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RIDE QUALITY AND INTERNATIONAL STANDARD ISO 2631 ("GUIDE FOR THE EVALUATION OF HUMAN EXPOSURE TO WHOLE-BODY VIBRATION")

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SUMMARY

The evolution of the Standard, which is aimed at promoting research and production of more data, and providing some design guidance, is outlined and its contents summarised. Some of the assumptions and information on which it is based are analysed. Certain problem areas which the author considers need particular attention are briefly discussed.

Its application to vehicle ride quality is considered in the context of the safety, efficiency and comfort of crew and passengers. The importance of establishing the precise criteria against which vibration limits are required is underlined, particularly the difficulties of first defining comfort and then postulating appropriate levels.

Some current and future work related to improving the Standard is outlined and additional suggestions offered.

INTRODUCTION

Problems of ride quality have been with us since transport began, from the ancient coracles and chariots to the more recent aircushion and spacecraft. Vibration is an important, sometimes a dominating feature of the ride environment, and causes undesirable effects ranging from back troubles and other pathological problems (ref.1), contributing to fatal air crashes by impairing pilot efficiency (ref.2), to 'simple' discomfort. Consequently it has been a topic for considerable research, and numerous 'standards' for acceptable vibration levels have been postulated. None of these is universally applicable and none has received widespread acceptance until the recent issue of ISO Standard 2631 (ref.3).

The objects of this paper are, in the context of vehicle vibration requirements, to review briefly the evolution of ISO 2631, to outline its contents and their foundation, and to analyse them. The application of the Standard to vehicle ride quality is discussed. Finally the work proceeding or planned to improve and supplement the Standard is reviewed and suggestions made to fill other important gaps.

This Symposium is concerned primarily with ride quality requirements related to passenger comfort and acceptance. However, the safety and performance of the crew and vehicle are also influenced by ride characteristics, so that all these aspects are covered in this paper.

Apart from certain factual information related to ISO 2631, the paper presents my personal views which are not necessarily those of the ISO Sub-Committee (ISO/TC108/SC4) involved.

EVOLUTION OF ISO 2631 AND GENERAL REMARKS

Work on the Standard officially commenced in June 1964 at the first meeting of Working Group 7 of ISO Technical Committee 108 at Aix-les-Bains, where the first draft proposal,"Classification of the Influence of Mechanical Vibration of Man", was tabled. This copied almost entirely a German specification, VDI 2057 of October 1963 (ref.4) which in turn evolved from the work of Dieckman on 'K Values' (ref.5). It was aimed primarily at defining levels for various strengths of perception of vibration, that is, the response of the body as a load-measuring device. Only tentative examples were given, in an Appendix of the relevance of these curves to subjective tolerance, which was acknowledged to be influenced by important variables other than vibration *per se*. A graph summarizing the proposals, which applied equally to vertical and horizontal vibration, is given in fig.1, with the implied time-dependency of tolerance in fig.2. The final document (ref.3) was published in July 1974, after approval by 19 countries with the UK and USSR expressing disapproval on technical grounds. For comparison, extracts from it are included in figs.1 and 2.

In the metamorphosis of the Standard there were considerable changes, not only in the shape and levels of the 'limits' but also in its coverage and fundamental purpose. Perhaps the most important change has been in the emphasis in the final document, which is absent from the original, that its first purpose is "... to facilitate the evaluation and comparison of data gained from continuing research in this field" and only second "... to give provisional guidance as to acceptable human exposure to whole-body vibration". Another change in philosophy particularly important in relation to this Symposium concerns the original declared scope of the work of the ISO Working Group which was "... with a goal to ensure safety and performance capability of man". 'Comfort' considerations soon began to be discussed and included, but for myself, the Standard still has the flavour of a document aimed mainly at industrial working life exposure, with the "maintenance of proficiency" as the focal point. Levels for the preservation of health and comfort are factored above and below the "fatigue-decreased proficiency boundary" (F-DP). As discussed in more detail subsequently, in my opinion its recommendations should only be used with considerable discretion for design standards, particularly those related to passenger comfort or acceptance.

It appears that the evolution has had to depend on considerable assumptions necessary at the time because of lack of information. The final document may at first sight have the appearance of considerable precision and coverage, particularly if designers turn to the graphs and tables without carefully reading the all-important qualifications in the text. In fact in an authoritative paper (ref.6) on the subject, it is contended that the Standard "relates various human responses to the dynamic motions and exposure time experienced. ... [but] makes no judgment on the permissibility or advisability of the occurrence of these responses in specific situations (e.g., vehicles). It recognizes that to a considerable extent human responses, primarily behavioral

and performance effects, depend upon the attitude, motivation, age, experience, and many other biodynamic and psychological factors which characterize the exposure situation...". This important reservation on the applicability of the Standard to vibration requirements is not, however, included in the document itself. Rather, it is an expert interpretation which may well not be applied by the normal, less well-informed user of the Standard.

In fact, as discussed subsequently, human response to vibration is such a complex problem that personally I consider it most unlikely that it will ever be possible to produce clear cut standards covering all situations. Designers, operators, etc., should use 2631 for general guidance. They should explore the many variables in their particular situation and if necessary adjust the proposed levels. This difficulty has been appreciated by the ISO Sub-Committee involved, which is working to fill some of the gaps and to produce addenda for specific applications such as vibration in buildings and in ships.

PRECIS AND ANALYSIS OF ISO 2631

The main contents of the document including the recommended limits and the important supporting text are summarised below. The paragraph numbers in brackets refer to the appropriate paragraphs in ISO 2631. Information in quotes is taken verbatim from the Standard. Important information which may be overlooked in scanning the full Standard is printed in italics. The précis (P) is slightly indented to distinguish it from the analysis (A).

My limited analysis of the Standard is based to some extent on official records and presented some difficulties in preparation. The Standard itself only gives limited information on the logic and evidence on which it is based, and the references included are not specifically cited in the text. The background to the Standard has however already been covered in some depth in a paper (ref.6) at a previous Symposium on vehicle ride quality, and to some extent in an AGARD paper (ref.7). For the sake of completeness my analysis reiterates some of the contents of these earlier papers.

P. (0) "INTRODUCTION"

PURPOSE "*First*, to facilitate 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."

OVERRIDING QUALIFICATION "These limits are defined explicitly in numerical terms to avoid ambiguity and encourage precise measurement. *However when using these criteria and limits, it is important to bear in mind the restrictions placed upon their application.*"

(1) "SCOPE AND APPLICATION"

("Addenda ... providing modified guide lines for particular applications may be issued from time to time".)

Primarily whole-body vibration applied to standing or seated *man*. *Provisionally* applies to recumbent or reclining man, *not* to local vibration to limbs or head.

1-80Hz, periodic and random or non-periodic vibration.

Criteria	Nomenclature of corresponding limit	Application
"Preserving comfort"	"Reduced comfort boundary"	Passenger (transport) accommodation
"Preserving working efficiency"	"Fatigue-decreased proficiency" (F-DP) (previously entitled "Fatigue time-limit of decreased proficiency")	Vehicle driver or machine operator
"Preserving safety or health"	"Exposure limit"	(Not declared, assumed to apply to any situation.)

Population cover "... 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."

A. The criteria are simplified generalisations and have important subdivisions which considerably influence the appropriate limits, for example the nature of the task and physical, psychological or 'activity' discomfort.

Reaction to vibration varies widely between individuals and individual groups. A more specific definition of population cover and limits for particular populations is ultimately needed. (See subsequent proposals for vibration below 1Hz.)

Average reaction of a group (and most of the evidence for the limits seems to be based on average results on fit young men) may be less relevant than reaction of particular individuals. The proposals do not necessarily apply accurately to women and certainly not to children or old people.

P. (3) "CHARACTERISATION OF VIBRATION EXPOSURE"

DIRECTION: Linear vibration only, using an orthogonal system related to major body axes:-

a_z , foot-to-head (longitudinal, popularly 'vertical' for standing or seated man)

a_x , chest-to-back (fore and aft)

a_y , side-to-side (lateral)

"Angular vibrations ... are frequently an important part of a vibration environment. For example ... the pitching or rolling motions of the seat may be more disturbing than the rectilinear

vibrations. However little information on the effects of angular (or the rotational) vibration is yet available." In practice, the centre of rotation can often be assumed to be far enough from the body for the resulting motion to be represented by linear vibration alone. The Standard requests that, wherever practical, data on angular vibration should be recorded to increase knowledge.

The limits given in the Standard "... should be regarded as very tentative in the case of vibrations having high crest factors ...".

INTENSITY: *Primary quantity shall be acceleration* in m/s^2 rms $\left(\text{or } g = \frac{m/s^2}{9.81}\right)$ *measured at entry into body itself.*

If peak values are measured, convert to rms. For random vibration *crest factor* (peak/rms) must be determined. *Limits given can only be applied very tentatively if crest factor exceeds 3.*

A. Relatively little field or laboratory work has been carried out on angular vibration. Limits will be particularly difficult to define because of measurement problems and the fact that reaction will be critical to the position of the centre of rotation in relation to the body.

To define the input completely, strictly speaking another linked parameter such as force or impedance is needed. As an extreme example two surfaces may vibrate (accelerate) together with little or no force or interaction between them. This may be important with regard to the effects of posture, arm and foot rests, harnesses, etc. In many situations however, acceleration alone is probably an adequate descriptor of the vibration input, particularly in view of the many other variables involved.

'Crest factor' is not precisely defined, particularly the duration over which the peak/rms ratio should be measured. Ride comfort in certain situations will depend on reaction to 'jolts and bumps' with crest factors exceeding 3. There is little or no guidance for such situations either in this Standard or elsewhere. (ISO/TC108/SC4 has recognised and is endeavouring to fill this important gap. Also, a draft Standard is in preparation for desirable limits for large single shocks (covering accidents, etc.).)

P. (4) "VIBRATION EVALUATION GUIDE"

"FATIGUE-DECREASED PROFICIENCY BOUNDARY" (F-DP) Beyond this boundary "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 are expressed as rms acceleration versus frequency for exposure times from 1 minute to 24 hours and are summarised in figs.3 and 4 for longitudinal and transverse (fore and aft and lateral) vibration respectively. The recommended proportional reduction in permissible vibration with time is shown as the curve in fig.5.

The limits are for general guidance only and the value applying t a particular situation"... depends on many factors including individual factors as well as the nature and difficulty of the task ... a more stringent limit may have to be applied when the task is of a particular demanding perceptual nature or calls for the exercise of a fine manual skill. By contrast some relaxation of the limit might be possible when ... the performance of the task (for example, heavy manual work) i relatively insensitive to vibration ... tentative data ... suggests tha a *range of correction of +3dB to -12dB (that is ... 1.4 to 0.25 times t rms acceleration specified by the boundary)* may be envisaged." A graph illustrating this range is given in fig.6.

