The complexity of vibration and the diverse range and variability in human response to vibration pose interesting problems for the scientist wishing to establish relationships between vibration and its effects. Vibration has many different forms (Figs. 1.2 and 1.3). Vibration evaluation must involve consideration of its frequency and its direction and how it changes over time as well as its magnitude.

Human responses to vibration are varied and differ greatly over time and from one person to the next. A vibration limit is meaningless without the specification of the relevant criterion stating with what probability a specified effect is prevented by the limit.

Experimental studies of human response to vibration require special safety precautions. The risks inherent in vibration exposures should be assessed and weighed against the benefits to be obtained from the study. Experiments are of little value when hypotheses are not formulated and tested or when the experimental conditions are poorly reported.

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2
An Introduction to Whole-body Vibration

Whole-body vibration occurs when the body is supported on a surface which is vibrating. There are three principal possibilities: sitting on a vibrating seat, standing on a vibrating floor, or lying on a vibrating bed. *Local vibration* occurs when one or more limbs (or the head) are in contact with a vibrating surface. Both whole-body and local vibration can cause vibration throughout the body. Seated persons exposed to whole-body vibration are also often simultaneously exposed to local vibration of the head (e.g. from a head-rest), the hands (e.g. on a steering wheel), and the feet (e.g. on the floor). Vibration may also enter the body as a result of contact with the backrest of a seat.

2.1 Introduction

The variety of sources of vibration of the body are such that only a broad distinction is usually made between whole-body and local vibration. The terms 'local vibration', 'segmental vibration', 'hand–arm vibration' and 'hand-transmitted vibration' are often used if a vibrating device is held in the hands (or controlled by a foot) and the effect of interest is local to that source of vibration (see Section 13.1). Whole-body vibration is usually said to occur when the whole environment is undergoing motion and the effect of interest is not local to any particular point of contact. While this separation of the two conditions is not precise it is sufficient for the present purposes. Chapters 13–20 concern the effects of vibration on the hands caused by their local vibration, while Chapters 2–12 concern all other conditions.

Some examples of the principal environments causing whole-body vibration are given in Table 2.1. The body is highly sensitive to many types of motion and almost any environment can produce sufficient whole-body vibration for there to be a need to assess its importance. The nature of the vibration, the characteristics of the exposed persons and the effects of the vibration can vary greatly from one environment to another. These three areas of variability contribute to the cause–effect model of human response to vibration outlined

Table 2.1 Examples of environments in which whole-body vibration occurs

Road transport	*Rail transport*
Cars	Trains
Vans	Monorails
Trucks	Ski lifts/cable cars
Buses	Other guided transport
Coaches	*Aerospace systems*
Carriages	Fixed-wing aircraft
Motor cycles	Rotary-wing aircraft
Pedal cycles	Spacecraft
Off-road vehicles	*Buildings*
Tractors	Houses
Earth-moving machinery	Offices
Forest machines	Workshops
Tanks	Off-shore structures
Animal riding	Lifts and escalators
Marine systems	*Industrial equipment*
Ships	Cranes
Boats	Fork-lift trucks
Hovercraft	Equipment control stations
Hydrofoil	
Submarines	
Swimmers and divers	

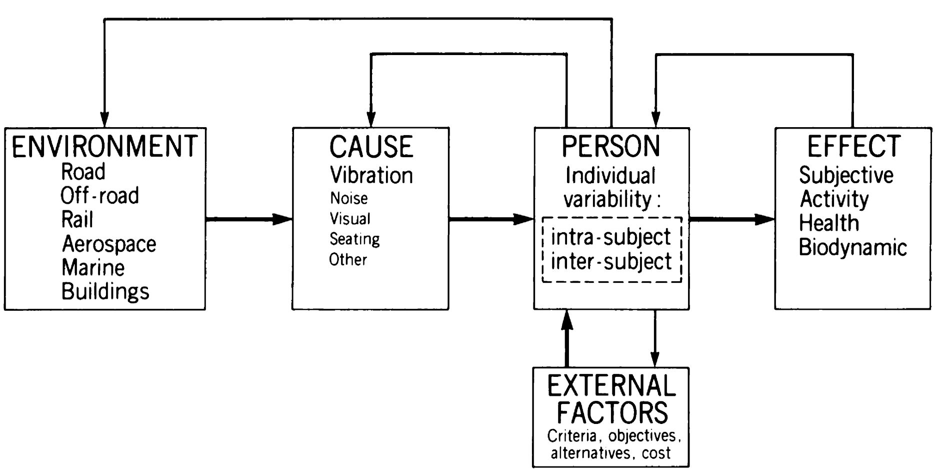

Fig. 2.1 Outline model of the relation between a vibration environment and its effects.

