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Evaluation of human exposure to whole-body vibration — Part 1 : General requirements

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for approval before their acceptance as International Standards by the ISO Council. They are approved in accordance with ISO procedures requiring at least 75 % approval by the member bodies voting.

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Evaluation of human exposure to whole-body vibration — Part 1 : General requirements

0 Introduction

Vehicles (air, land and water), as well as machinery (for example, in industry and agriculture), expose man to mechanical vibration which can interfere with comfort, working efficiency and, in some circumstances, health and safety. Various methods of rating the severity of exposure and defining limits of exposure based on laboratory or field data have been developed in the past for specific applications. None of these methods can be considered applicable in all situations and consequently none has been universally accepted.

In view of the complex factors determining the human response to vibrations, and in view of the shortage of consistent quantitative data concerning man's perception of vibration and his reactions to it, this International Standard has been prepared first, to facilitate the evaluation and comparison of data gained from continuing research in this field; and, second, to give provisional guidance as to acceptable human exposure to whole body vibration. The limits proposed in this International Standard seem to be a fair compromise between the available data and should satisfy the need for recommendations which are simple and suitable for general application. These limits are defined explicitly in numerical terms to avoid ambiguity and to encourage precise measurement in practice. However, when using these criteria and limits it is important to bear in mind the restrictions placed upon their application.

Because of the wide variety of possible conditions and effects of human exposure to vibrations, and because of the existing shortage of firm data, more detailed guidance is hardly warranted at the present time. Nevertheless, it is hoped that this International Standard not only proves useful in the assessment of existing or predicted vibration environments but also stimulates the reporting and critical evaluation of new findings about the effects of vibration on man.

There are basically three kinds of human exposure to vibration, namely :

a) Vibrations transmitted simultaneously to the whole body surface or substantial parts of it. This occurs when the body is immersed in a vibrating medium. There are circumstances in which this is of practical concern; for example, when high intensity sound in air or water excites vibrations of the body.

b) Vibrations transmitted to the body as a whole through the supporting surface, namely, the feet of a standing man, the buttocks of a seated man or the supporting area of a reclining man. This kind of vibration is usual in vehicles, in vibrating buildings and in the vicinity of working machinery.

c) Vibrations applied to particular parts of the body such as the head or limbs; for example, by vibrating handles, pedals or head-rests, or by the wide variety of powered tools and appliances held in the hand.

It is also possible to recognize the condition in which an indirect vibration nuisance is caused by the vibration of external objects in the visual field (for example, an instrument panel).

This International Standard, however, applies chiefly to the common condition (b) above; and, in particular, where the vibration is applied through the principal supporting surface to the body of a standing or seated man. In the case of vibrations applied directly to a reclining or recumbent man, insufficient data are available to make a firm recommendation; this is particularly true of vibration transmitted directly to the head, when tolerability is generally reduced. Tolerance may also be reduced when conditions (b) and (c) exist together. Provisionally, however, the limits for the standing or seated man may also be used for the reclining or recumbent man. It shall be appreciated that some circumstances will arise in which the rigorous application of these limits would be inappropriate.

This International Standard comprises the following parts :

Part 1 : General requirements.

Part 2 : Evaluation of human exposure to vibration and shock in buildings (1 to 80 Hz).[1)]

Part 3 : Evaluation of exposure to whole-body z-axis vertical vibration in the frequency range 0,1 to 0,63 Hz.

Part 4 : Evaluation of crew exposure to vibration on board sea-going ships (1 to 80 Hz).[1)]

1) At present at the stage of draft.

1 Scope and field of application

This part of ISO 2631 defines and gives numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz. It may be applied, within the specified frequency range, to periodic vibrations and to random or non-periodic vibrations with a distributed frequency spectrum. Provisionally, it may also be applied to continuous shock-type excitation in so far as the energy in question is contained within the 1 to 80 Hz band.

These limits (defined in detail in clause 4) are given for use according to the three generally recognizable criteria of preserving comfort, working efficiency, and safety or health. The limits set according to these criteria are named respectively in this part of ISO 2631 the "reduced comfort boundary", "fatigue-decreased proficiency boundary" and the "exposure limit". For example, where the primary concern is to maintain the working efficiency of a vehicle driver or a machine operator working in vibration, the "fatigue-decreased proficiency boundary" would be used as the guiding limit in laying down vibration specifications or in carrying out vibration control measures, while, in the design of passenger accommodations, the "reduced comfort boundary" should be considered.

According to the criteria mentioned, these limits are specified in terms of vibration frequency, acceleration magnitude, exposure time and the direction of vibration relative to the torso. This direction is defined according to the recognized anatomical axes of the human body (see clause 3).

This part of ISO 2631 is applicable only to situations involving people in normal health : that is, persons who are considered fit to carry out normal living routines, including travel, and to undergo the stress of a typical working day or shift.

No information given in this part of ISO 2631 shall be extrapolated to frequencies outside the range 1 to 80 Hz (see notes below).

It has been well established that differences in response to vibration occur both between and within individuals. These differences affect the level and shape of the curves and the relative effects of simple and complex motions. The guidance given in this part of ISO 2631 is based on the average response of subjects in a variety of situations. Thus two motions, which are assessed as equally severe by the recommended evaluation procedure may have different effects. Individuals, and groups of individuals, will sometimes disagree on which of two motions is worse and variables such as posture and subject activities can have large effects.

