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EFFECTS OF VIBRATION ON HUMANS

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SUMMARY

The various International Standards concerned with vibration and the preservation of human comfort, performance and health are compared. Examples of the complexity of vibration encountered by man on land, at sea, in the air, in buildings and on vibrating tools are presented and considered in relation to the current Standards.

INTRODUCTION

Vibration of the body may occur at work, on the way to work, at home, and in leisure and pleasure activities. Vibration can be exhilarating, pleasant, or otherwise beneficial. It can however, cause annoyance, discomfort, interference with activities, injury or disease.

In many environments the surface supporting the body is vibrating and there is *'whole-body'* vibration. *'Local'* vibration occurs when primarily only a part of the body (most often the hand) is in contact with the source of vibration.

Knowledge of the effects of vibration on humans must consist of information on the cause-effect relationship. This requires quantitative knowledge of:

- (a) The cause: vibration-related variables (frequency, direction, duration, posture etc)
- (b) The effect: effect-related variables (comfort, performance, health, prevalence etc)
- (c) The relation between the cause and the effect.

Vibration-related variables

Human reaction to vibration is highly dependent on the vibration frequency and direction in addition to the vibration magnitude. For example, while 0.5 ms^{-2} rms at 0.25 Hz produces motion sickness, the same level at 4 Hz will cause 'no' motion sickness. With 0.5 ms^{-2} rms vertical vibration at 4 Hz there may be difficulty in drinking without spilling the drink. This motion at 0.25 Hz will cause little direct interference with drinking - although the desire for food and drink may be lacking!

Few environments consist of a single frequency, single direction, motion of constant magnitude. The normal situation involves complex multi-frequency or random vibration which occurs in several axes (Figure 1) and may change rapidly from moment to moment. Useful measurements of such motions must be determined by either an average, or a sum, of the motion occurring in a given time period.

Although it has not always been accepted (e.g. |1|) it is now widely considered appropriate for the effect of complex single axis vibration to be assessed by the use of frequency-weighting networks (e.g. |2|, |3|, |4|). The methods of summing motion occurring in different axes differ between standards. 'Time-weightings' are partially defined in various documents but no single time-dependency is yet accepted for all effects of vibration on the body. In general, the method of summing exposures over a day are either ambiguous or insufficiently tested. Methods of summing exposures over years of employment have not been tried - although a measure of the time before adverse symptoms appear (i.e. latency) is sometimes used as a measure of the severity of the 'effect' rather than the 'cause'.

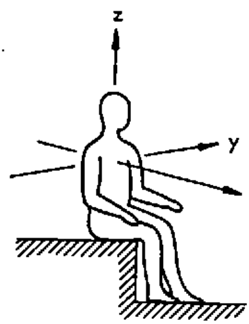

Fig.1. Coordinate system for sitting persons as defined in ISO 2631 |1|.

Effect-related variables

Three principal effects of vibration on the body are identified: interference with (a) health (b) performance and (c) comfort.

The *health* criterion relates to bodily injury - usually due to repeated long-term exposures to vibration. Both whole-body and local vibration may cause health problems. Severe whole-body vibration exposures most often occur in off-road vehicles (tractors, forest machines, etc). The most common sources of local vibration injury are hand-held vibrating tools and workpieces.

Vibration may disturb *performance* by direct mechanical interference - such as shaking of the hand or eye. It may also be responsible for various indirect effects due to physiological changes induced by vibration, changes in motivation or arousal. The majority of experimental evidence is concerned with direct effects on vision and hand activities.

Discomfort is clearly relevant to judging the relative 'ride' of two vehicles or the relative discomfort of vibration transmitted through two alternative seats. (The 'ride-quality' of a vehicle will not be sufficiently assessed by considering comfort if performance is also affected (e.g. illegible writing on a train)). The subjective feeling of comfort may be disturbed by the perception of low levels of vibration in a building or the symptoms of motion sickness in a ship.

Selecting the relevant criteria (i.e. health, performance or comfort) is not a sufficient definition of the effect of vibration. It is also necessary to state (i) what type of person is being affected (young, old, male, female, fit or ailing); (ii) what percentage of this group is affected; (iii) to what degree the vibration-exposed persons are affected.