"EXPOSURE LIMIT" This limit, summarised in figs.3 and 4, is of the sam shape as the F-DP boundary but set at twice the level (6dB). The limit is stated to be set at approximately half the level of the threshold of pain, or limit of voluntary tolerance obtained from laboratory studies *men.*

"REDUCED COMFORT BOUNDARY" This boundary, summarised in figs.3 and 4, *assumed* to follow the same shape as the F-DP boundary but at approximat one third of its level (-10dB). *"In the transport situation the reduce comfort boundary is related to the difficulties of carrying out such operations as eating, reading and writing."*

The boundary is qualified by the following statement, the significance of which is illustrated graphically in fig.7. "It is anticipated that additional tables will be developed ... for a finer differentiation of comfort in various situations, such as in offices, in various types o private residence, *on ships,* etc. *The range of such correction factors might extend from +3dB (1.4 ×) to -30dB (1/30) (the approximate threshol of perception).*"

"NOTE ... 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."

A. The shape of the acceleration/frequency curves is the same for all three criteria and is based on the assumption that the overriding influence on human response to vibration is due to the biomechanical response of the body and bod parts. This contention is supported by empirical evidence from laboratory and field research, mainly on young men.

More specifically, for the a_z (longitudinal) direction the trough in the acceleration/frequency limits assumes a minimum in driving point impedance between 4 and 8Hz, that is a major resonance of the human body in this frequency region. The corresponding minimum between 1 and 2Hz in the a_x and a_y (transverse) directions assumes minimal impedance and a major (shoulder girdle) resonance in this region. The increasing slope at 45^o on the log/log scale of the a/f curves above 8 and 2Hz respectively, implies that if the body behaves as a linear mass/spring/velocity-damped system, then the response is directly related to the total force acting on the mass, that is, to the total input force.

The decreasing slope in the a_z/f curves between 1 and 4Hz is proportional to $a/\sqrt{f}$ ($\frac{1}{2}$ on log/log scale), which is a compromise between the original VDI proposals (ref.4) of a constant a_z and an alternative suggestion that it should be proportional to $1/f$ (1:1 on the log/log scale).

The shape is a simplified generalisation which may be a reasonable approximation in certain specific cases. It is open to considerable adjustment, firstly because the body, and the associated response to vibration, frequently do not behave as a single order mass-spring-system. There are several important sub-systems, head-on-shoulders, spine, etc., usually with resonant frequencies higher than the dominant ones (*circa* 5Hz and 2Hz for a_z and a_x , a_y directions respectively) and for certain applications these may modify the shape of the curves particularly above 8Hz (a_z) and 2Hz (a_x and a_y). Also the a_z shape between 1 and 4Hz fails to reflect the likely peak in tolerance around $1\frac{1}{2}$ to 2Hz, attributable perhaps to evolutionary acclimatization to walking frequency (ref.8). The criteria of acceptability may be founded on one or more of the several possible response characteristics of the body system. These could range from absolute displacement, relative displacement, applied force, absorbed power (heat) in the total body system or a sub-system, to force in a particular body sub-system. It seems likely that the basic responses controlling safety, efficiency and comfort will differ even for a particular situation. For example safety (preservation of health) is likely to be dominated by the load or force in particular body parts whereas performance may be dependent on relative and/or absolute displacement. This emphasises the importance of the qualification in the Standard concerning the simple hierarchical relation between exposure, F-DP and reduced comfort limits.

The shape and acceptable levels are affected by many variables not at present covered in this Standard. Some of these are briefly considered subsequently. Apart from possible variations due to different biodynamic criteria (above) it is conceivable that the appropriate shape may differ between a short exposure, a long casual exposure and a repeated working life exposure.

With regard to the actual levels specified, the Standard informs us that:-

(i) The F-DP boundary is based on data "mainly from studies on aircraft pilots and drivers".

(ii) The exposure limit is "set at approximately half the level considered to be the threshold of pain (or limit of voluntary tolerance) for healthy human subjects ..."

(iii) The reduced comfort boundary "is derived from various studies conducted for the transport industries".

Apart from the time-dependency, no specific variations in the suggested levels for the three criteria are suggested. The possible wide variation needed to cover specific situations is acknowledged in the tentative correction factors of +3 to -12dB for F-DP and +3 to -30dB for reduced comfort. The much wider range for reduced comfort is presumably because this reaction is more susceptible to psychological influences than is reduced proficiency.

It appears (ref.9) that the a_z acceleration levels and the +6 and -10dB hierarchical relationships between "exposure limit" and "F-DP" and "reduced comfort" and "F-DP" are, for durations between 1 and 100 minutes, based largely

on a survey by Notess (ref.10). My own plot, in fig.8, of the Notess data supports the indications from a previous survey (ref.11) that for short exposures the F-DP and reduced comfort levels are set on the high side, certainly for random vibration. This may explain the negative bias in the tentative correction factors (-12 and -30dB as against +3 and +3dB for F-DP an reduced comfort respectively).

The difficult problem of variation in levels with duration of exposure i discussed below and that of population effects has already been mentioned.

P. "EVALUATION OF FREQUENCY SPECTRUM" The preferred method of evaluation i to compare the acceleration level for single or multiple (discrete) frequencies or for 1/3rd octave bands, separately against the recommende level at each frequency or 1/3rd octave band centre frequency. *This procedure assumes "that in respect of human tolerance no significant interactions occur between the vibration effects of different frequencie but states that there is no published evidence to decide between the accuracy of this preferred method and the suggested simplified alternati weighting and summation procedure (below).*

Under "NOTES" an alternative method of evaluation is described "to allow the characterisation of a vibration environment ... by a single quantity and to simplify measurements for situations in which spectrum analysis is difficult or is inconvenient". The overall vibration signal between 1 and 80Hz is weighted by an electronic network which adjusts ea 1/3rd octave band level to the equivalent of the 4-8Hz level for longi- tudinal (a_z) and the 1-2Hz level for transverse (a_x, a_y) vibration. The *by implication* these weighted 1/3rd octave levels are summed to give one overall rms level (analogous to the dBA overall weighted level for noise This level is then compared with the permissible value in the 4-8Hz band for a_z and 1-2Hz band for a_x, a_y . The Standard declares (in my opinion not necessarily correctly for all applications) that this method "results in an over-conservative assessment of the effects of vibration ... for a vibration spectrum closely following the shape of th limits the summated level is 13dB (4½ ×) higher than for the preferred worst single frequency or 1/3rd octave band method". It does not clearl point out that the summation method may be the more accurate if, as discussed subsequently, for a multi-frequency input the conditions are such that human reaction is caused by an integrated effect rather than b response to one particular frequency or 1/3rd octave band.

MULTIAXIS VIBRATION For vibration occurring in more than one axis simultaneously it is recommended that "the corresponding limits apply separately to each vectorial component in the three axes" (therefore it i assumed that there is no interaction between the axes).

A. For complex single axis vibration, the Standard implies that reaction is dominated by the vibration at one frequency or in a single 1/3rd octave band, that is there is little or no interaction between different frequencies. An alternative method of weighting and integrating the component parts to give one characteristic number is suggested but it is implied that this is mainly to simplify data measurement and analysis and stated that it "results in an over- conservative assessment of the effects of vibration".

For multiaxis vibration it is recommended that each axis should be evaluated separately.

Since, as discussed previously, the acceleration/frequency contours are based on biodynamic response, then some integrated effect in reaction is to be expected for a complex vibration. Therefore, the levels obtained by the second method may be the more accurate and not 'over-conservative'.

Surprisingly, little clear cut evidence exists to elucidate this important point, for performance, comfort or safety criteria. Work at ISVR, Southampton University indicates that for short duration sensation at least, the integrating method is the more accurate, although the shape of the contours is by no means correct for all individuals.

For multiaxis vibration also, biodynamic considerations supported by some laboratory work (ref.12), suggest that some interactions will occur and that a summation method may therefore be more appropriate.

P. DURATION OF VIBRATION The tolerable acceleration level is assumed to decrease with increasing exposure time from 1 minute up to 24 hours, that is a daily permissible dose, as illustrated in fig.5. This relationship applies "... *when the exposure is repeated daily over many years, for example for an industrial worker ... or for a transport driver. For exposure which is much less frequently experienced, for example by the casual traveller the acceptable exposure ... may well be higher*".

This time relationship applies to continuous exposure or (without mitigation for recovery) to intermittent exposures. A fractionating method of summing for exposure times at different amplitudes or frequencies is given.

A. This is perhaps the most important yet least substantiated part of the Standard. The limited supporting evidence used (refs.6, 9, 10, 13) dates back to 1956. It covers frequencies of about 1Hz only and some of it apparently consisted of people's *estimates* based on short exposures, rather than on actual *experience* of prolonged vibration. More recent investigations (refs.14 and 15) indicate that for casual exposures at least, any performance decrement due to vibration does not get worse with time, at least for exposures up to 3 hours.

In fact, two different time-dependency relationships may apply. The first (which should perhaps be asymptotic to the horizontal at 24 hours to cover continuous exposure in ships, etc.) would safeguard health against repeated exposures over many years, that is provide a cumulative working life "exposure limit". In this connection the work in hand by NIOSH (refs.16 and 17) could produce information concerning the validity of the present curve. The second shape, for F-DP and reduced comfort boundaries, and applying to both working life and casual exposures may well be much flatter than the present curve.

Lastly, the Standard does not give the precise method of evaluating the acceptability of a complex long duration exposure, where the level is varying continuously. The whole question of defining, measuring and calculating the vibration dose would be considerably simplified if an energy relationship (dose $\propto a^2t$) were adopted, as suggested in fig.5. This would enable a vibration dose meter to be used, analogous to a noise dose meter. This problem is discussed further in the next section.

Here, there are two basic considerations. The first concerns the reaction of the vehicle occupants to vibration *per se*, the second the significanc of this reaction in the overall acceptability of a particular means of transport. This paper concentrates mainly on the first aspect, although the secon which has already been considered fundamentally in a paper at a previous ride quality symposium (ref.18) and elsewhere (ref.19), is particularly relevant to vibration requirements for the comfort of passengers.

As discussed in more detail elsewhere (ref.11), human reaction to whole-body vibration (HRV) is very complex, but can be represented by the following qualitative equation:-

$$HRV = f(V,G,E,Ph,Ps,Ad,Ac)$$

where V = Vibration input
G = Geometry of seat and other interfaces
E = other Environmental inputs (noise, etc.)
} physical, largely extrinsic factors

Ph = Physiological influences (health, biorhythms, etc.)
Ps = Psychological influences (mental state, motivation, experience, expectation, etc.)
} physiological factors

Ad = Adaptibility (posture etc.)
Ac = Activity (driving, etc. for crew; speaking, talking, drinking, eating, etc. for passengers)
} behavioural factors

f = 'function of'.