NOTES

1 The limits specified in this part of ISO 2631 are based upon data available from both practical experience and laboratory experimentation in the field of human response to mechanical vibration. To date, useful observations have been made mainly in the frequency range between about 1 and 100 Hz. The frequency range, its subdivisions and the corner frequencies defined in this part of ISO 2631 have been selected in accordance with ISO 266 and with national standards in several countries.

2 Vibrations in the frequency range below about 1 Hz are a special problem, associated with symptoms such as kinetosis (motion sickness) which are of a character different from the effects of higher frequency vibrations. The appearance of such symptoms depends on complicated individual factors not simply related to the intensity, frequency or duration of the provocative motion. Mechanical vibrations applied to the feet or buttocks above the frequency range considered in this part of ISO 2631 increasingly produce sensations and effects which are highly dependent upon local factors such as the precise direction, site and area of application of the vibration to the body and the presence of damping materials (for example, clothing or footwear) which may control the vibratory response of the skin and superficial layers of the body. For these reasons, therefore, it is not possible on the basis of present data to formulate generally valid recommendations for frequencies outside the 1 to 80 Hz band.

In some applications, constant sensitivity to accelerations has been tentatively assumed for the frequency range 0,63 to 1 Hz.

2 References

ISO 266, *Acoustics — Preferred frequencies for measurements.*

IEC Publication 184, *Methods for specifying the characteristics of electro-mechanical transducers for shock and vibration measurements.*

IEC Publication 222, *Methods for specifying the characteristics of auxiliary equipment for shock and vibration measurement.*

IEC Publication 225, *Octave, half-octave and third-octave band filters intended for the analysis of sounds and vibrations.*

3 Characterization of vibration exposure

3.1 Direction of vibration

3.1.1 Rectilinear vibrations transmitted to man should be measured in the appropriate directions of an orthogonal coordinate system having its origin at the location of the heart (see figure 1).

NOTE — The terminology commonly used in biodynamics relates the coordinate system to the human skeleton in a normal anatomical position. Accelerations (motion) in the foot-(or buttocks-)to-head (or longitudinal) axis are designated $\pm\ a_z$; accelerations in the fore-and-aft (anteroposterior or chest-to-back) axis, $\pm\ a_x$; and in the lateral (right-to-left side) axis, $\pm\ a_y$. These axes are illustrated in figure 1.

3.1.2 Angular (or rotational) vibrations about a centre of rotation are frequently an important part of a vibration environment. For example, in tractors going over rough terrain, or in aircraft flying through turbulence, the pitching or rolling motions of the seat may be more disturbing than the rectilinear vibration up and down. However, little information on the effects of angular (or rotational) vibration is yet available. In practice, the centre of vibratory rotation can often be assumed to lie far enough from the point of application of vibration to the body for the resulting motion to be represented by translatory vibrations alone. Nevertheless, whenever practicable, rotational vibrations in roll, pitch and yaw (as related to the anatomical axes) should be measured and reported, in order to increase our knowledge of the human response to such excitation.

3.1.3 In this part of ISO 2631 separate limits are specified according to whether the vibration is in the (anatomically) longitudinal ($\pm a_z$) direction or transverse ($\pm a_x$ or $\pm a_y$) plane.

3.2 Location of measurement

Because the limits given in this part of ISO 2631 apply to vibration at the point of entry into the human body itself (that is, at the body surface, but not, for example, at the substructure of a resilient seat, which may transform the vibration *en route* to the man), vibration measurements shall be made as close as possible to the point or area through which the vibration is transmitted to the body. For example, if the man is standing on a floor or sitting on a platform without any resilient material between the body and the supporting structure, then the measuring transducer or pick-up should be fastened to that rigid structure. Where some resilient element, such as a seat cushion, does exist between the body and the vibrating structure, it is permissible to interpose some form of rigid transducer support (for example, a thin, suitably formed metal sheet) between the subject and the cushion; but care shall be taken to ensure that such a device does not significantly influence the transfer of vibration through the cushion to the man or introduce rotational motions otherwise not present. If it is not practicable to measure the vibration at the point of input to the man in such a way, then the transmission characteristics of the seat cushion or other resilient element shall be determined and taken into account when calculating the actual vibration transmitted to the body. In such cases, the characteristics of the cushioning system shall be reported.

NOTE — For research purposes which require the precise definition of the vibratory input to human subjects, it has become customary in laboratory studies of biodynamic and physiological responses to replace seat cushions by rigid packs or platforms, because variation of the measuring conditions by different arbitrary seating arrangements can significantly affect the experimental results. Some of the variability of published research results in this field arises from differences between the experimental conditions adopted in different laboratories.

3.3 Intensity of vibration

The primary quantity used to describe the intensity of a vibration environment, irrespective of the type of transducer or pick-up used in actual measurements, shall be the acceleration. Acceleration should normally be expressed in metres per second squared (m/s^2).

NOTE — In physiological work, it is frequently the custom to express accelerations non-dimensionally in g units where $1g$ is the value of the standard acceleration due to gravity acting at the earth's surface. This usage is permissible within the context of experimental work in hand provided that, when reference is made to the limits given in this part of ISO 2631, the international standard value of g_n is used for conversion to values of acceleration expressed in metres per second squared.