Relating vibration to its effects

In the following sections, the guidance defined in various published standards and draft standards is summarised. A division has been made between guidance concerned with health, that concerned with human activities and that concerned with comfort and well-being. Information from some standards appears in more than one section. In some cases, the information is compared with an example of relevant laboratory findings. In all cases the vibration is that entering the body and not that at a point below resilient seating. Individual standards should be consulted directly for precise interpretations. Additional unpublished proposals for new standards and draft revisions of existing standards are not presented.

HEALTH EFFECTS

International Standard ISO 2631 (1974, 1978) |1| presents 'exposure limits' for 1 to 80 Hz whole-body vibration exposures in each of the three principal translational axes. These define "maximum safe exposure" for durations from 1 minute to 24 hours. The exposure limit was said to be set at "approximately half the threshold of pain (or limit of voluntary tolerance) for healthy human subjects restrained to a vibrating seat". As with other guidance defined in ISO 2631, the z-axis limits show maximum sensitivity to acceleration in the range 4 to 8 Hz while the x- and y-axis limits are lowest in the range 1 to 2 Hz. Amendment 1 to ISO 2631 |2| notes that "in some applications tentatively constant sensitivity to acceleration has been assumed for the frequency range 0.63 to 1 Hz". In Figures 2a and 2b the ISO 2631 contours are shown without this extrapolation for durations of (a) 1 minute, (b) 1 hour, (c) 4 hours, (d) 8 hours and (e) 24 hours. The values shown apply to continuous single-frequency vibration.

Amendment 1 indicates that if a single number is required to specify broad-band vibration then the inverse of the contours shown in Figures 2a and 2b may be used to define weighting networks.

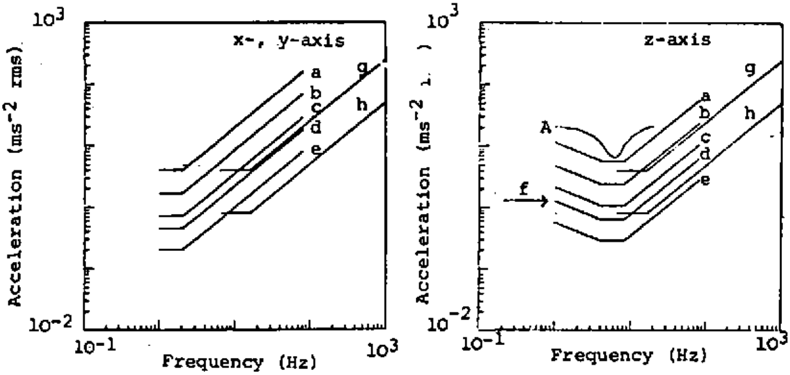

Fig.2a and 2b. Acceleration limits for preserving health (see text).

Draft International Standard 7096 |5| defines a frequency-weighted z-axis vibration limit of 1.25 ms^{-2} rms for earth-moving machinery. This is shown by the arrow (f) in Figure 2b. Various adverse effects of whole-body vibration have been reported |6| but no specific injury or disease is defined in these two standards. An experimentally determined one-minute subjective tolerance contour for z-axis vibration |7| is shown as curve (A) for comparison on Figure 2b.

There are many different standards and limits concerned with local vibration exposures |8|. Some are restricted to the circulatory disorder sometimes known as Vibration-induced White Finger (VWF), others, such as Draft International Standard DIS 5349 |4| refer more widely to "diseases affecting the blood vessels, nerves, bones, joints, muscles or connective tissues of the hand and forearm". However, there is little originality in the different standards and the ranges of vibration magnitudes and frequencies are similar. The most important differences occur in the time-dependencies.

Figures 2a and 2b show the two contours in DIS 5349 which define the 'maximum acceptable levels': (g) for daily vibration exposure up to 30 mins, and (h) for daily exposures of 4 to 8 hours. (Three further contours are defined for periods of 30 to 60 mins, 1 to 2 hours and 2 to 4 hours). These "provisional limits are not to be exceeded" within any third-octave band in any axis. The curves are only defined between 8 and 1000 Hz. They show greatest sensitivity to acceleration in the frequency range 8 to 16 Hz.