in Fig. 2.1. There is an almost limitless range of other environmental and external factors which can influence, and sometimes determine, the acceptability of vibration. For example, vibration in a vehicle may become unacceptable because a person becomes aware of a better alternative, or merely because other unpleasant aspects of the vehicle (e.g. noise, ventilation, seating) have been improved. The existence of feedback pathways in the cause–effect model further complicates matters: people may perceive an adverse effect of vibration and this may influence their choice of environment; drivers may alter the vibration by reducing the speed of the vehicles in which they are travelling; alternatively, the effects may be greatly ameliorated by a change of posture.

Chapters 3–7 are concerned with effects of whole-body vibration. The biodynamic response of the body is considered in Chapter 8 and the dynamic performance of seats in Chapter 9. Whole-body vibration standards are summarized in Chapter 10. The principles involved in the measurement of whole-body vibration exposures are presented in Chapter 11 and some examples of vibration conditions are given in Chapter 12.

2.2 Some general observations

Given the opportunity to expose themselves to vibration in the laboratory, readers would make a range of observations which would greatly assist their understanding of both vibration and human response to vibration. For example, a motion with an acceleration magnitude of 1.0 $m s^{-2}$ root mean square (r.m.s.) and a frequency of 0.2 Hz (i.e. a 5s period) has a peak-to-peak displacement of almost 2 m and would probably remind the reader of the vertical oscillations of a ship. The same magnitude of acceleration with a frequency of 1 Hz has a peak-to-peak displacement of about 70 mm and may remind the reader of the side-to-side motion experienced in a train on a very rough section of track. At 5 Hz the frequency is similar to that which occurs during laughter and an acceleration of 1 $m s^{-2}$ r.m.s. will feel vaguely like the vertical vibration on the seat of a small old car on a rough road, the motion has a peak-to-peak displacement of almost 3 mm. At higher frequencies the displacement associated with an acceleration magnitude of 1.0 $m s^{-2}$ r.m.s. becomes difficult to see with the eye. At 20 Hz the vibration will feel like that in a helicopter but have a peak-to-peak displacement of only about 0.2 mm. At 60 Hz a sinusoidal 1.0 $m s^{-2}$ r.m.s. vibration could remind the reader of vibration experienced in a building, but, although the peak-to-peak displacement is only about 0.02 mm, the magnitude of vibration will be greater than that which would be tolerated in the home.

The dramatic manner in which the displacement of vibration decreases in proportion to the square of the vibration frequency (when the vibration acceleration is unchanged) must be recognized. Over the frequency range 0.2–60 Hz, vibration produces many different types of sensation and the acceptability of the motion varies, but it does not fall as rapidly as the decrease in vibration displacement with increasing frequency. The magnitude of a vibration displacement which is visible to the eye of an observer therefore gives a very poor indication of the severity of a vibration.

2.2.1 Responses to vertical vibration

During sinusoidal vertical oscillation at frequencies below about 2 Hz most parts of the body move up and down together. The immediate sensation is of alternately being pushed up and then floating down. The eyes are able either to view objects moving with the body or to compensate for the motion and look at non-moving objects. Free movements of the hand may be disturbed causing some interference with hand-positioning activities. If the motion has a frequency below about 0.5 Hz it may eventually cause symptoms of motion sickness: sweating, nausea or vomiting (see Chapter 7).