The magnitude of a vibration, that is, the acceleration (or, if quoted, the velocity or displacement), should be expressed as a root-mean-square (r.m.s.) value. When peak values are measured, these shall be converted as appropriate to r.m.s. values before reference to the limits given in this part of ISO 2631. For the adequate description of vibration which is markedly non-sinusoidal, random or broad-band, the crest factor (ratio of maximum peak to r.m.s. value) of the time function shall be determined or estimated : the limits given in this part of ISO 2631 should be regarded as very tentative in the case of vibrations having high crest factors (that is, greater than 3; see below).

Recent research has indicated that motions with crest factors greater than 3 can often be compared satisfactorily with the limits given in this part of ISO 2631. However, it is clear that the importance of some motions which contain occasional extremely high peak values may be underestimated by the recommended evaluation method. Work is in progress to determine how such motions may be meaningfully compared with the limits. Until this information is available the following procedure is tentatively recommended.

The acceleration signal should be weighted by the appropriate filter network defined in table 3 and described in 4.2.4. The maximum peak value of this weighted signal is its maximum deviation from the mean value. The crest factor is then the ratio of this maximum peak value to the weighted r.m.s. value of the signal. Accelerations with crest factor as great as 6 can be evaluated by this part of ISO 2631. When the crest factor is greater than about 6, the recommended vibration evaluation method may underestimate the effect of the motion.

In practice, the crest factor will depend on the period over which the peak value and the r.m.s. value are determined. The minimum period for evaluating the crest factor is 1 min. In addition to occasional peak values, the large variations in level which can occur over periods longer than 1 min can raise the crest factor. However, these motions may often be evaluated using the equivalent exposure time calculations described in 4.4.

It is sometimes inconvenient to determine the peak value of the weighted signal as described above. Peaks determined on an unweighted signal (with band-pass filtering between 1 Hz and 80 Hz only) will normally be greater than those from a weighted signal. An upper estimate of the crest factor may therefore be determined from unweighted signals first. If the value exceeds 6 it will be necessary to weight the signal to determine whether the criterion is really exceeded. The r.m.s. value should always be determined from the weighted signal.

NOTE — Measurements of rotational vibrations, whenever made, should be reported in units of r.m.s. angular acceleration, radians per second squared (rad/s^2).

3.4 Measuring equipment

Vibration measuring equipment generally consists of the following parts : a transducer or pick-up, an amplifying device (electrical, mechanical or optical), and an amplitude or level indicator or recorder. Where practicable (as in electronic instrumentation) and appropriate, networks may be included to limit the frequency range of the equipment and to apply the recommended frequency-weighting to the input signal. For many applications, where it is not essential to rely solely upon on-the-spot determinations, the use of a suitable tape recording system to obtain representative records for subsequent analysis will be the method of choice. An r.m.s.-rectifying device may also be included for convenience, so that r.m.s. values may be read off or recorded directly.

All vibration measuring equipment should be properly calibrated. This should be done in accordance with existing standards or recommendations governing the calibration of such equipment. The basis of operation and the characteristics of any measuring equipment used should be reported together with the results obtained with it. It is important to report such characteristics as the frequency sensitivity, the dynamic properties (for example, the time constant), the dynamic range and resolution of the equipment; and when appropriate, the precision of r.m.s.-rectifying, frequency-weighting, tape recording, frequency analysis or such other operations as may be performed upon the signal.

NOTES

1 It is recommended that IEC Publication 184 be used for specifying the vibration-transducers and IEC Publication 222 for specifying the auxiliary equipment, including amplifiers, frequency-selective equipment and carrier systems.

2 With respect to the subjective judgement of the vibration intensity, it appears that the integration time for the human vibration perception decreases from 2 to 0,8 s over the frequency range from 2 to 90 Hz.

3.5 Random or broad-band vibration analysis

In the measurement of random or distributed vibration, of which narrow-band analysis not exceeding one-third octave is the appropriate method of description, the one-third octave band filters used in any recording or analytical network shall be in accordance with IEC Publication 225. The frequency range given in IEC Publication 225 shall be extrapolated accordingly to corresponding lower frequencies.

For some applications, it will be appropriate to equip electronic vibration measuring apparatus with a frequency-weighting network defined as corresponding to the limits for vertical (a_z) and horizontal (a_x and a_y) vibration respectively given in clause 4, tables 1 and 2 and figures 2a and 3a (see note 2 of 4.2.4). A network so defined shall not deviate from the recommended values by more than ± 1 dB at two fixed frequencies; 6,3 Hz and 31,5 Hz for a_z measurements and 1,25 Hz and 31,5 Hz for a_x and a_y measurements.

3.6 Exposure time

This part of ISO 2631 includes a computational procedure (see 4.4) for assessing the effective daily exposure to vibration. This is intended to take account, as far as is possible, of variations in the intensity of vibration and any intermittency or interruption of exposure to vibration which may occur during the period in question. Whenever measurements are made of human exposure to vibration which is varying in intensity, or which is discontinuous, the time-history of such exposure should be reported in detail.

4 Vibration evaluation guide

4.1 General considerations

There are four physical factors of primary importance in determining the human response to vibration, namely, the intensity, the frequency, the direction, and the duration (exposure time) of the vibration. In the practical evaluation of any vibration of which a physical description can be given in terms of those factors, three main human criteria can be distinguished. These are :

a) the preservation of working efficiency ("fatigue-decreased proficiency boundary");

b) the preservation of health or safety ("exposure limit"); and

c) the preservation of comfort ("reduced comfort boundary").