The unusual comparison of whole-body and hand-arm health-related vibration limits shown in Figures 2a and 2b reveal some surprising differences. For example, in some cases vibration which is above the short-time (up to 30 min) limit for hand-arm vibration is apparently 'safe' for whole-body vibration for up to 6 hours! While there are considerable biodynamic and physiological differences between the two cases such large differences must be questionable.

The vibration magnitude is generally expressed in terms of the root mean square acceleration as a function of frequency as shown in Figures 2a and 2b. However, assuming single frequency sinusoidal vibration the two sets of contours may be represented in terms of vibration displacement (metres, peak to peak) as shown in Figures 2c and 2d. It may be seen that while the low frequency short-time whole-body z-axis limit approaches 1 m pk-pk, the displacement at high frequencies is very small. Around 10 Hz and at higher frequencies, movements of about 1 mm are in excess of several of the limits. Visual appearance of the vibration clearly does *not* allow any conclusions about the safety of either hand-arm or whole-body vibration exposures.

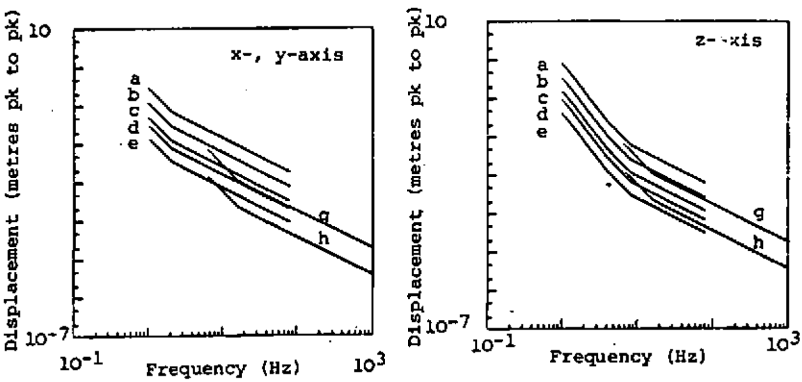

Fig.2c and 2d. Displacement limits for preserving health (see text).

INTERFERENCE WITH ACTIVITIES

International Standard 2631 defines fatigue - decreased proficiency limits "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 limits for (a) 1 min, (b) 1 hour, (c) 4 hours, (d) 8 hours and (e) 24 hours are shown in Figure 3a for x- and y-axis vibration and in Figure 3b for z-axis vibration. These curves are one-half the corresponding exposure limits shown in Figure 2a and 2b.

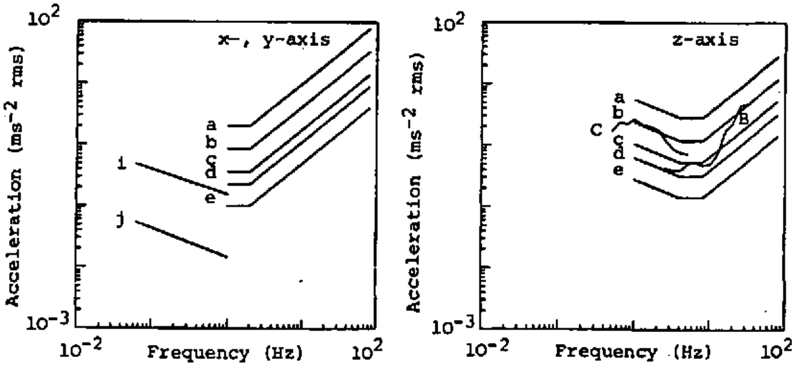

Fig.3a and 3b. Acceleration limits for preserving performance (see text).

Draft International Standard DIS 6897 |9| presents guidance on evaluating the response of occupants of fixed structures (especially buildings and off-shore structures) to low frequency horizontal motion. This includes, for the frequency range 0.063 to 1.0 Hz, two levels relevant to the effects of motion on activities. For storms occurring once in 5 years the limit (i) in Figure 3a applies to the worst consecutive 10 min periods when "work of a somewhat demanding nature has to be performed". When the motion occurs frequently with a duration in excess of 10 mins a lower limit (j) applies to buildings "where routine precision work is carried out".