Vertical oscillation of a seated person at some frequencies above about 2 Hz causes amplification of the vibration within the body. The frequency of greatest amplification (i.e. resonance frequency) varies for different parts of the body, for different individuals, and with changes of body posture (see Chapter 8). It is commonly suggested that the first major resonance occurs at about 5 Hz—the transmissibility of vertical vibration to the head is sometimes a maximum at about 4 Hz (Section 8.3)—the driving force per unit acceleration (i.e. apparent mass) is a maximum at about 5 Hz (Section 8.4), and vibration acceleration often causes greatest discomfort at about 5 Hz (Section 3.3). Interference with simple hand activities (e.g. writing and drinking) can also be greatest at 4 or 5 Hz (Section 4.3).

At frequencies above 5 Hz the force required to generate a given vertical acceleration at the seat falls rapidly with increasing frequency while the vibration reaching the head and the discomfort produced by the acceleration decrease relatively slowly. The voice may be caused to warble by vibration between about 10 and 20 Hz. Vision may be affected at any frequency but blurring observed at frequencies between about 15 and 60 Hz may be associated with resonances of the eye within the head as well as the complex dynamic response of the body between the seat and the head (Section 4.2).

2.2.2 Responses to horizontal vibration

Horizontal (i.e. fore-and-aft or lateral) vibration of the seated body causes a different range of sensations. At frequencies below about 1 Hz the oscillation tends to cause the body to sway but this may be resisted by muscular action or support from a seat so as to maintain a fairly stable upright position. In the frequency range 1–3 Hz it is difficult to stabilize the upper parts of the body and discomfort caused by vibration acceleration tends to be greatest. With increasing frequency, horizontal vibration is less well transmitted to the upper body: at frequencies above about 10 Hz, horizontal vibration of a supporting seat surface is mostly felt near to the point of contact with the seat.

The presence of a backrest can greatly alter the effect of horizontal motion. At low frequencies a backrest can help stabilize the upper body and reduce the effects of motion. At high frequencies a backrest is the prime cause of vibration being transmitted to the upper body and it may greatly increase the effects of, in particular, fore-and-aft vibration (see Sections 3.3.5, 8.3.3 and 8.4.5).

2.2.3 Posture

Posture can have a large influence on the amount of vibration transmitted to a seated person and determine the extent of any detrimental effects. In the region of a body resonance a small alteration in position or muscle tension may help to reduce vibration severity. The effects of postural changes increase with increasing frequency; minor variations in the orientation of the lower back and the angle of the head can cause substantial changes in the vibration transmitted up the spine to the head. A change in body position which alters the contact with a vibrating surface, such as a backrest, also modifies the effects of the vibration.

2.2.4 Seating

If readers were to experience a range of sinusoidal motions while seated on a typical soft car seat they would observe that the seat can greatly increase or decrease the motion depending on the vibration frequency and vibration direction. At low frequencies (below 1 or 2 Hz) the dynamics of many seats have little influence, but in the region of 4 Hz they noticeably amplify vertical vibration so that a tolerable $1.0\,m\,s^{-2}$ r.m.s. becomes an unacceptable magnitude of, perhaps, $2.0\,m\,s^{-2}$ r.m.s. At some higher frequency many seats attenuate vertical vibration and above about 10 Hz the influence of the motion is greatly reduced (see Chapter 9).

2.2.5 Standing position

In a normal standing position the effects of vertical vibration are often similar to those in the seated position. However, the influence of frequencies above about 3 Hz may be greatly reduced by bending at the knees. Horizontal vibration at frequencies below about 2 Hz tends to cause instability in standing persons which may be reduced by grasping a handhold or, with lateral vibration, placing the legs further apart.

2.2.6 Recumbent positions

A person may lie either on one side of the body, or on the front (i.e. prone), or on the back (i.e. supine) or in some variation on these positions (e.g.

semisupine). The full length of the body (from feet to head) may be exposed to the same vibration or parts may be well isolated from the motion. A couch may either provide stability to resist horizontal motion or allow substantial movement. The variations in the conditions of recumbent persons are considerable and the number of relevant studies is small. However, although the conventional biodynamic axes of vibration rotate with the body, it is clear that sensitivities to vibration in some axes are different when the body is in a lying position as compared with a sitting or standing position (see Section 3.3.8).