The recommended limits of exposure set according to these three criteria are defined in 4.1.1 to 4.1.3. Each of these limits is defined graphically for the longitudinal (a_z) direction (figures 2a and 2b) and the transverse (a_x, a_y) directions (figures 3a and 3b). Numerical definition of the graphs in figures 2 and 3 is presented in tables 1 and 2. Typically, as in most transport situations, a_z (longitudinal) vibration will be applied to a sitting or standing person (a situation popularly referred to as "vertical vibration").

NOTE — It will be seen that, other factors being equal, somewhat higher levels of vibration are acceptable when health or safety is the criterion, in comparison with the limits appropriate to working efficiency; and, conversely, lower limits are set when the criterion is the preservation of comfort. This is in general accord with experimental observation and experience, but it should not be taken as implying that there exists in all circumstances a simple hierarchical relationship between the intensities of vibration likely to impair health, working efficiency or comfort.

4.1.1 Fatigue-decreased proficiency boundary

The fatigue-decreased proficiency boundary as a function of frequency and exposure time is shown in figures 2a and 2b (longitudinal vibration) and 3a and 3b (transverse vibration) for daily exposure times from 1 min to 24 h. The numerical values defining the boundary are presented in tables 1 and 2 respectively. The boundary specifies a limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency in many kinds of tasks, particularly those in which time-dependent effects ("fatigue") are known to worsen performance as, for example, in vehicle driving.

The actual degree of task interference in any situation depends on many factors, including individual characteristics as well as the nature and difficulty of the task. Nevertheless, the limits recommended here show the general level of onset of such interference, the frequency dependence and the time dependence commonly observed. The data upon which these limits are based come mainly from studies on aircraft pilots and drivers.

It should be noted that for man the most sensitive frequency ranges (in which the limit is accordingly set lowest) are 4 to 8 Hz for longitudinal (a_z) vibration and below 2 Hz for transverse (a_x, a_y) vibration; and that human tolerance of vibration decreases (demanding increasingly stringent limits) in a characteristic way with increasing exposure time (figures 2b and 3b). It is seen from a comparison of figures 2a and 3a that, whereas the tolerance for transverse vibration is lower than that for longitudinal vibration at very low frequencies, the converse is so for higher frequencies (above approximately 2,8 Hz).

NOTE — It is anticipated that with experience in the practical applications of this part of ISO 2631, correction tables will be worked out to vary the level of the fatigue-decreased proficiency boundary according to different environmental conditions of task requirements. For example, a more stringent limit may have to be applied when the task is of a particularly demanding perceptual nature or calls for an exercise of fine manual skill. By contrast, some relaxation of the limit might be possible in circumstances in which the performance of the task (for example, heavy manual work) is relatively insensitive to vibration. Tentative data, as yet too few to provide a basis for a firm recommendation, suggest that a range of correction of + 3 dB to − 12 dB (that is, a modifying factor of 1,4 to 0,25 times the r.m.s. acceleration specified by the boundary) may be envisaged.

4.1.2 Exposure limit (health or safety)

The exposure limit as a function of frequency and exposure time is of the same general form as the fatigue-decreased proficiency boundary, but the corresponding levels are raised by a factor of 2 (6 dB higher). In other words, maximum safe exposure is determined, for any condition of frequency, duration and direction, by doubling the values allowed according to the criterion of fatigue-decreased proficiency (see figures 2a, 2b and 3a, 3b and tables 1 and 2).

Exceeding the exposure limit is not recommended without special justification and precautions, even if no task is to be performed by the exposed individual.

NOTES

1 The exposure limit recommended is set at approximately half the level considered to be the threshold of pain (or limit of voluntary tolerance) for healthy human subjects restrained to a vibrating seat. (Such limit levels have been explored for male human subjects in laboratory research.)

2 At certain frequencies both above and below the band of maximum sensitivity, the acceleration levels permitted for short exposure times according to the exposure limit and the fatigue-decreased proficiency boundary exceed 7 m/s^2, which is equivalent to a peak value of approximately 10 m/s^2 or approximately 1g for sinusoidal vibration. Such vibration in the vertical direction can cause the subject to lift off his seat or platform, unless he is effectively restrained. Bouncing is unlikely to be a real problem, however, at frequencies above 20 Hz where the relatively small displacement, even at high acceleration levels, can be taken up by the compliant tissues of the body.

4.1.3 Reduced comfort boundary

The reduced comfort boundary, which is derived from various studies conducted for the transport industries, is assumed in this part of ISO 2631 to lie at approximately one-third of the corresponding levels of the fatigue-decreased proficiency boundary, and is, moreover, assumed to follow the same time and frequency dependence. Values for the reduced comfort boundary are, accordingly, obtained from the corresponding values for the fatigue-decreased proficiency boundary by a reduction of 10 dB (see figures 2a, 2b and 3a, 3b and tables 1 and 2). In the transport situation the reduced comfort boundary is related to difficulties of carrying out such operations as eating, reading and writing.