Unfortunately but not unexpectedly, ISO 2631 and in fact all the availab laboratory and field data cover and quantify only a small part of this equati In my view if 'HRV' is likely to be critical in any particular transport situation, it is necessary to explore this situation in depth against the back ground of the ISO *guide* and other information, and perhaps to conduct laboratory and field studies, before realistic limits, particularly regarding proficiency and comfort, can be postulated.

The significance of 'HRV' and any limits associated with it will vary considerably with the different sectors of the transported population and the criteria employed to judge acceptability. For this purpose the population car conveniently be divided into four main groups:-

(i) Drivers, pilots, seamen, etc. and other crew directly or indirectly responsible by their actions or their health for the safety of the vehicle and its occupants. For people in this group it is essential to ensure that vibration does not significantly impair their performance or by its immediate or cumulative effects, their health. The (safe) exposure limit and the F-DP boundary are particularly relevant, as are the physical and physiological factors in the equation above. Psychological influences are likely to have little effect on these limits.

(ii) Other vehicle crew such as cabin crew. For these, safety considerations will be less important but long-term health effects should be considered and vibration interference with activities such as serving food and drink. Again exposure limit and F-DP are the prime considerations.

(iii) Regular passengers such as commuters who may travel day after day, year after year. Here, long-term health (exposure limit) and comfort considerations (reduced comfort boundary) are important. Psychological influences, expectancy, experience, etc. may well predominate in the latter, but the purely vibration aspects of these will probably be subordinate to the broader question of overall acceptability.

(iv) Passengers making occasional business, social or pleasure trips. For these, comfort considerations (reduced comfort boundary) will predominate, with psychological influences playing a major part.

The preceding remarks have demonstrated the complexity of deriving realistic vibration ride quality limits. In this paper it is only possible to suggest a philosophy, the basic principles involved in such derivations. A simplified hypothetical example for aircraft ride is chosen to demonstrate this, using the recommendations in ISO 2631 with certain indicated adjustments which are considered justifiable.

Example

An aircraft is to be designed for use on routine flights from A to B and return, of 2 hours each way. It will carry a flight crew, cabin crew and passengers comprising regular commuters and casual travellers. What are the desirable maximum vibration levels for the occupants?

Solution

Maximum vibration levels must be checked against the three criteria of:-

(i) Health of crew and regular travellers.
(ii) Efficiency of operators and hence safety of occupants.
(iii) Comfort of passengers and crew.

In order to postulate limits against these criteria it is assumed that:-

(i) The operators will work an 8 hour day for a number of years. The ISO 8 hour exposure limit should therefore be applied to prevent any possibility of cumulative effects of vibration on health.

(ii) Based on published evidence to date (refs.14 and 15) the pronounced time-dependency in ISO 2631 is unlikely to apply directly to proficiency. The 2 hour F-DP level is assumed to be more appropriate than the much lower 8 hour F-DP level which should theoretically be applied.

(iii) The reduced comfort limit is also considered to be less dependent on exposure time, and the 2 hour reduced comfort level is assumed to apply even to travellers who make a return journey on the same day. The comfort limit is probably the most difficult to quantify. As indicated previously in this paper and discussed elsewhere (e.g. ref.18) it is affected by many variables other than by vibration *per se* and should be considered as only part of a wider *journey* acceptance criteria, that is, door-to-door satisfaction. An arbitrary level has been selected to facilitate comparison with the other limits, and in real life may well need considerable adjustment either way.

These three limits, including the alternative and more conservative 8 hour F-DP level are plotted in fig.9 as 'acceptable' vibration in rms m/s^2 against daily exposure time. The acceptable level can either be expressed as

the 'worst third octave' normalised to 4 to 8Hz or, probably more accurately, as one weighted, summed value. The levels which 'must' not be exceeded on safety or health grounds together with those which should preferably not be exceeded to ensure passenger comfort are indicated on the graph.

This is a very simplified treatment of a particular problem in which a steady vibration level has been assumed for each and every daily journey. In practice vibration level and frequency will vary considerably and probably in somewhat random fashion. ISO 2631 is not explicit on how to sum a long duration complex waveform but it is implied that, assuming the ISO time-dependency curves do apply, the following procedure will be necessary. This is given for the simplified weighted summation method and will be further complicated if the preferred 'worst third octave' method is to be applied:-

> From the taped or calculated record of weighted summed acceleration level versus time a histogram is constructed relating the various times t_1, t_2, etc. spent in various narrow bands of acceleration levels with centre amplitudes A_1, A_2, etc. having corresponding permissible exposure times of T_1, T_2, etc. The vibration is acceptable if
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> $$\sum \frac{t_1}{T_1} \leqslant 1 \quad .$$

As previously reasoned and assumed in the above example, the ISO time-dependency relationship may not apply to all three criteria. However to maintain driver proficiency a given maximum level must not be exceeded at any critical period. This raises the practical question of the likely short duration increases above the normal desired maximum, for example vibration on a rough runway or during severe turbulence. For this, each case must be considered on its own merits with a guiding principle that if an increase in vibration however short-lived, occurs simultaneously with a vital vehicle control activity, then it must not cause decrement in performance sufficient to impair safety or cause gross discomfort to the occupants.

The practical significance of temporal variations in vibration with reference to the desired comfort level is probably even more complex and is well beyond the scope of this paper. Also, the ride requirements to prevent severe discomfort and injury to passengers and crew due to sudden encounter with severe turbulence have not been considered. Fortunately such encounters are rare, but still enough to cause a significant number of severe injuries every year. The general problem of the ride requirements concerning repeated shocks is briefly considered in the next section.

It is appropriate to underline here some of the problems of relating the ISO reduced comfort levels to the vibration requirements for passenger comfort, problems evidenced by the qualifications concerning the possible wide variation in the levels which ISO 2631 has wisely included. Briefly as illustrated diagrammatically in fig.10 there are at least three different kinds of discomfort reaction. Each of these may be provoked by a widely different level, which in turn will vary with the type of transport and population covered. The first reaction is that due to direct physical or physiological disturbances and will usually only be provoked by relatively high vibration levels. The second is

that due to psychological or mental disquiet caused by vibration rising significantly above the level normally to be expected, thus engendering feelings of apprehension or alarm. The corresponding acceptable vibration level may well be very low in some transport such as cable cars, in fact little above perception! The third and perhaps the most common type of discomfort is that caused by interference with activity. Work by Brumaghim (ref.20), suggests that sensitive activities such as reading will tend to lower the discomfort reaction level.

Unfortunately, much vibration 'comfort' research has been concerned with very short duration, 'sensation' effects with no subject activity and the results cannot therefore be applied directly to real life situations. Surprisingly, little work seems to have been conducted on the effect of vibration on passengers' ordinary activities such as reading, writing, eating, drinking, thinking and sleeping, and even less on the effects of prolonged exposure. In an investigation (ref.14) at RAE eight subjects were subjected to four 3 hour sessions of vertical vibration at 5Hz and 1.2m/s^2 rms, that is, the one hour F-DP or the 3 hour exposure limit, whilst carrying out various tasks including writing. Although, on average, performance was immediately degraded by the vibration, there was no evidence of significant worsening with time. Also whereas subjects initially considered the vibration to be extremely uncomfortable they seemed to adapt to it and several spontaneously remarked that as time went on they "almost forgot about it".

POSSIBLE FUTURE IMPROVEMENTS RELATED TO ISO 2631

In the Standard itself some of the gaps are acknowledged and it is stated that "addenda ... may be issued from time to time". Some of the shortcomings have already been discussed in this paper. Planned or desirable modifications or additions are briefly outlined below. For completeness, modifications to 2631 and work on associated standards which may be only indirectly related to ride quality, are considered. Some of the improvements can be formulated from existing data, but most will need more information from laboratory and field experiments. The list may therefore serve as a useful guide for those evolving future research programmes.

Agreed necessary by ISO/TC108/SC4, proposals already drafted

(1) An addendum to 2631 covering exposure to vibration below 1Hz has been drafted. This will fill an important gap, since in several forms of transport there is much energy in this region which causes a most undesirable reaction, motion sickness. The proposals, based on a critical literature survey (refs.21 and 22) and aimed at preventing motion sickness in 90% of adult casual travellers are summarised in fig.11. This shows the very sharp frequency dependence of reaction and indicates the particular need to minimize vibration in the 0.1 to 0.3Hz range. Tentative "reduced comfort" limits are shown in fig.12. These are for exposures up to 4 minutes only, there being an almost complete lack of data for longer periods. At this lower level, 'comfort' reaction, at least for short exposures, is much less frequency dependent than the motion sickness reaction.

(2) A "Guide to the evaluation of human exposure to mechanical shock" is aimed at defining acceptable limits for a sudden and violent (accident type) shock and will eventually be issued as a separate standard.

(3) A "Guide to the evaluation of hand-transmitted vibration" is well advanced and should be issued as a separate standard in the next year or so. Although aimed primarily at minimisation of the occupational risk ('white fingers') of continued exposure to vibration from chain saws, vibrating tools, etc., it is relevant to vibration from steering wheels, handlebars, etc. in transport.

(4) An addendum to 2631: "Vibration and shock limits for occupants in buildings" is well advanced. This gives various weighting (reduction) factors to the acceleration levels in 2631 for different types of buildings, and is relevant to traffic-induced vibration.

Agreed necessary by ISO, some work commenced

(1) An addendum to 2631 defining acceptable vibration levels in ships is planned. Data are being collected mainly by Japan.

(2) Information is being collected, aimed ultimately at providing recommended limits for human exposure to repeated ('low level') shocks and vibration with crest factors greater than 3. This will cover an important gap in ride quality (rough ride) requirements for many forms of transport. A possible approach to this is shown in fig.13.

(3) Information is being collected on the transmission of vibration through the body with particular reference to the effects of posture, seat and harness design. Weighting factors may eventually be introduced into 2631 to cover these effects. For example harness tends to attenuate main body (low frequency resonances but to amplify higher frequency (head, shoulder) vibration.

(4) Basic information on body impedance, analogues, etc. is being prepared.

(5) The tentative nature of the time-dependency curve in 2631 has been recognised and it will be reviewed when more data are available.

(6) Work has commenced on the problem, for complex spectra, of 'worst frequency or 1/3rd octave level' versus 'summed, weighted assessment'. As previously discussed some recent evidence suggests that the latter method may be more accurate.

Other suggested improvements

The following list is based on experience as a research worker on aircraft and other vibration effects. It is by no means comprehensive and reiterates some of the points made in the above analysis of 2631.