2.3 Effects of whole-body vibration

It is convenient to consider human response to whole-body vibration as involving five separate effects: degraded comfort; interference with activities; impaired health; perception of low-magnitude vibration; and the occurrence of motion sickness (see Chapters 3 to 7, respectively).

The consequences of vibration exposure are not simple: the perception of motion, the sensations it produces and the interference with health and activities are all complex phenomena. Some of the mechanisms involved in the various effects are sufficiently well understood to offer firm conclusions. However, in all areas there is scope for much greater understanding of the phenomena. Often, several combinations of effects of vibration will occur simultaneously: a motion may be uncomfortable, interfere with some tasks and be a potential source of injury. In these circumstances one effect of vibration may modify the influence of another effect. For example, a person may modify their posture so as to lessen discomfort and reduce any effect on health, but thereby increase detrimental effects on activities.

The effects of vibration on the body are dependent on the manner and extent to which vibration is transmitted to and through the body. However, the biodynamic responses of the body (e.g. transmissibility and impedance, see Chapter 8) do not directly indicate the relative importance of different motions. If the transmission of vibration to the body is altered (e.g. by a change of posture) there will also tend to be a change in the degree to which the vibration has a detrimental effect. If both the location and the mechanism of the relevant influence of vibration are known it may be possible to predict the effect of a vibration from a knowledge of its transmission to the relevant part. In practice this approach is often complex and the temptation to make naive assumptions should be resisted. For example, the effects of vibration on vision cannot be predicted simply from measures of the transmission of translational vibration from a seat to the head.

Biodynamic data can provide insight into the responses of the body and have some important applications (such as to the optimization of seat dynamics, see Chapter 9). Nevertheless, biodynamics is a tool rather than an end-point and knowledge of how much vibration occurs at various locations is of little value without a knowledge of the relation between the vibration at these locations and the effect of interest.

Various standards for assessing whole-body vibration have been promulgated. The standards attempt to define simple methods of quantifying complex vibration conditions. No simple standard can offer an evaluation procedure which can accurately predict all known effects of vibration on the body and most standards do not even mention the variables which are known to have a large influence on response. A standard which attempted to quantify all variables in relation to their effects would be exceedingly complex. In consequence, most standards do not provide the information necessary to reduce vibration effects optimally. To some extent, a desire for simplicity excludes an understanding of the responses of the body to vibration from the process of formulating standards.

2.4 Vibration axes

International Standard 2631 (International Organization for Standardization, 1974, 1978, 1985a) defined an orthogonal co-ordinate system for the expression of the magnitudes of vibration occurring in different directions (see