NOTES

1 In practice, there will be limits to the usefulness of this part of ISO 2631. The fatigue-decreased proficiency boundary and reduced comfort boundaries in particular are presumed to apply most directly to vibration in transport and near industrial machinery. These limits may not be very powerful in the evaluation of disturbance due to building vibration (for example, caused by traffic or footfall) in private homes, offices or similar situations in which the socio-psychological and economic factors related to human disturbance are more subtle or complex. Acceptable vibration levels in residential buildings, for example, may not lie much above the threshold of perception, especially during the night, but shall, in any case, be expected to vary greatly with individual circumstances. The threshold of perception varies from one subject to another and depends upon the conditions of measurement. The upper range of the threshold of perception has approximately the same frequency dependence as the curves of figures 2a and 3a. In the frequency bands of maximum sensitivity, namely 4 to 8 Hz for longitudinal and 1 to 2 Hz for transverse vibrations, the threshold lies at approximately 0,01 m/s^2 (about $10^{-3}\,g$). The individual threshold for many people may lie at still lower levels.

2 It is anticipated that additional tables will be developed through the practical use of this part of ISO 2631, providing for a finer differentiation of comfort in various situations, such as in offices, in various types of private residence, on ships, etc. The range of such correction factors might extend from + 3 dB to − 30 dB (approximate threshold of perception), but their formulation awaits more substantial data than are available at present.

4.2 Evaluation of frequency spectrum

4.2.1 Evaluation of discrete (single) frequencies

The limits shown in figures 2 and 3 and given in tables 1 and 2 are valid for discrete frequency vibrations acting in the foot-to-head (a_z) or the transverse directions (a_x, a_y) respectively.

4.2.2 Evaluation of discrete (multiple) frequencies

When vibration occurs simultaneously at more than one discrete frequency within the range 1 to 80 Hz, the r.m.s. acceleration of each frequency component shall be evaluated separately with reference to the appropriate limit at that frequency.

4.2.3 Narrow-band "random" vibration concentrated in one-third octave band or less

In the case of narrow-band vibration concentrated in a one-third octave band or less, the r.m.s. value of the acceleration within the band shall be evaluated with reference to the appropriate limit at the centre frequency of that band.

4.2.4 Broad-band vibration

In the case of broad-band distributed vibration, whether random or not, occurring in more than a one-third octave band, the r.m.s. value of the acceleration in each such band shall be evaluated separately with respect to the appropriate limit at the centre frequency of that band.

NOTES

1 The above procedures assume that in respect of human tolerance no significant interactions occur between vibration effects at different frequencies. There exists at present no published evidence to decide between the accuracy of the presently recommended rating procedure and the weighting procedure discussed as a permissible approximation in note 2 below.

2 In order to allow the characterization of a vibration environment with respect to its effects on man by a single quantity and to simplify measurements for situations in which spectrum analysis is difficult or inconvenient, the overall vibration signal for the frequency range 1 to 80 Hz may be weighted with an electronic network. This weighting network, to be inserted between the vibration pick-up and the meter, shall have an insertion loss with a frequency response according to the curves of figure 2a for a_z and of figure 3a for a_x or a_y vibration measurements. The insertion loss is to be zero for the band 4 to 8 Hz for a_z measurements, and for the band 1 to 2 Hz for a_x and a_y measurements. The network characteristics shall not deviate more than ± 1 dB between two fixed frequencies and more than ± 2 dB over the other frequency ranges. The two fixed frequencies are 6,3 Hz and 31,5 Hz for a_z measurements and 1,25 Hz and 31,5 Hz for a_x and a_y measurements.

Recent research on comfort and on performance has shown that where the vibration spectrum consists of several vibration components or is a broad-band motion, the weighted method often provides a good approximation to the effects of the motion. Therefore, when a single number is desired to quantify the effect of vibration of this type for a single axis, the weighting method is now recommended in preference to the rating method. However, when overall weighted values of acceleration are reported, it is recommended that the frequency composition of the motions should also be quoted. The overall weighted value is primarily recommended for comparison with the overall weighted value of other vibrations. For direct comparison of these values with the guidance given in the tables and figures, appropriate adjustment of these values may have to be considered.

The overall weighted vibration values so measured shall be reported as a_{zw} and a_{xw} or a_{yw} respectively, according to the direction of measurement, and are to be compared to the permissible values in the 4 to 8 Hz band for a_z and in the 1 to 2 Hz band for a_x and a_y vibration.

It is appreciated that this proposed method for single number characterization of a vibration environment and for comparison of this number with the exposure criteria is only an approximation. However, in most practical cases the difference between the detailed one-third octave band boundary evaluation method and the weighted overall vibration measurement method is small. Moreover, the weighting method results in an over-conservative assessment of the effects of the vibration; that is, depending on the vibration spectrum the permissible a_{zw}, a_{xw} and a_{yw} values could be raised above the values determined by the most sensitive frequency band in figure 2a (4 to 8 Hz) and figure 3a (1 to 2 Hz). In such cases where the evaluation according to the weighted overall acceleration method results in inadmissible levels, the detailed method using one-third octave band frequency analysis is the recommended method of choice. In the least favourable case that the spectrum to be measured is a broad-band spectrum with a one-third octave band spectrum corresponding to the insertion loss of the filters, that is, the shape of the rating curves in figure 2a or figure 3a respectively, the weighted overall vibration level would be 13 dB above the one-third octave levels in the most sensitive frequency bands (4 to 8 Hz in figure 2a; 1 to 2 Hz in figure 2b). These exposure criteria applied to the approximate weighting method would be 13 dB too conservative, yielding accelerations four times lower than would be permitted using the one-third octave band analysis method. In the most favourable case that all vibration energy is in a single one-third octave band the two methods yield identical results.