(1) More specific definitions of *criteria*, the first essential for progress on better *limits*, particularly for ride quality, passenger comfort considerations.

(2) A better definition of population cover and/or limits for specific populations. This needs more laboratory and field information on individual rather than average response of men, women and children.

(3) Adjustment to the shape of the acceleration/frequency curves. Different shapes may be needed for different criteria (safety, proficiency and comfort) and for sub-divisions of these.

(4) The gap in angular vibrations in the present specification requires filling as soon as better information is available.

(5) A better definition of 'crest factor' is needed, together with guidance in human response to vibrations with high crest factors (linked with (2) in previous list).

(6) Adjustments (weighting factors) are needed to the F-DP and reduced comfort boundaries, against more specific criteria, and hence an elaboration of the present suggested +3 to -12 and +3 to -30dB variations in recommended levels.

(7) The appropriate methods of evaluation of complex single or multiaxis vibration need to be defined for various applications.

(8) The whole question of the time-dependency of acceptable acceleration levels requires to be reviewed. As an interim measure, a constant energy relationship in place of the present shape, would seem more plausible and would considerably simplify analysis.

CONCLUDING REMARKS

ISO Standard 2631 should make an important contribution to our understanding and alleviation of the unwanted effects of vibration on man, particularly if its many qualifications are heeded. Firstly it provides a common basis for the gathering, analysis and comparison of field and laboratory information, and secondly it provides some design guidance which will become more and more useful as the Standard is improved. It has important implications for legislators, operators and research workers alike: this should stimulate work to explore further some of its controversial proposals.

The production of the Standard has been hampered by the lack of suitable data and the long time involved in its preparation and approval. Thus it is already in need of some updating and refinement. However in view of all the considerable technical, administrative and other difficulties which had to be surmounted, the final document, which has been approved by the great majority of the countries involved, represents a considerable achievement.

It is hoped that this paper will be useful to those involved in vehicle ride quality, firstly by helping them to understand, interpret and apply what is inevitably a complex standard. Secondly it may encourage research which will assist current efforts to improve the Standard. Specific topics which it is considered need especial attention have been discussed and most are in some way applicable to ride quality. The comments concerning the need for more realistic comfort tests, including individual not just average response, are particularly relevant.

ACKNOWLEDGMENTS

I should like to acknowledge the considerable help received from my colleagues at RAE and elsewhere, particularly Dr. G. Bobbert, in preparing thi paper. Also ISO 2631, and hence this paper, would probably never have emerged but for the stimulating efforts of Dr. H. von Gierke.

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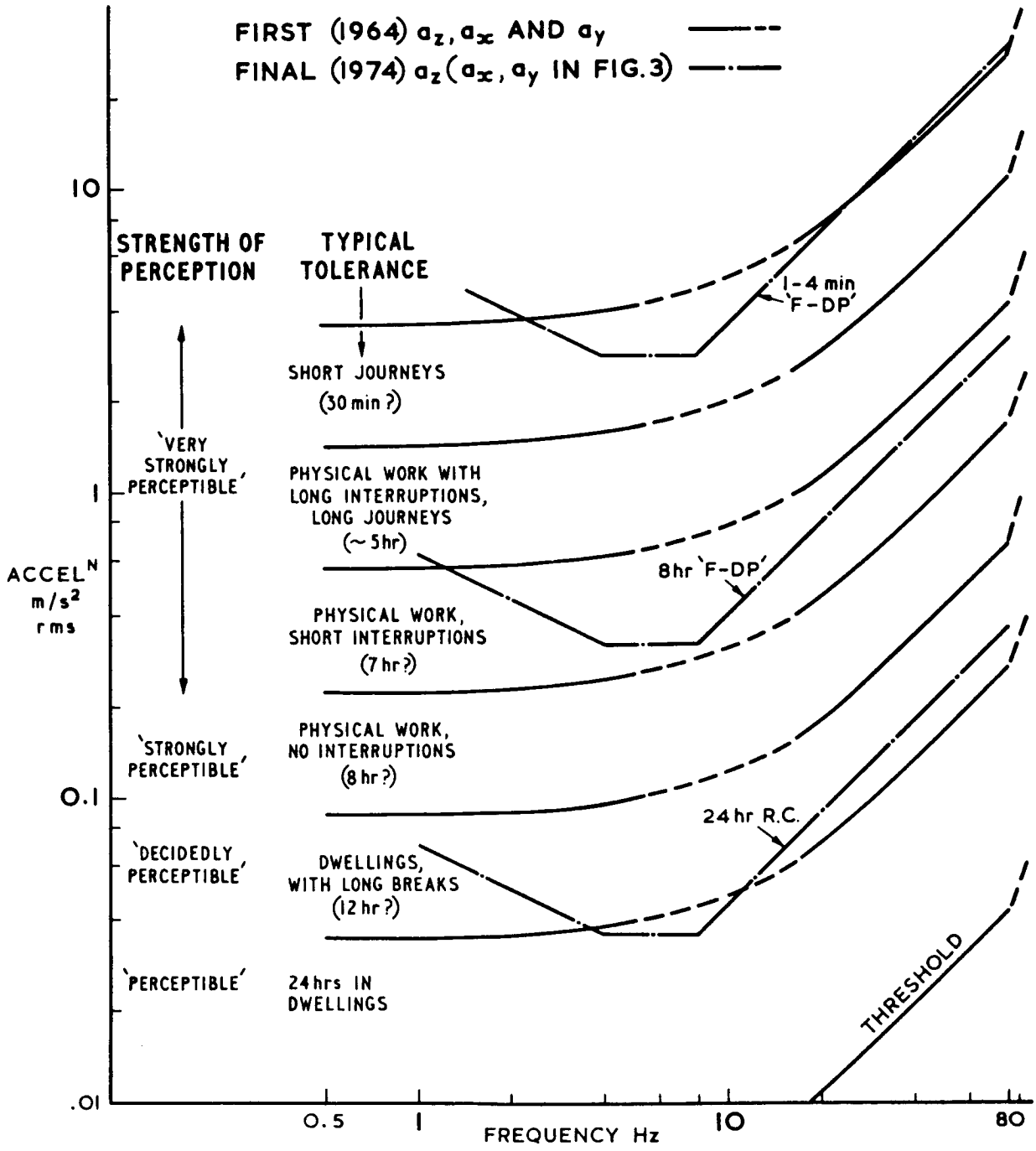

Figure 1.- Evolution of ISO 2631: Acceleration/frequency curves.

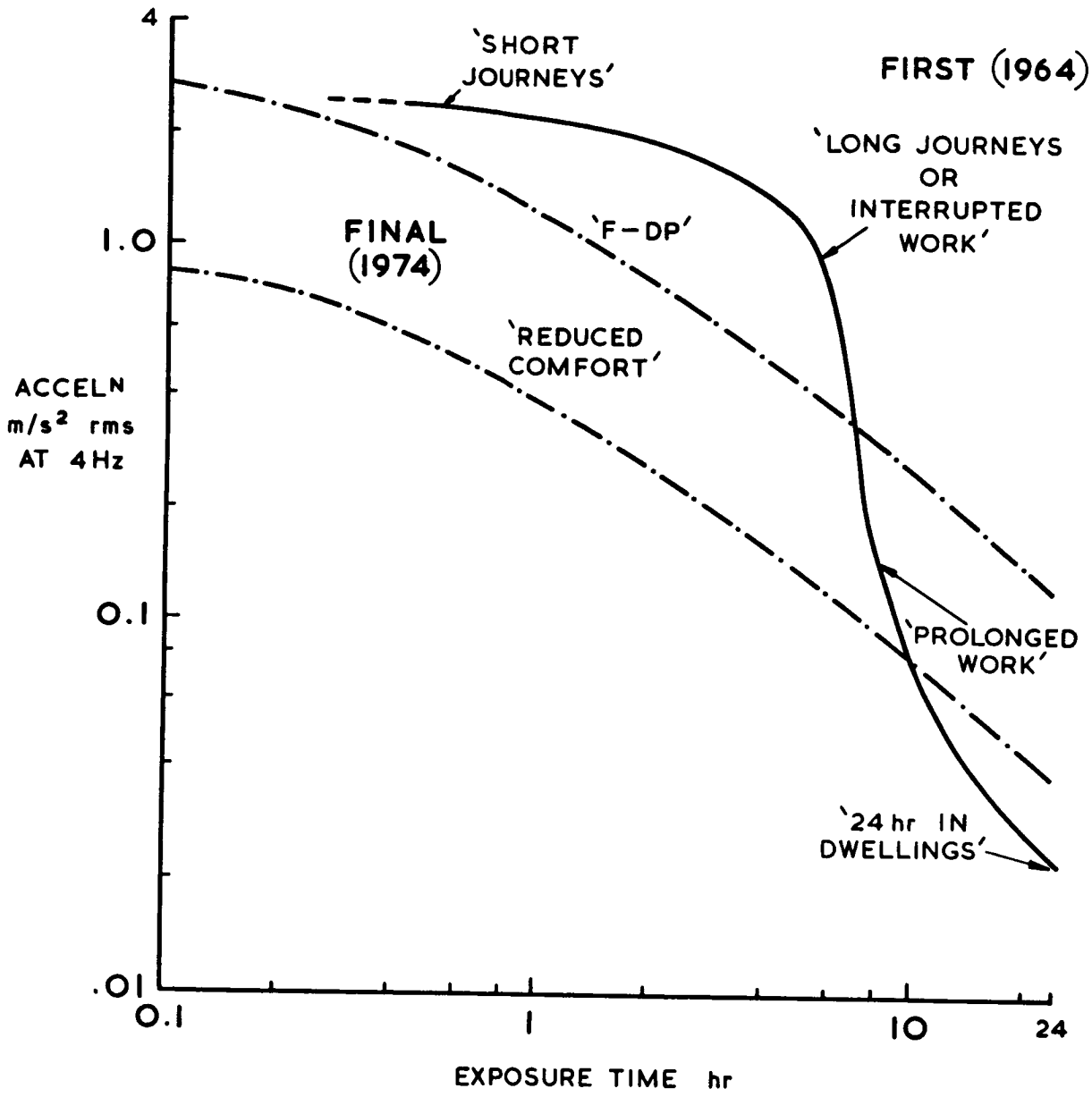

Figure 2.- Evolution of ISO 2631: Time-dependency.