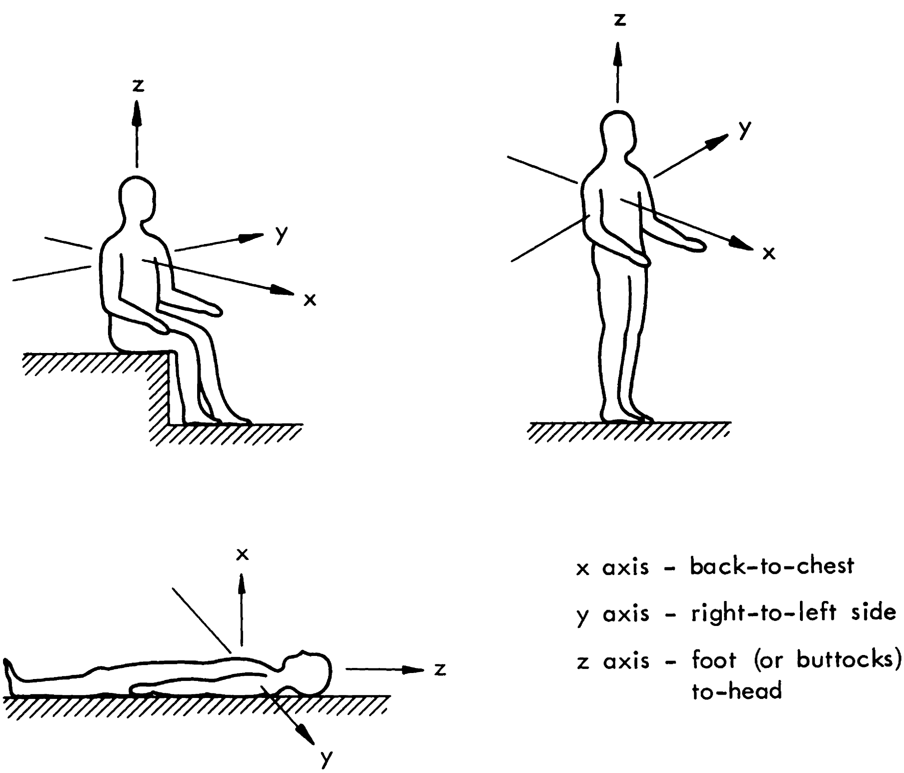

Fig. 2.2 Co-ordinate system for mechanical vibration influencing humans as defined in ISO 2631 (International Organization for Standardization, 1974, 1978, 1985a).

Fig. 2.2). This co-ordinate system has its origin in the heart and rotates with the body. This system has two fundamental problems: the heart is not a well-defined origin for an anatomical co-ordinate system and it is not a convenient location at which to measure vibration!

Basicentric co-ordinate systems are more convenient for practical measurements. Figure 2.3 illustrates a basicentric co-ordinate system which is useful for assessing the vibration exposure of seated persons. In this example there are six orthogonal axes on the seat (three translational and three rotational), three translational axes at the back and three translational axes at the feet. At all three locations the origin of the co-ordinate system lies at a point between

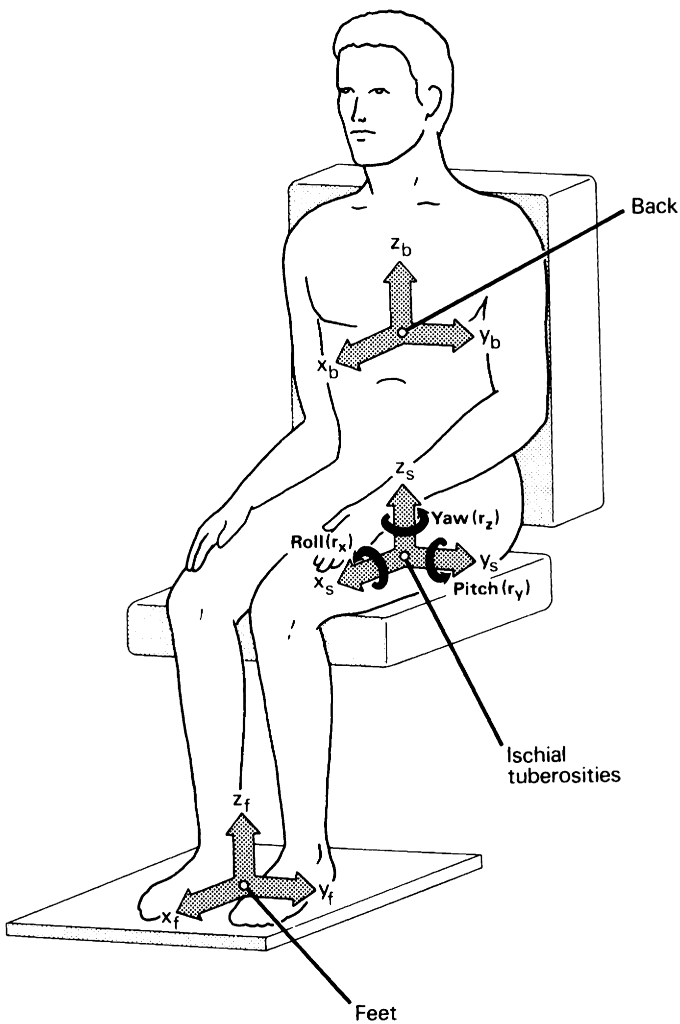

Fig. 2.3 A 12-axis basicentric co-ordinate system. The origins of the axes are (i) beneath the ischial tuberosities, (ii) between the back and the backrest and (iii) beneath the feet.