A time dependency for the direct effects of vibration on performance of many common tasks is irrelevant. It is not credible that if 2.8 ms^{-2} rms is required to spill coffee at the start of a 24 hour train journey then only 0.14 ms^{-2} rms is required to produce the same effect at the end of the journey. Indeed, practice and desperation are more likely to improve performance as time proceeds!

While fatigue may be affected by long periods of vibration, most existing experimental data are concerned with direct mechanical effects. Interference with hand activities is highly dependent on the nature of the activity (the aircraft control dynamics, control sensitivity, cup size etc!). Interference with visual performance depends on the nature of the visual task and other factors. Two contours showing the effect of z-axis vertical vibration on reading performance appear on Figure 3b. Curve (B) is for vertical vibration of the body only |10| (see Moseley et al, 1982) while curve (C) is for simultaneous vibration of the body and the display |11|.

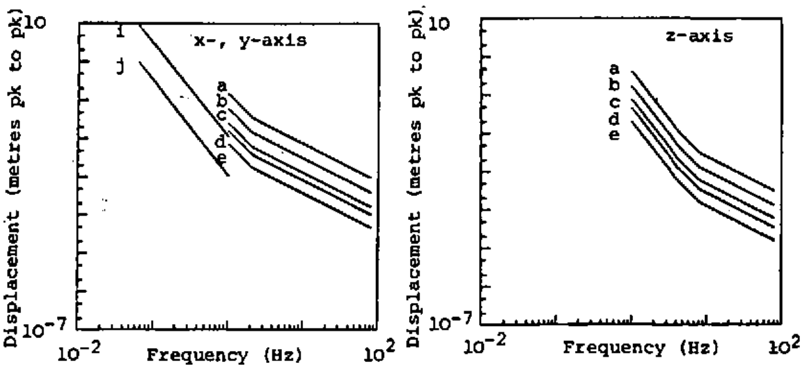

Fig.3c and 3d. Displacement limits for preserving performance (see text).

The presentation of the above standards as displacement limits in Figures 3c and 3d shows that whereas up to 10 metres of movement are concerned at 0.063 Hz, less than 1/10th of a millimetre may be relevant to performance evaluation at 80 Hz.

COMFORT AND WELL-BEING

International Standard 2631 also defined reduced comfort boundaries. These are set at approximately one-third of the corresponding fatigue-decreased proficiency boundaries. The standard states that the comfort boundaries are related to "difficulties of carrying out such operations as eating, reading and writing". This is not entirely consistent with the Standard's declaration that reduced comfort boundaries should be used for the design of passenger accommodation. Neither is it fully consistent with the definition of comfort in ISO 5805 |12| ("comfort: *subjective* state of well-being in relation to an induced environment including mechanical vibration (or shock)"). The reduced comfort boundaries are shown for: (a) 1 minute, (b) 1 hour, (c) 4 hours, (d) 8 hours and (e) 24 hours in figures 4a and 4b. Curves D and E in Figure 4b are two experimentally determined median equivalent comfort contours for vertical vibration which are equivalent to reference vibrations at 10 Hz and 2 Hz respectively |13|, |14|.

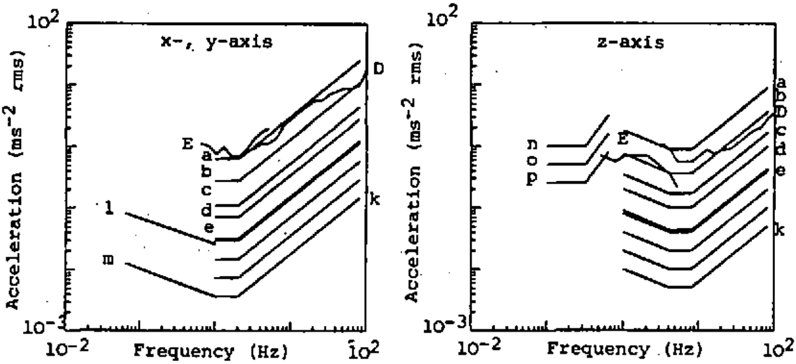

Fig. 4a and 4b. Acceleration limits for preserving comfort (see text).