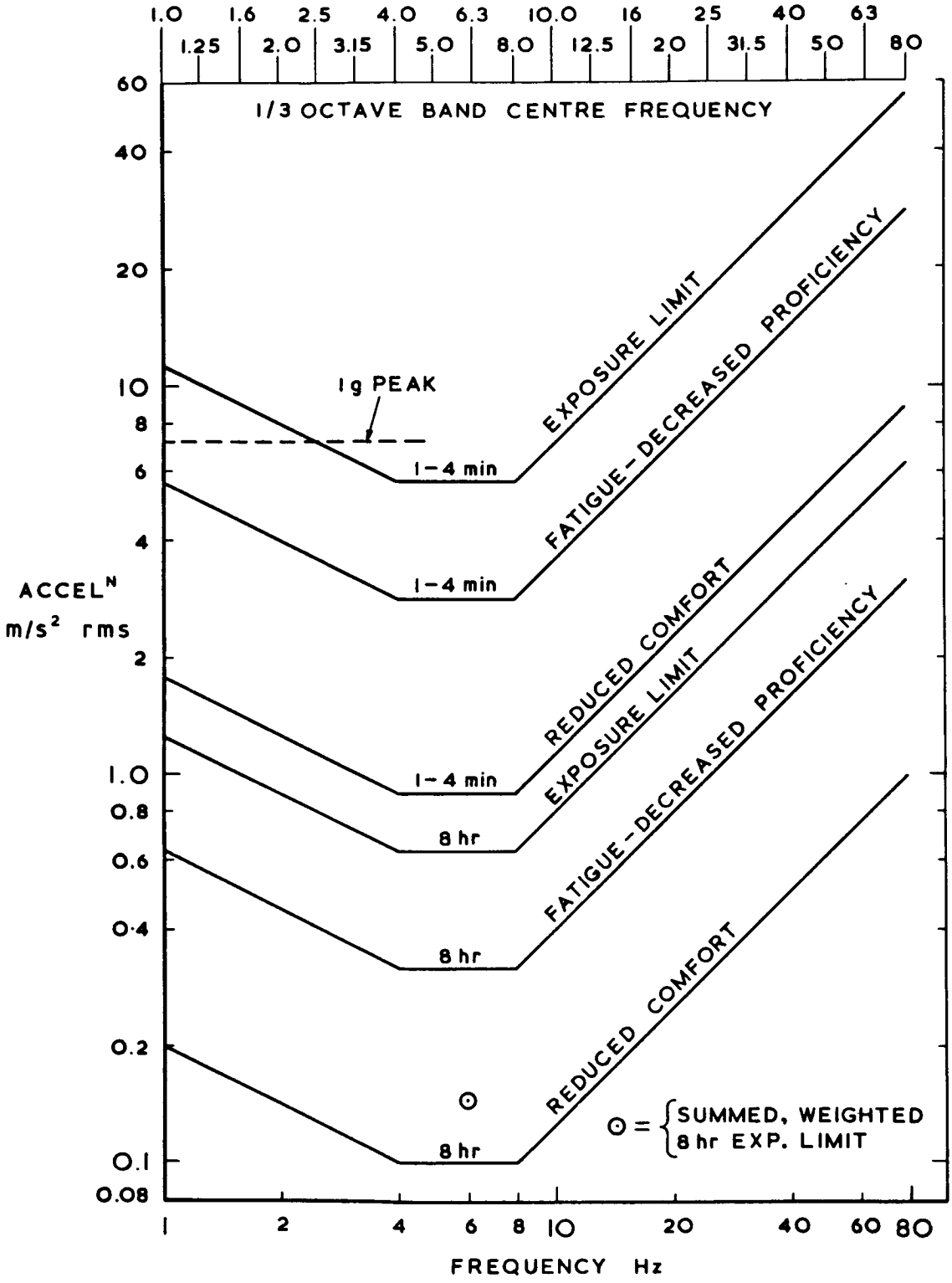

Figure 3.- ISO 2631: Acceleration/frequency curves for longitudinal, a_z, axis.

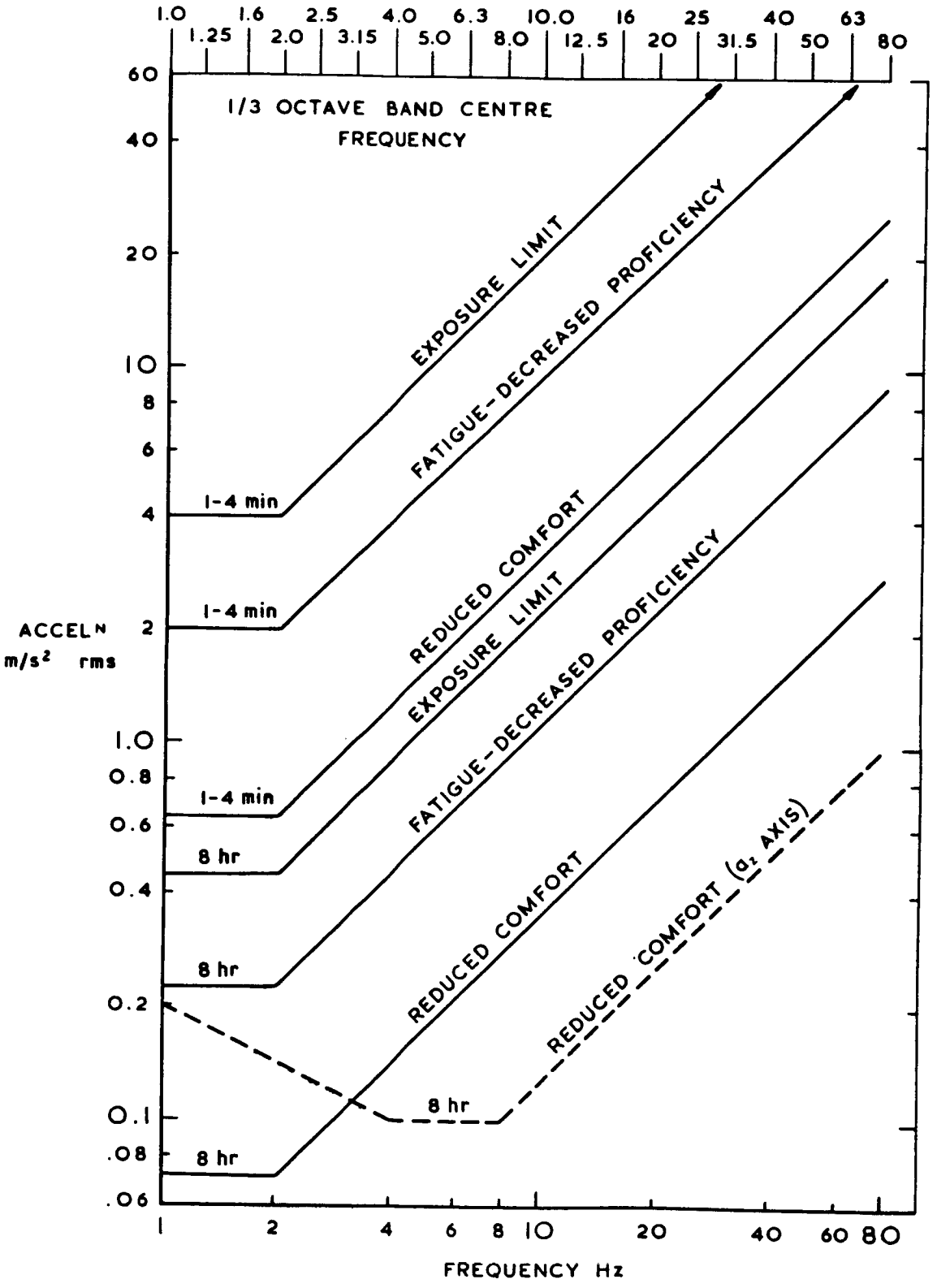

Figure 4.- ISO 2631: Acceleration/frequency curves for transverse, a_x, a_y, axes.

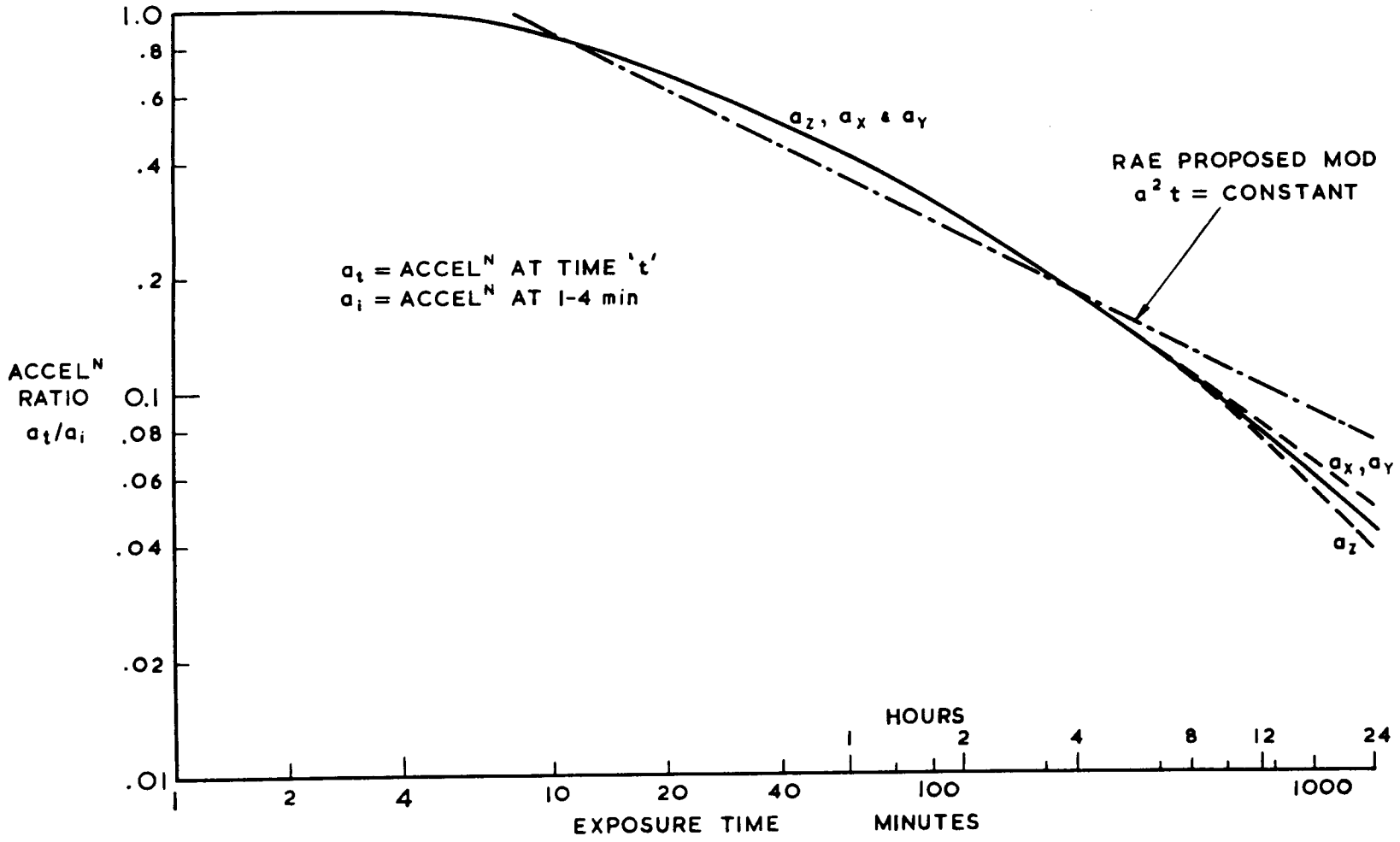

Figure 5.- ISO 2631: Acceleration time-dependency.

