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THE MEASUREMENT AND ASSESSMENT OF GROUNDBORNE NOISE AND VIBRATION

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1. INTRODUCTION

The Association of Noise Consultants formed a Working Group to develop Guidelines[1] on the measurement and assessment of groundborne noise and vibration. The need arose following difficulties with the use of the British Standard documents such as the 1992 version of BS 6472 for vibration assessment, the lack of suitable measurement equipment for vibration dose values, the widely different measurement data obtained by various organisations, the different criteria adopted by consultants and local authorities and their current involvement in major projects involving groundborne noise and vibration issues.

Although a wide range of vibration issues and sources is covered in the document, particular attention has been paid to railway vibration and groundborne noise, as a result of a number of major projects under development. While the guidelines cover a broad range of issues, one of the most important topics is guidance on the use of the VDV index.

2. FUNDAMENTAL ISSUES IN THE MEASUREMENT OF VDV

British Standard 6472:1992 Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)[2] introduced into UK vibration assessment practice the concept of Vibration Dose Value (VDV), as an extension of the root-mean-quad approach which appeared in the previous version.

VDV is a complicated index, and the text of BS 6472 is extremely compact, with the result that interpretation of the guidance on the calculation and application of VDV is frequently misunderstood.

The major issues arising from the application of BS 6472, and in many respects the general use of weighted and/or dose-related vibration indices are these:

i) Correct use of weighting functions
ii) Appropriate use of time-integration methods

Flowcharts reproduced from the ANC Guidelines are given in Charts 0 to 4 to aid users in applying the procedures of BS 6472.

2.1 Weighting Functions

There are two issues associated with the use of weighting functions. The first is correct choice of weighting curve and the second is the application of the weighting curve.

Earlier versions of BS 6472 and ISO 2631[3] introduced weighting curves as charts which appeared analogous to rating systems used in noise assessment, such as Noise Criterion (NC) or Noise Rating (NR) curves. In these cases, the required technique involves plotting an octave-band spectrum on a set of curves and reading off the index value by inspecting for the highest curve reached in any band. It is true that for the case of vibration at a single frequency, it is appropriate to enter the amplitude on a set of vibration assessment curves and merely read off the curve number. However, many real-life vibration signals are not primarily single-frequency. Use of the noise rating analogy would suggest that in the case of a vibration signal containing several components all that is required is to plot the components on the curve chart and read off the highest curve value.

However, the appearance of BS 6841[4], which includes Laplacian domain expressions for the generation of vibration weighting curves, made it clear that the curves of BS 6472 and ISO 2631 are not of the NC/NR family, but are in fact akin to noise weighting scales such as the 'A-weighting'. In other words, all components of a spectrum should be taken into account by weighting according to the value of the weighting curve at each frequency, and taking the power sum of the weighted components.

An important side issue is the correct choice of weighting curve from BS 6841. Although confined to a note, there is a clear statement that weighting W_g is the curve which corresponds to the curves for z-axis, as inspection of the curve characteristics clearly confirms. However, the main text of BS 6841 indicates that W_b should be used in the z-axis for comfort assessment, and this frequently gives rise to confusion. Added confusion arises from the fact that different weighting curves are proposed by the sister standard ISO 2631, and that ISO 2631[5] itself has undergone curve changes through its various versions. For the x-axis and z-axis, BS 6472 uses weighting curves W_d.

Given that the weighting curves are analogous to noise weighting curves, it follows that true measurement of weighted acceleration requires the use of an instrument with an appropriate weighting network. Although the printed curves in BS 6472 suggest that weighted acceleration or weighted velocity can be used, care is required because it is necessary to preserve the phase characteristics of the Laplacian domain weighting functions of BS 6841 when dealing with signals with a high crest factor.

As in noise assessment, approximations to weighted values can be made by the use of 1/3 octave spectra, manually weighting the band levels and re-combining them. In restricted circumstances the resulting error is not significant.

It is important to note that plotting the 1/3 octave spectrum of a broad-band vibration signal on to one of the curve charts in BS 6472 and reading off the highest curve number does not give the correct answer.

2.2 Time Integration

Where VDV differs markedly from analogous noise indices such as SEL is that it is based not on integration of the square of the signal, but on integration of the fourth power of the signal. For signals with low crest factors, the relationship between the fourth power integral and the second power integral can be estimated, and BS 6472 indicates a multiplier of 1.4 (based on typical signals). This gives rise to the concept of estimated VDV, or eVDV.

When the crest factor is low (not more than 6), and the variation over time is simple, eVDV can be estimated from r.m.s. average values by multiplying by 1.4 and by the duration over which the average has been obtained, raised to the power of 0.25.

2.3 VDV manipulation

BS 6472 gives guidance on the acceptability of vibration in two ways. For simple cases, where the vibration is predominantly of one frequency and of easily definable duration, determination of a curve number and associated multiplying factors enables use of a table of satisfactory magnitudes. In other cases, VDV is determined for periods corresponding to daytime and night time, and used to estimate the probability of "adverse comment". Unlike the noise analogy, where a dose-related unit such as SEL is used to compute a time average over an assessment period, VDV is used directly, as a dose concept. This means that for the same level of vibration, the VDV value for a 16-hour day is by definition higher than the VDV value for an 8-hour night. Manipulation is required where VDV values are known for vibration events or periods shorter than the assessment period. If only one vibration event occurs, its period VDV will be the same for any period, of whatever length, that is longer than the duration of the event. Where several events of known or identical VDV values occur within the assessment period, they can be combined by raising each to the fourth power, summing them, and taking the fourth root. Because of the use of the fourth root, this means that VDV is not very sensitive to number of events or duration.