4.3 Vibration in more than one direction simultaneously

If vibrations occur in more than one direction simultaneously ("multiaxis" or "multiplanar" vibration), the corresponding limits apply separately to each vectorial component in the three axes.

If two or three vectorial components of a multiaxis vibration have similar magnitudes when the a_x and a_y components are multiplied by 1,4, the effect on comfort and performance of the combined motion can be greater than that of any single component.

To assess the effects of such a motion a procedure is proposed in which the vibration spectra in each of the axes should first be weighted (see note 2 of 4.2) to give the overall weighted vibration values a_{xw}, a_{yw} and a_{zw}. These three values are then combined to give the amount of the vector sum, a :

$$a = \sqrt{(1,4\, a_{xw})^2 + (1,4\, a_{yw})^2 + a_{zw}^2}$$

where the factor 1,4 is the ratio of the longitudinal to the transverse curves of equal response in the frequency ranges where humans are most sensitive.

This amount of the vector sum can be used primarily for comparison with the vector sum of other motions. Evaluations for comfort and performance may be made by comparing the vector sum with the overall weighted acceleration value for z-axis vibration (derived from table 1 and figures 2a and 2b).

4.4 Duration (exposure time) of vibration

4.4.1 As the basis for evaluating exposure time, the relationship between any given boundary and time illustrated in figures 2b and 3b is assumed. The tolerable acceleration level increases with decreasing exposure time, as shown in figures 2b and 3b. Values of this function are given in tables 1 and 2 for daily exposure times from 1 min to 24 h. The effect of exposure time is also shown in figures 2a and 3a where the limits for longitudinal and transverse vibration respectively are expressed as functions of frequency with selected values of exposure time as the parameter. These limits apply when the exposure is continuous for the period stated, and when the exposure is repeated daily over many years, for example for an industrial worker in a vibrating environment or for a transport driver. For exposure which is much less frequently experienced, for example by the casual traveller, the acceptable exposure, i.e. the tolerable combination of acceleration and time, may well be higher.

There is a more convenient method for approximating the manner in which the tolerable acceleration levels decrease with increasing exposure time up to 8 h. If a_1 is the tolerable level for a 1 min exposure (as tabulated in tables 1 and 2) and t_0 is 10 min then the level for an exposure of t min is a_t where :

$$a_t = a_1 \qquad t \leqslant 10 \text{ min}$$

$$a_t = a_1 \times \sqrt{\frac{t_0}{t}} \qquad 10 \text{ min} < t < 480 \text{ min}$$

This approximation to the curves in figures 2b and 3b allows slightly greater levels for periods between 4 min and about 25 min and also greater levels for periods longer than about 2,5 h (see figure 4). However, understanding of the effects of vibration duration is far from complete and the above approximation to the curves may be considered adequate for most practical purposes.

NOTE — This approximation might be tentatively extended up to 24 h per day, particularly if it is incorporated into instrumentation.

In the case of an interrupted daily exposure, or division of the exposure into several intervals, the effects of vibration on man may be mitigated by some degree of recovery, which, if it occurred, would allow prolongation of the tolerable total exposures indicated in figures 2a and 2b or figures 3a and 3b. However, quantitative data concerning a recovery effect are not yet available, and such an effect is, therefore, not allowed for in this part of ISO 2631.

4.4.2 If the exposure to vibration is interrupted by pauses during the working day, but the intensity of exposure remains the same, then the effective total daily exposure time is simply obtained by addding up the individual exposure times.

4.4.3 If the r.m.s. acceleration amplitude varies appreciably with time, or if the total daily exposure is composed of several individual exposure times, t_i, at different levels; A_i, then an "equivalent total exposure" is obtained by the following procedure.

4.4.3.1 First, a convenient notional value; A', is chosen within the range of the values A_i. By reference to the appropriate data shown in figures 2b or 3b and given in tables 1 or 2 a corresponding permissible time, τ', is found for A'. In the same manner, corresponding permissible times, τ_i, are found for each of the values A_i.

4.4.3.2 The "equivalent exposure times", t'_i, are then calculated from the relationship

$$t'_i = t_i \times \frac{\tau'}{\tau_i}$$

For the notional acceleration, A', these times are equivalent to the actual time values, t_i, for the different accelerations, A_i.

4.4.3.3 The equivalent effective times, t'_i, thus obtained are next summed to give :

$$T' = \Sigma_i \, t'_i = \tau' \, \Sigma_i \frac{t_i}{\tau_i}$$

The time T' is the "equivalent total exposure time" for the notional acceleration, A'; τ' is the permissible exposure time for the acceleration A'.

4.4.3.4 The ratio τ'/T' is the deciding factor in judging the permissibility of an "equivalent exposure" thus calculated. This ratio shall not be less than unity; that is, $\Sigma_i \, (t_i/\tau_i)$ may not exceed unity.

4.4.3.5 For vibrations occurring simultaneously in different axes, equivalent total exposure times shall be calculated and evaluated separately for each axis, as stated in 4.3.