Draft Addendum 1 to International Standard 2631 is concerned with acceptable magnitudes of 1 to 80 Hz building vibration |15|. It defines limits for continuous and intermittent vibration and impulsive shock. The Standard is based upon the curves in ISO 2631 but with a baseline curve applicable to critical areas set close to the threshold of perception (curve k in Figure 4). Curves set at 2, 4 and 8 times this base curve are intended for residential, office and workshop areas respectively. (Other levels apply to impulsive motions etc). The values are said to "represent good environmental standards". "Moderate complaints" will occur at double the stated levels and "major complaints" will occur at four times the levels unless prior warning is given. In Figures 4a and 4b it may be seen, for example, that the curve for workshops (i.e. 8 x base curve) and the curve for major complaints in residences (i.e. 4 x 2 x base curve) are both approximately equal to the 24 hour reduced comfort boundary.

Draft International Standard 6897 | 9 | defines "satisfactory magnitudes" for 0.063 to 1 Hz horizontal motion during the worst 10 consecutive minutes of a storm with a return period of five years (curve l)). It also defines a lower threshold of perception for horizontal motion in this frequency range (curve m)). It may be seen in Figure 4a that at 1 Hz these two low frequency curves encompass the 8-fold range for good environmental standards specified in ISO DAD 1 (1980) for continuous vibration.

Motion sickness does not naturally relate to other subjective reactions - but it has been defined as "severe discomfort" in Addendum 2 to ISO

2631, | 3 |. This Standard defines the magnitudes of vertical 0.1 to 0.63 Hz vibration which cause symptoms of sickness in about 10% of unadapted seated or standing men. Sensitivity to acceleration is maximum in the range 0.1 to 0.315 Hz. In Figure 4b the curves (n), (o), and (p) apply to 1/2 hour, 2 hour and 8 hour exposure periods. It may be seen that if the ISO 2631 reduced comfort contours were extended down to 0.63 Hz by horizontal extrapolation (as mentioned in ISO 2631 AM 1) the 2 hour sickness level at 0.63 Hz would approximately correspond to the 1 minute reduced comfort boundary. In general, at 0.63 Hz only motions appreciably in excess of the extended reduced comfort boundary should induce significant sickness symptoms. (Indeed, motion sickness is most often associated with much lower frequencies).

Expressed in terms of the peak-to-peak displacement (as in Figures 4c and 4d) it may be seen, for example, that at 0.315 Hz less than 0.5m peak-to-peak is required to produce 10% sickness within 2 hours. In contrast, when considering building vibration, at all frequencies the limits for good environmental standards are too small to see with the unaided eye.

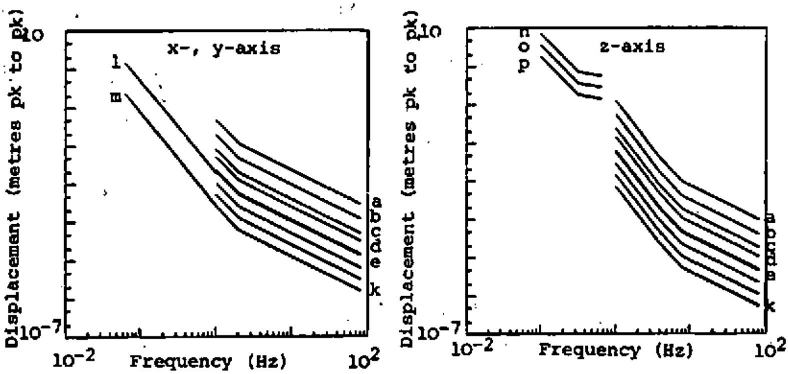

Fig.4c and 4d. Displacement limits for preserving comfort (see text).

REAL VIBRATION

The vibration encountered by man is often complex and time-varying. The standards attempt to define simple methods of averaging (or summing) the vibration to obtain an estimate of its relative severity or absolute effect. Useful averaging of vibration to indicate the severity of the motion must involve consideration of the detailed form of the range of possible motions. Few publications give precise data on real vibration conditions and some standards have been defined with little knowledge of the nature of real motions to which they can be applied. Examples of real motions are presented in this section.