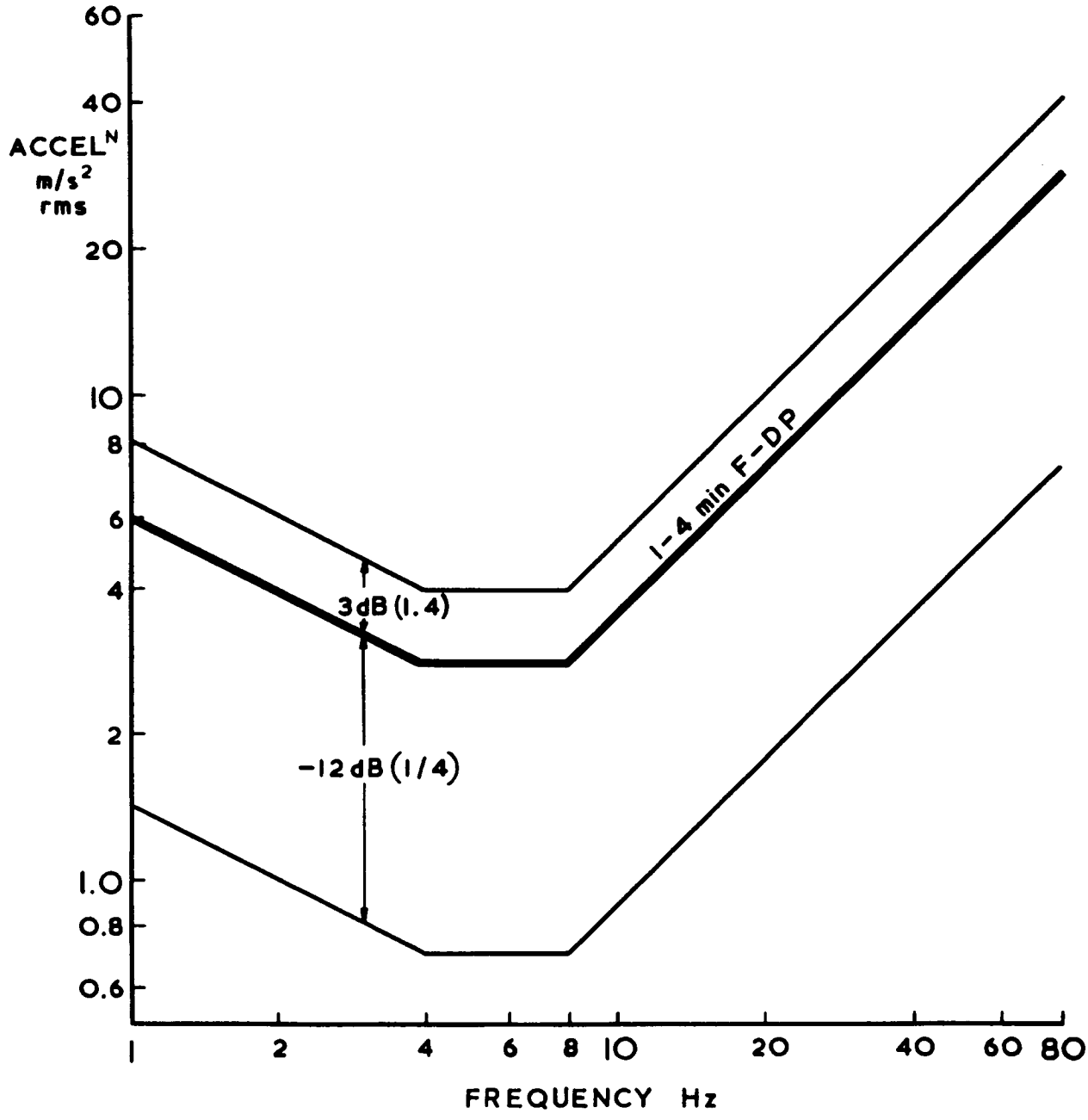

Figure 6.- ISO 2631: Tentative correction factors (a_z, F-DP).

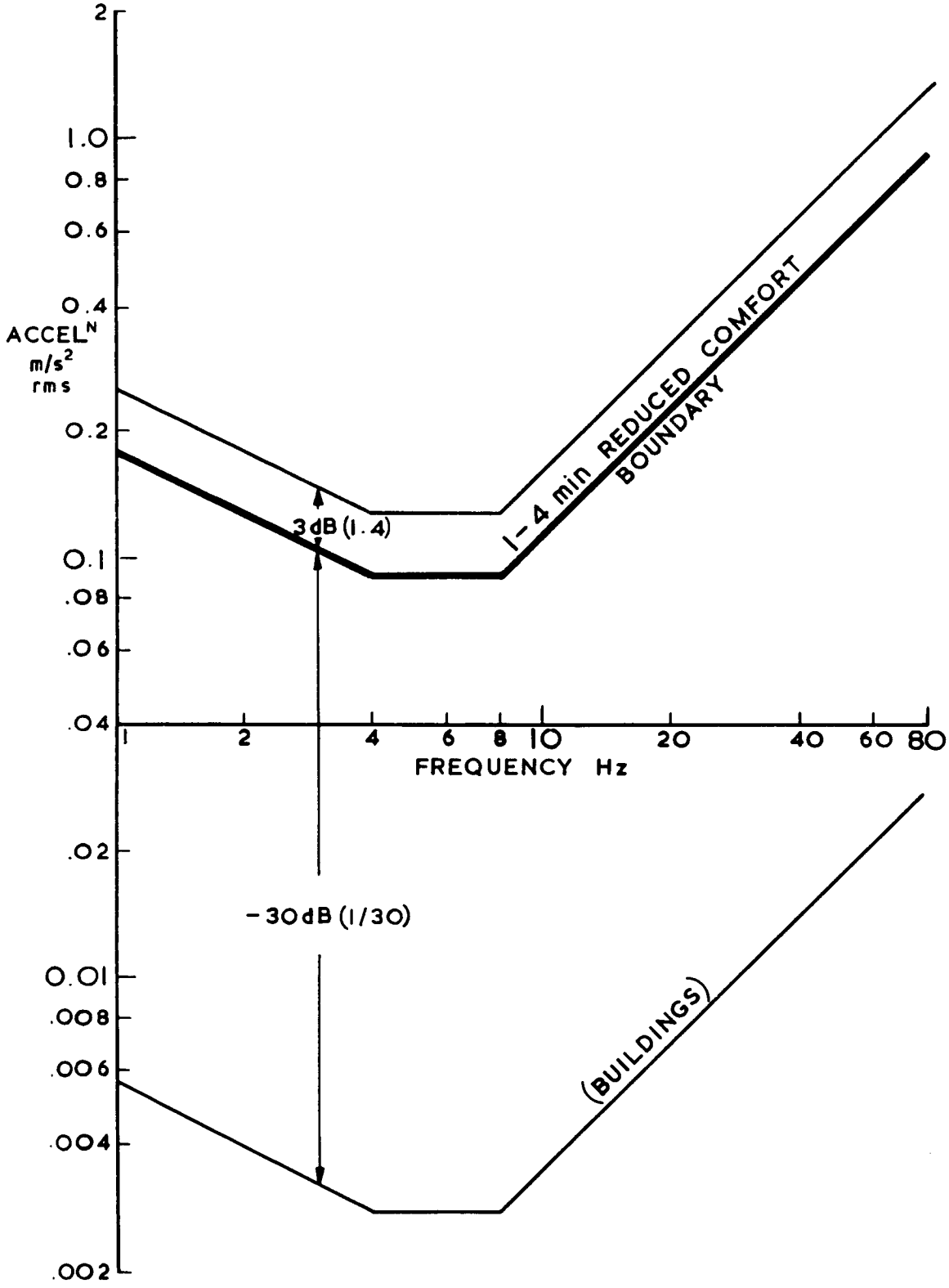

Figure 7.- ISO 2631: Tentative correction factors (a_z, reduced comfort).