4.4.4 In cases where exposure to vibration, whether continuous or intermittent, goes on for more than 24 h, the limits specified in this part of ISO 2631 shall be taken as applying to each 24 h period or residual part thereof; or in other words, in computing an equivalent total exposure time, the period over which individual exposure shall be integrated is limited to 24 h.

Table 1 — Numerical values of "fatigue-decreased proficiency boundary" for vibration acceleration in the longitudinal, a_z, direction [foot-(or buttocks-)to-head direction] (see figure 2a)

Values define the boundary in terms of r.m.s. value of pure (sinusoidal) single frequency vibration or r.m.s. value in one-third octave band for distributed vibration.

Frequency (centre frequency of one-third octave band) Hz	Acceleration, m/s^2 Exposure times								
	24 h	16 h	8 h	4 h	2,5 h	1 h	25 min	16 min	1 min
1,0	0,280	0,425	0,63	1,06	1,40	2,36	3,55	4,25	5,60
1,25	0,250	0,375	0,56	0,95	1,26	2,12	3,15	3,75	5,00
1,6	0,224	0,335	0,50	0,85	1,12	1,90	2,80	3,35	4,50
2,0	0,200	0,300	0,45	0,75	1,00	1,70	2,50	3,00	4,00
2,5	0,180	0,265	0,40	0,67	0,90	1,50	2,24	2,65	3,55
3,15	0,160	0,235	0,355	0,60	0,80	1,32	2,00	2,35	3,15
4,0	0,140	0,212	0,315	0,53	0,71	1,18	1,80	2,12	2,80
5,0	0,140	0,212	0,315	0,53	0,71	1,18	1,80	2,12	2,80
6,3	0,140	0,212	0,315	0,53	0,71	1,18	1,80	2,12	2,80
8,0	0,140	0,212	0,315	0,53	0,71	1,18	1,80	2,12	2,80
10,0	0,180	0,265	0,40	0,67	0,90	1,50	2,24	2,65	3,55
12,5	0,224	0,335	0,50	0,85	1,12	1,90	2,80	3,35	4,50
16,0	0,280	0,425	0,63	1,06	1,40	2,36	3,55	4,25	5,60
20,0	0,355	0,530	0,80	1,32	1,80	3,00	4,50	5,30	7,10
25,0	0,450	0,670	1,0	1,70	2,24	3,75	5,60	6,70	9,00
31,5	0,560	0,850	1,25	2,12	2,80	4,75	7,10	8,50	11,2
40,0	0,710	1,060	1,60	2,65	3,55	6,00	9,00	10,6	14,0
50,0	0,900	1,320	2,0	3,35	4,50	7,50	11,2	13,2	18,0
63,0	1,120	1,700	2,5	4,25	5,60	9,50	14,0	17,0	22,4
80,0	1,400	2,120	3,15	5,30	7,10	11,8	18,0	21,2	28,0

Table 2 — Numerical values of "fatigue-decreased proficiency boundary" for vibration acceleration in the transverse, a_x or a_y, direction (back-to-chest or side-to-side) (see figure 3a)

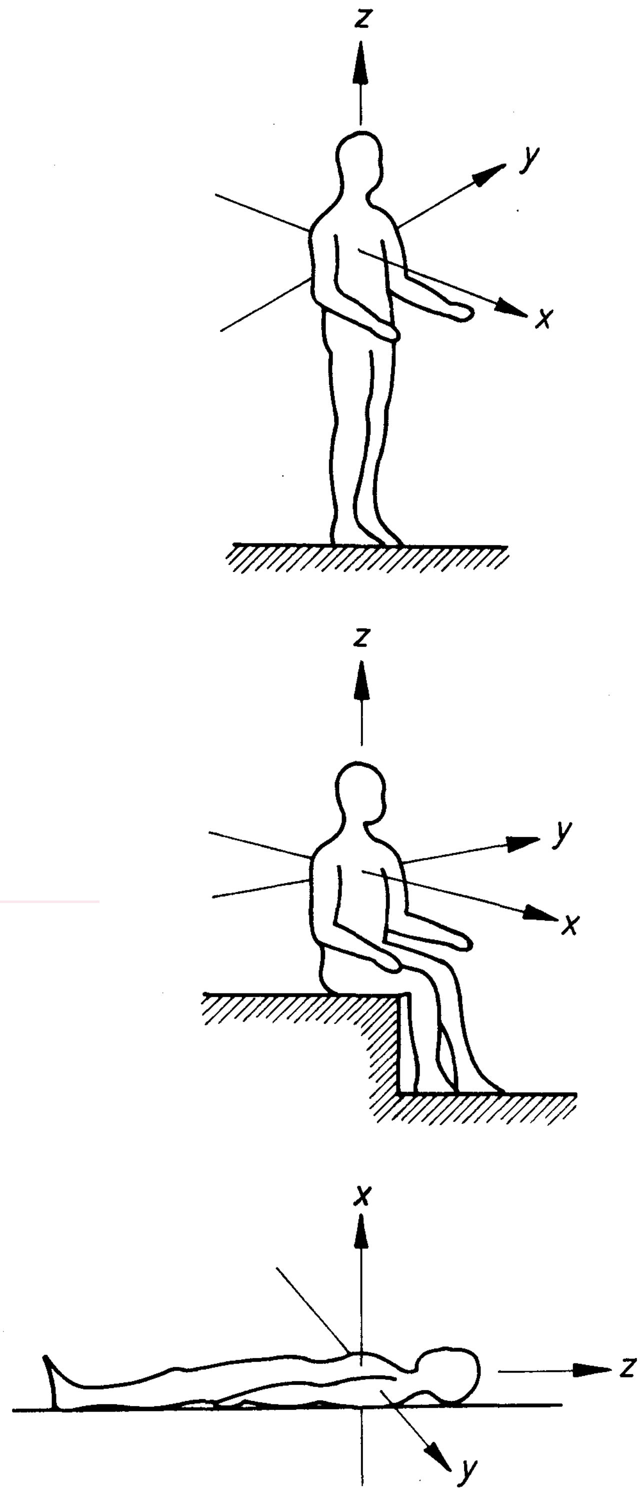
Values define the boundary in terms of r.m.s. value of pure (sinusoidal) single frequency vibration or r.m.s. value in one-third octave band for distributed vibration.