Road vehicles

Figure 5a shows an 8 second acceleration time history of vertical vibration recorded on the seat of a car. The power spectral density of a longer record in the same vehicle is shown in Figure 5b. This motion can only usefully be assessed in terms of ISO 2631 by referring to Amendment 1 in which the crest factor limit was raised to 6 and the frequency weighting method of summing complex motions was advocated. Even with these changes, excluding seat back, feet and rotational seat vibration may limit the accuracy of the conclusions.

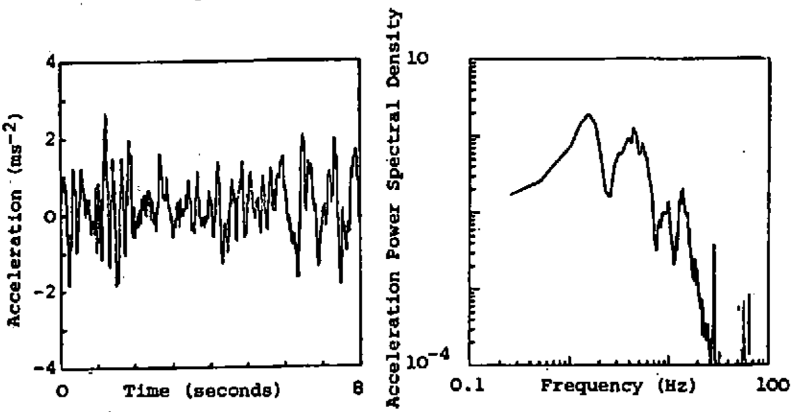

Fig.5a and 5b. Acceleration time history and power spectrum for vertical vibration on a car seat.

Aircraft

A sixteen second acceleration time history and corresponding power spectrum from z-axis vibration in a low flying aircraft are shown in Figures 6a and 6b. The motion contains much low frequency energy and is of a random nature. The standards currently give little guidance on the effect of vibration at frequencies below 1 Hz on human performance and there have been few systematic experiments with random vibration.

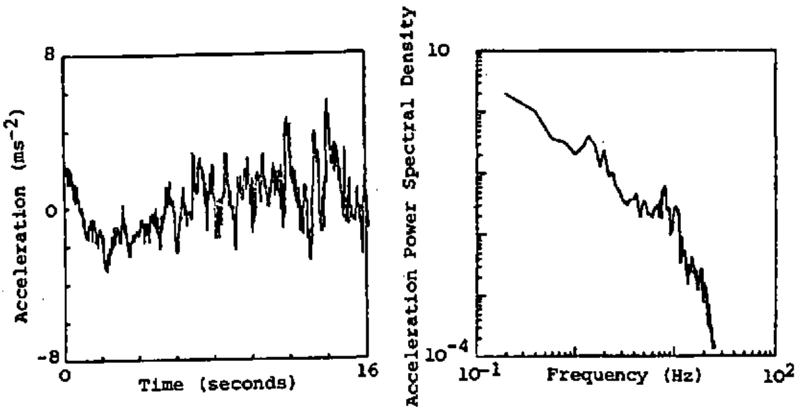

Fig.6a and 6b. Acceleration time history and power spectrum for vertical vibration in a low flying aircraft.

Ships

An 80 second z-axis acceleration time-history from a ship and the corresponding power spectral density (from a very much longer period) are shown in Figures 7a and 7b. The motion in this axis is dominated by one frequency component within the range covered by ISO 2631 ADD 2 but the magnitude of the oscillations varies from cycle to cycle. Ships also roll and pitch so the magnitude of vertical motion changes in different parts of a ship. Furthermore, the effect of the motion varies considerably from person to person.

Buildings

Buildings may vibrate due to internal movements (e.g. foot-fall, doors banging) or external excitation (e.g. industrial machinery, blasting, road and rail traffic). Figures 8a and 8b show the acceleration time history and corresponding power spectral density of vibration in a building due to the passage of a train. The evaluation of this motion with respect to ISO 2631 DAD 1 requires that an equivalent root mean square acceleration value is determined. However there is no widely agreed procedure for the determination of an rms value equivalent to the changing motion shown in Figure 8a.