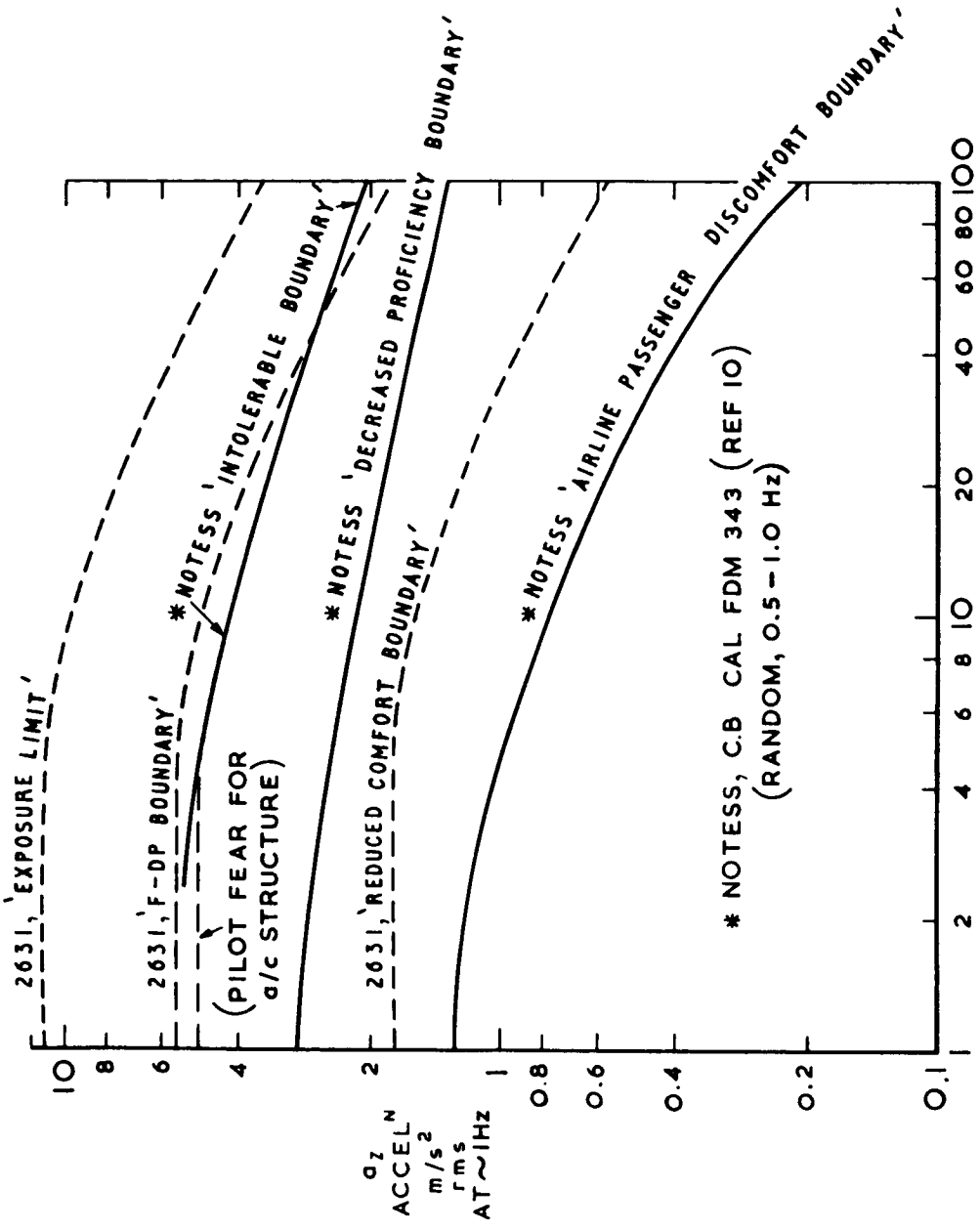

Figure 8.- Acceleration versus time from Notess and ISO 2631.

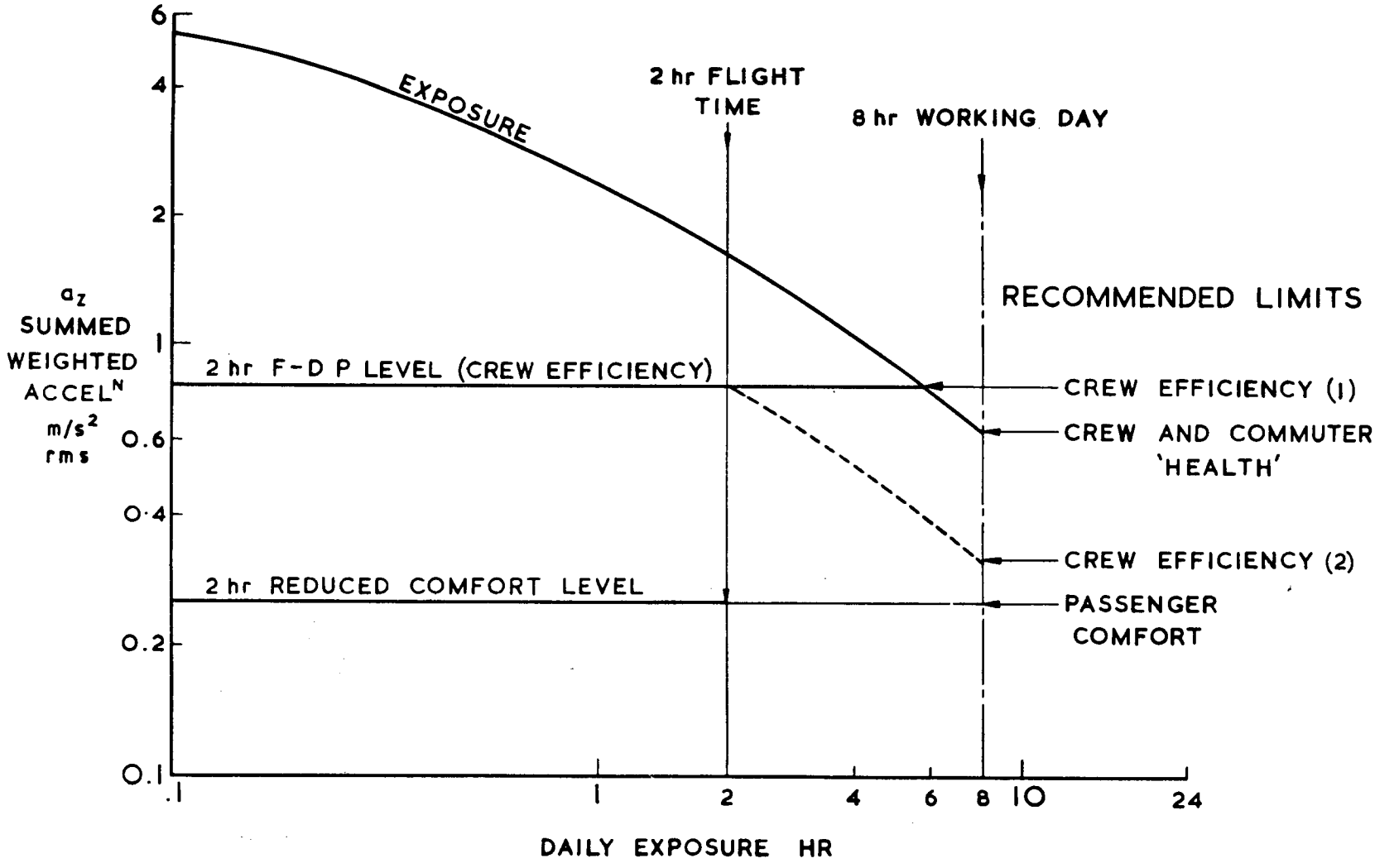

Figure 9.- ISO 2631: Application to aircraft ride quality requirements.

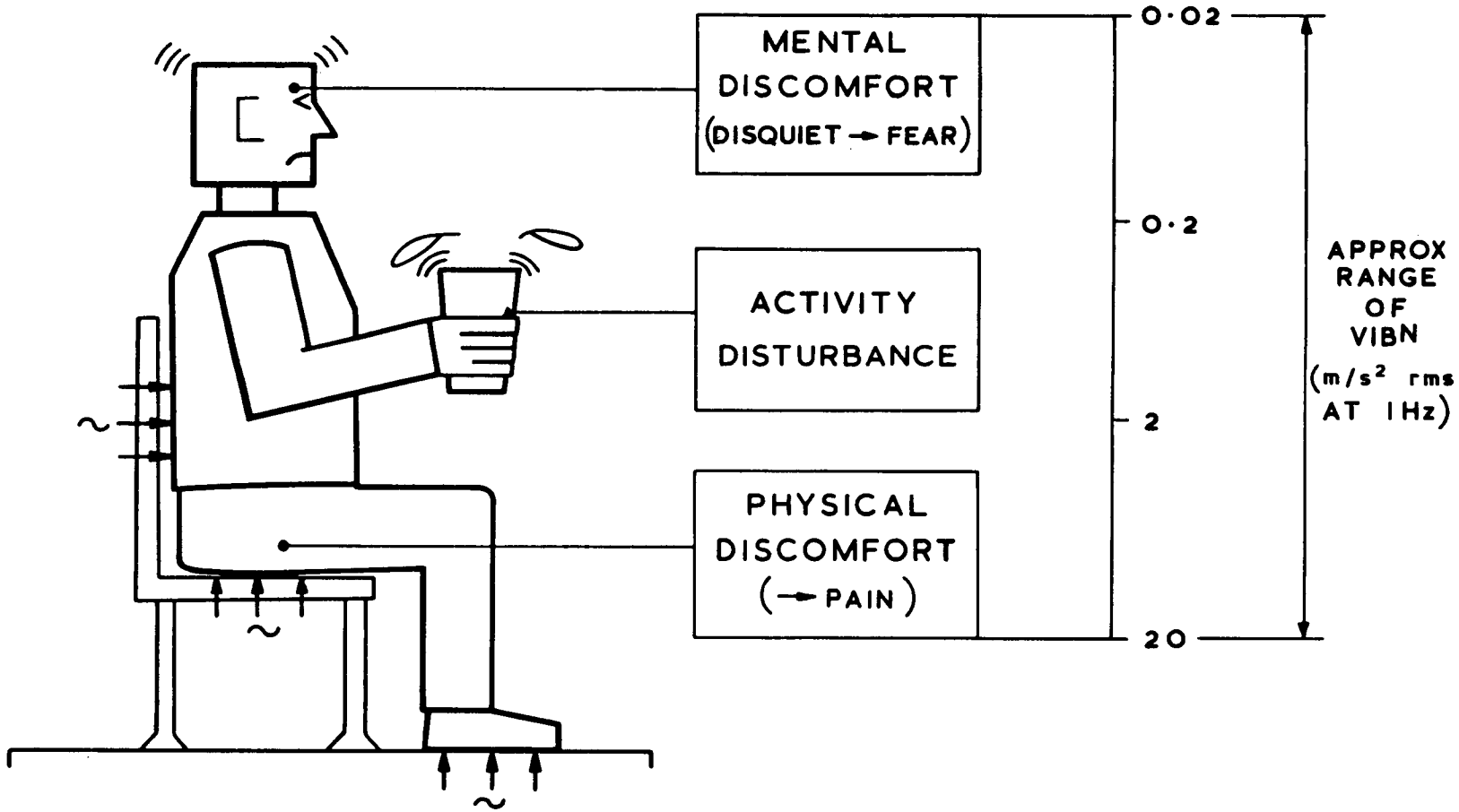

Figure 10.- Vibration: Discomfort.