Frequency (centre frequency of one-third octave band) Hz	Acceleration, m/s^2 Exposure times								
	24 h	16 h	8 h	4 h	2,5 h	1 h	25 min	16 min	1 min
1,0	0,100	0,150	0,224	0,355	0,50	0,85	1,25	1,50	2,0
1,25	0,100	0,150	0,224	0,355	0,50	0,85	1,25	1,50	2,0
1,6	0,100	0,150	0,224	0,355	0,50	0,85	1,25	1,50	2,0
2,0	0,100	0,150	0,224	0,355	0,50	0,85	1,25	1,50	2,0
2,5	0,125	0,190	0,280	0,450	0,63	1,06	1,6	1,9	2,5
3,15	0,160	0,236	0,355	0,560	0,8	1,32	2,0	2,36	3,15
4,0	0,200	0,300	0,450	0,710	1,0	1,70	2,5	3,0	4,0
5,0	0,250	0,375	0,560	0,900	1,25	2,12	3,15	3,75	5,0
6,3	0,315	0,475	0,710	1,12	1,6	2,65	4,0	4,75	6,3
8,0	0,40	0,60	0,900	1,40	2,0	3,35	5,0	6,0	8,0
10,0	0,50	0,75	1,12	1,80	2,5	4,25	6,3	7,5	10
12,5	0,63	0,95	1,40	2,24	3,15	5,30	8,0	9,5	12,5
16,0	0,80	1,18	1,80	2,80	4,0	6,70	10	11,8	16
20,0	1,00	1,50	2,24	3,55	5,0	8,5	12,5	15	20
25,0	1,25	1,90	2,80	4,50	6,3	10,6	16	19	25
31,5	1,60	2,36	3,55	5,60	8,0	13,2	20	23,6	31,5
40,0	2,00	3,00	4,50	7,10	10,0	17,0	25	30	40
50,0	2,50	3,75	5,60	9,00	12,5	21,2	31,5	37,5	50
63,0	3,15	4,75	7,10	11,2	16,0	26,5	40	45,7	63
80,0	4,00	6,00	9,00	14,0	20	33,5	50	60	80

Table 3 — Weighting factors relative to the frequency range of maximum acceleration sensitivity[1] for the response curves of figures 2a and 3a

Frequency (centre frequency of one-third octave band) Hz	Weighting factor for	
	longitudinal vibrations (figure 2a)	transverse vibrations (figure 3a)
1,0	0,50 = − 6 dB	1,00 = 0 dB
1,25	0,56 = − 5 dB	1,00 = 0 dB
1,6	0,63 = − 4 dB	1,00 = 0 dB
2,0	0,71 = − 3 dB	1,00 = 0 dB
2,5	0,80 = − 2 dB	0,80 = − 2 dB
3,15	0,90 = − 1 dB	0,63 = − 4 dB
4,0	1,00 = 0 dB	0,5 = − 6 dB
5,0	1,00 = 0 dB	0,4 = − 8 dB
6,3	1,00 = 0 dB	0,315 = − 10 dB
8,0	1,00 = 0 dB	0,25 = − 12 dB
10,0	0,80 = − 2 dB	0,2 = − 14 dB
12,5	0,63 = − 4 dB	0,16 = − 16 dB
16,0	0,50 = − 6 dB	0,125 = − 18 dB
20,0	0,40 = − 8 dB	0,1 = − 20 dB
25,0	0,315 = − 10 dB	0,08 = − 22 dB
31,5	0,25 = − 12 dB	0,063 = − 24 dB
40,0	0,20 = − 14 dB	0,05 = − 26 dB
50,0	0,16 = − 16 dB	0,04 = − 28 dB
63,0	0,125 = − 18 dB	0,0315 = − 30 dB
80,0	0,10 = − 20 dB	0,025 = − 32 dB

1) 4 to 8 Hz in the case of $\pm a_z$ vibration
1 to 2 Hz in the case of $\pm a_y$ or $\pm a_x$ vibration.



a_x, a_y, a_z = acceleration in the directions of the x-, y- and z-axes
x-axis = back-to-chest
y-axis = right side to left side
z-axis = foot-(or buttocks-)to-head

Figure 1 — Directions of basicentric coordinate systems for mechanical vibrations influencing humans