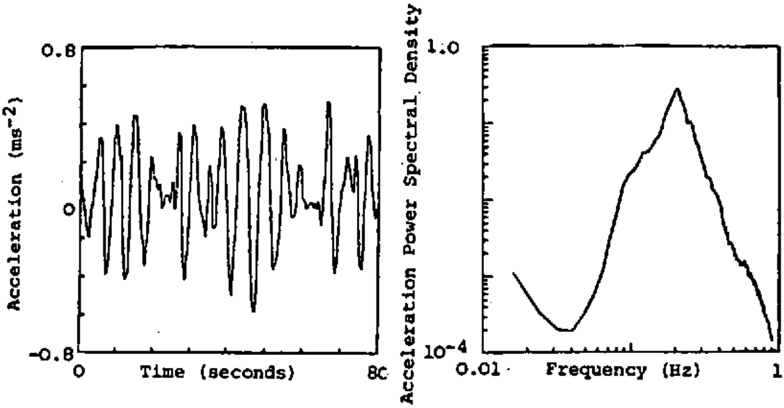

Fig.7a and 7b. Acceleration time history and power spectrum for vertical ship motion.

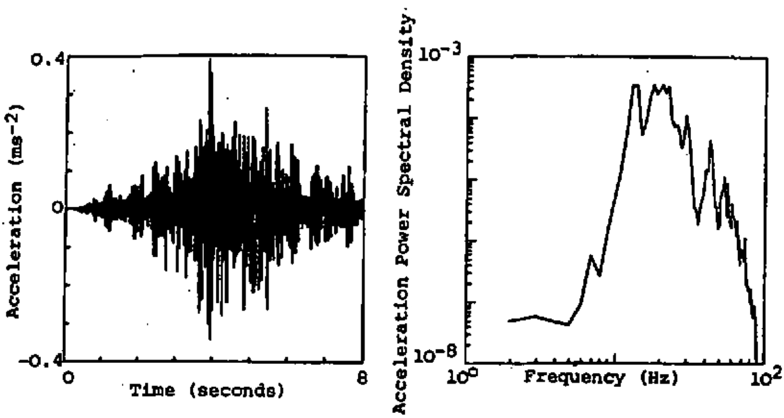

Fig.8a and 8b. Acceleration time history and power spectrum of vertical building vibration during the passing of a nearby train.

Hand-tool vibration

An example of vibration from a percussive metal-working tool is shown in Figures 9a and 9b. While the repetition rate appears in the vibration spectrum, the dominant frequency for unweighted energy appears at about 100 Hz. After frequency-weighting according to ISO DIS 5349 (1979) the lower frequencies are found to be the more important with this tool. The reliable measurement of vibration on some percussive tools presents significant difficulties which are not yet fully resolved. The use of rms averaging of this type of vibration is widely assumed, without proof, to be an indicator of its potential for harming the body.

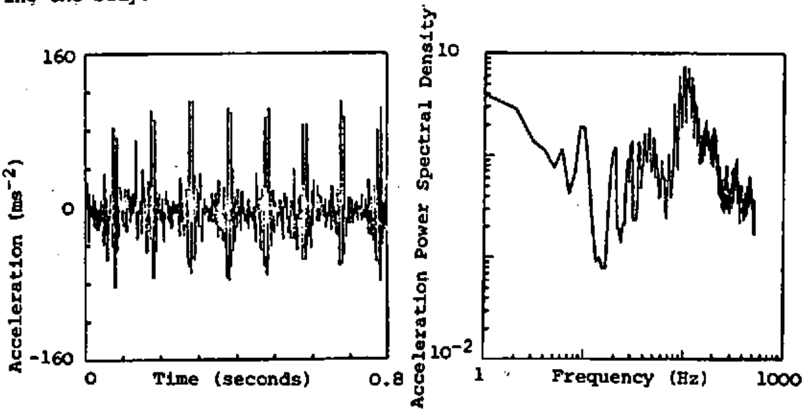

Fig.9a and 9b. Acceleration time history and power spectrum of vibration on a percussive metal-working tool.

CONCLUSIONS

Current standards provide useful guidance on the uniform collection, Presentation and interpretation of human vibration exposure data. However there are certain anomalies, inadequacies and unproven assumptions which could result in false conclusions. Probably the greatest single problem concerns the correct evaluation of time-varying stimuli.

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