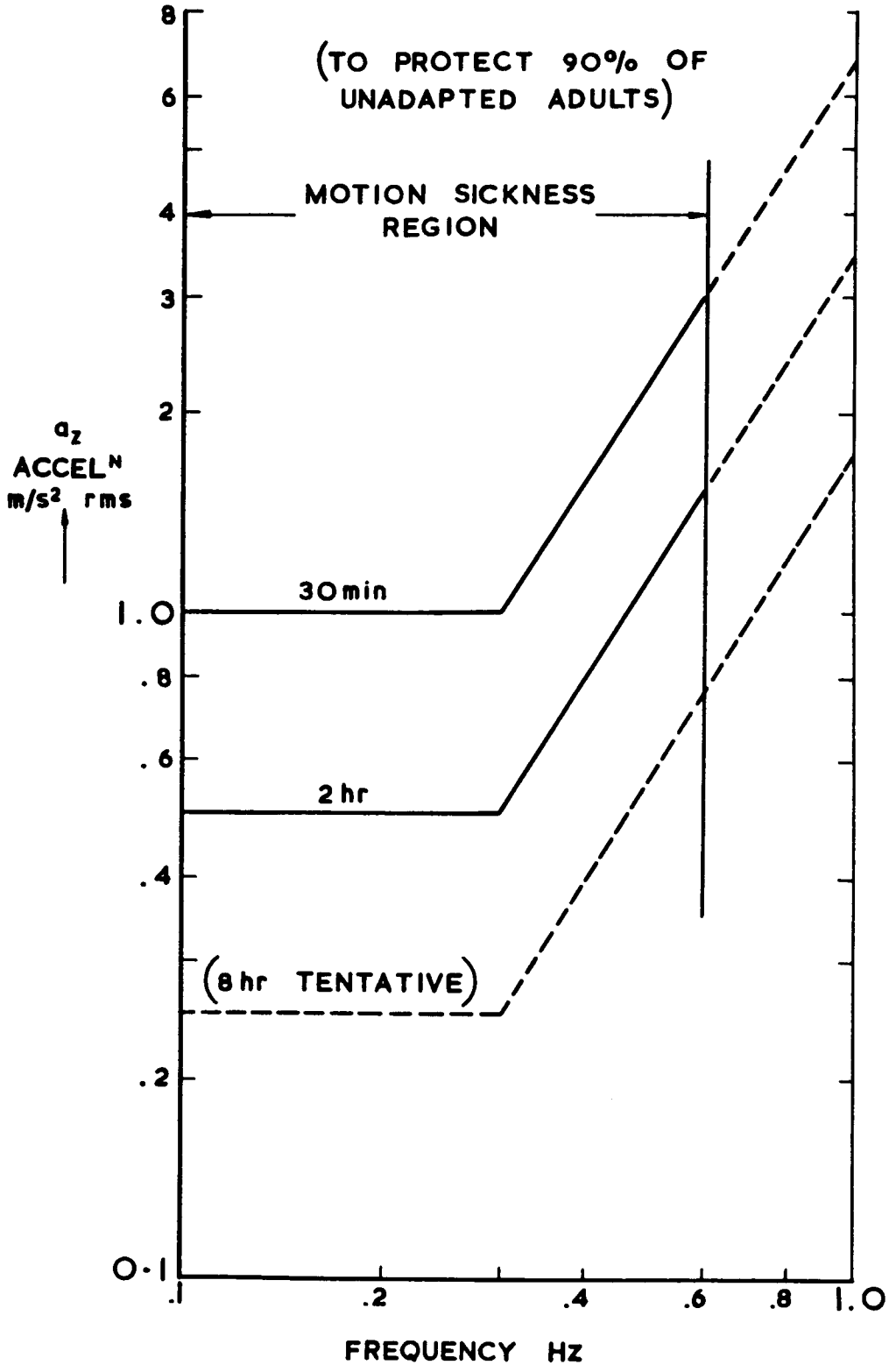

Figure 11.- Proposed 'severe discomfort boundaries', 0.1-1.0Hz.

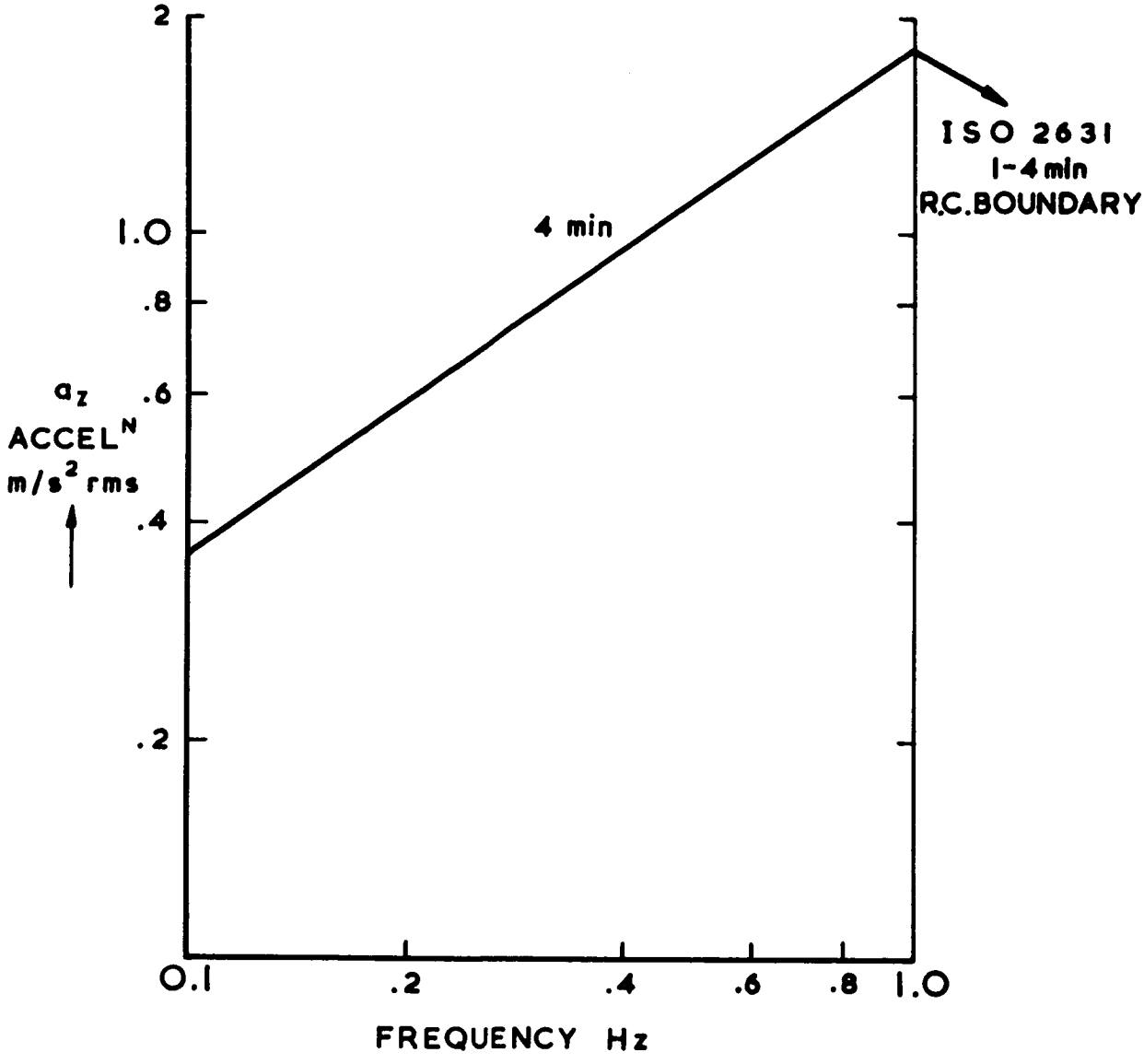

Figure 12.- Possible 'reduced comfort' boundary, 0.1-1.0Hz.

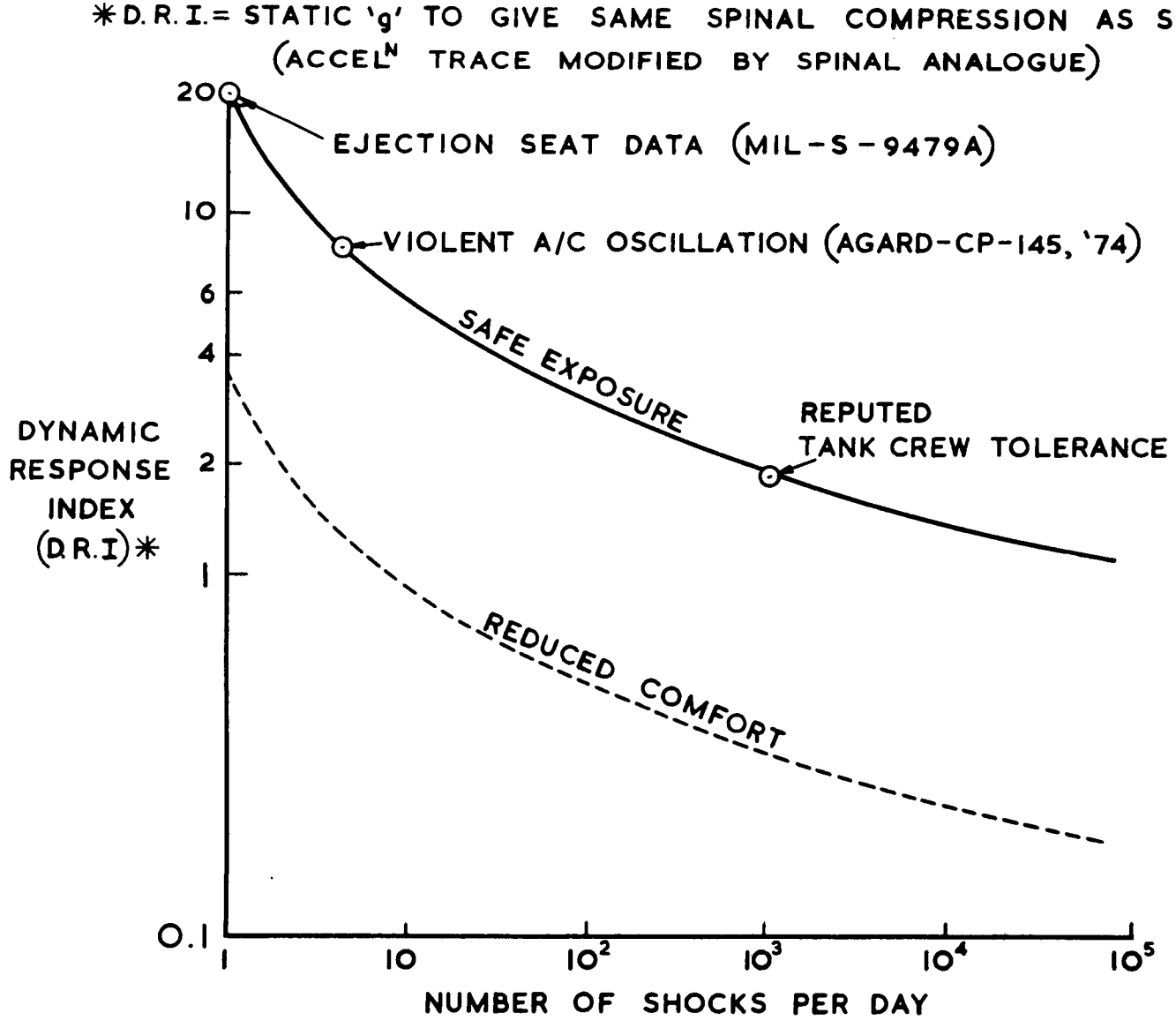

Figure 13.- Possible approach for acceptable levels of repeated shocks.