Tables are presented in BS 6472 indicating threshold VDVs for "low probability of adverse comment","adverse comment possible" and "adverse comment probable". However, analysis of the derivation of the tables shows that they are only precise for z-axis vibration. This arises from the fact that the x- and y- axis curves in BS 6472, at their most sensitive frequencies, have a base value lower than that for the z-axis (0.00357 ms^{-2} as opposed to 0.005 ms^{-2}). By contrast, the weighting functions in BS 6841 are all equal to unity at their most sensitive frequency. Strictly speaking, it is necessary either to revise the weighting curves, or to revise the table of adverse comment for use in the x- and y-axes. However, given the lack of international agreement of weighting functions, this anomaly is only one of several uncertainties associated with the assessment of vibration.

2.4 Instrumentation for the measurements of VDV

Because of the uniqueness to the UK of BS 6472, and its choice of weighting curves, and the international nature of most measuring instrumentation, it is important in choosing instruments for the direct measurement of VDV to ensure that they employ weighting W_g for z-axis and W_d for x- and y-axes. The term "VDV" described only the 4^{th} power integration concept, and does not define the weighting curve. An instrument may faithfully measure VDV, but to a standard quite different from that of BS 6472 and BS 6841.

3. WIDER ISSUES IN THE ASSESSMENT OF VIBRATION

The use of VDV is but one aspect of the topic of vibration measurement, assessment and prediction. For example, the much longer established index "peak particle velocity" (PPV) is in widespread use, not only as an alternative to VDV for vibration from blasting, or as a simpler and more easily monitored measure of construction vibration.

While the effect of vibration on humans is a major area of interest, VDV is only relevant to this area, and is inappropriate to the other major area of interest, the effect of vibration on buildings. Potential for structural damage is normally monitored using PPV. Despite the simpler nature of the PPV index, there is still conflicting advice on British Standards[6,7] on thresholds for vibration damage to buildings.

Besides issues related to the mathematical nature of the vibration index, there are many equally important issues such as method of measurement. While variations in the impedance of the transmitting medium can normally be neglected in noise measurement (with issues such as façade effects and meteorological influences being the only significant considerations) vibration is transmitted in media with widely differing impedances. Since the only vibration quantities readily measurable are displacement, velocity or acceleration, all of which are sensitive to the impedance of the medium such that for the same power a low impedance medium (such as a suspended floor in resonance) will exhibit amplitudes many times greater than a high impedance medium such as a large piece of mass concrete embedded in the ground. Furthermore, the effect of vibration on humans depends on vibration at the point of entry into the human body. For low impedance locations, such as resonant floors, the presence of the human body modifies the vibration characteristics.

In many cases, the main consideration is the likely effect of vibration in the environment (for example from an existing railway on the surface or underground) on a proposed new building. This may involve the assessment of vibration in "free-field", i.e. on an area of bare ground. Not only is it necessary to have regard to the effect of the presence of the proposed building on the ultimate vibration amplitudes, but also the choice of transducer and transducer installation affects the values measured in the ground. Widely differing practices are evident, from driving spikes into the earth to burying transducers in the ground. In buildings transducers may be attached to the structure in different ways, and the choice of location on the structure will produce significant differences in the results.

4. GROUNDBORNE NOISE

Vibration is a concern not only as a direct stimulus to humans or as a potential cause of building damage, but also indirectly by re-radiation of vibration as noise. This occurs classically where underground railways pass beneath noise-sensitive buildings.

From its point of generation to the re-radiating surface, the vibration which causes ground-borne noise differs from "classical" vibration only to the extent that acoustic frequencies are involved and significant levels of noise can be radiated by vibration at amplitudes below the threshold of perception by the sense of touch.

While indices such as VDV and PPV are appropriate to vibration affecting humans, and in the latter case buildings, re-radiated groundborne noise is assessed using conventional noise assessment indices. The relationship between the amplitude of vibration in the surfaces of a receiving room is complex, although rules-of-thumb are used.

5. PREDICTION OF GROUNDBORNE NOISE AND VIBRATION

Because of the wide variety of the characteristics of the media through which vibration is transmitted, the prediction of vibration and groundborne noise is much more complex than the prediction of airborne noise.

Not only are structural dynamics involved, but the effects of layered media and the existence of at least three different types of wave propagation (shear waves, body waves and surface waves), and in some cases more, with widely differing wavespeeds and propagation characteristics, make the prediction of received levels far from straightforward. Techniques are available ranging from simplified algebraic methods only acceptable in restricted simple cases, through empirical methods to detailed computer modelling. The appropriate choice of technique depends on the purpose for which the prediction is required. Scoping models for use in the preliminary assessment, preliminary design and environmental impact assessment models and detailed design models require different levels of complexity. Simple models with few input parameters are appropriate for scoping purposes, while models capable of considering all the parameters that are critical to determining the absolute levels of groundborne vibration and the benefits, or otherwise, of different design and mitigation options are needed for environmental assessment and preliminary design models. For detailed design models, numerical approaches which can model vibration in the time domain in 3-dimensions may be appropriate.

REFERENCES

1 Measurement & Assessment of Groundborne Noise & Vibration, Association of Noise Consultants, 2001.

2 BS 6472:1992, Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)

3 ISO 2631-2:1989, Evaluation of human exposure to whole-body vibration. Continuous and shock-induced vibration in buildings (1 to 80 Hz).

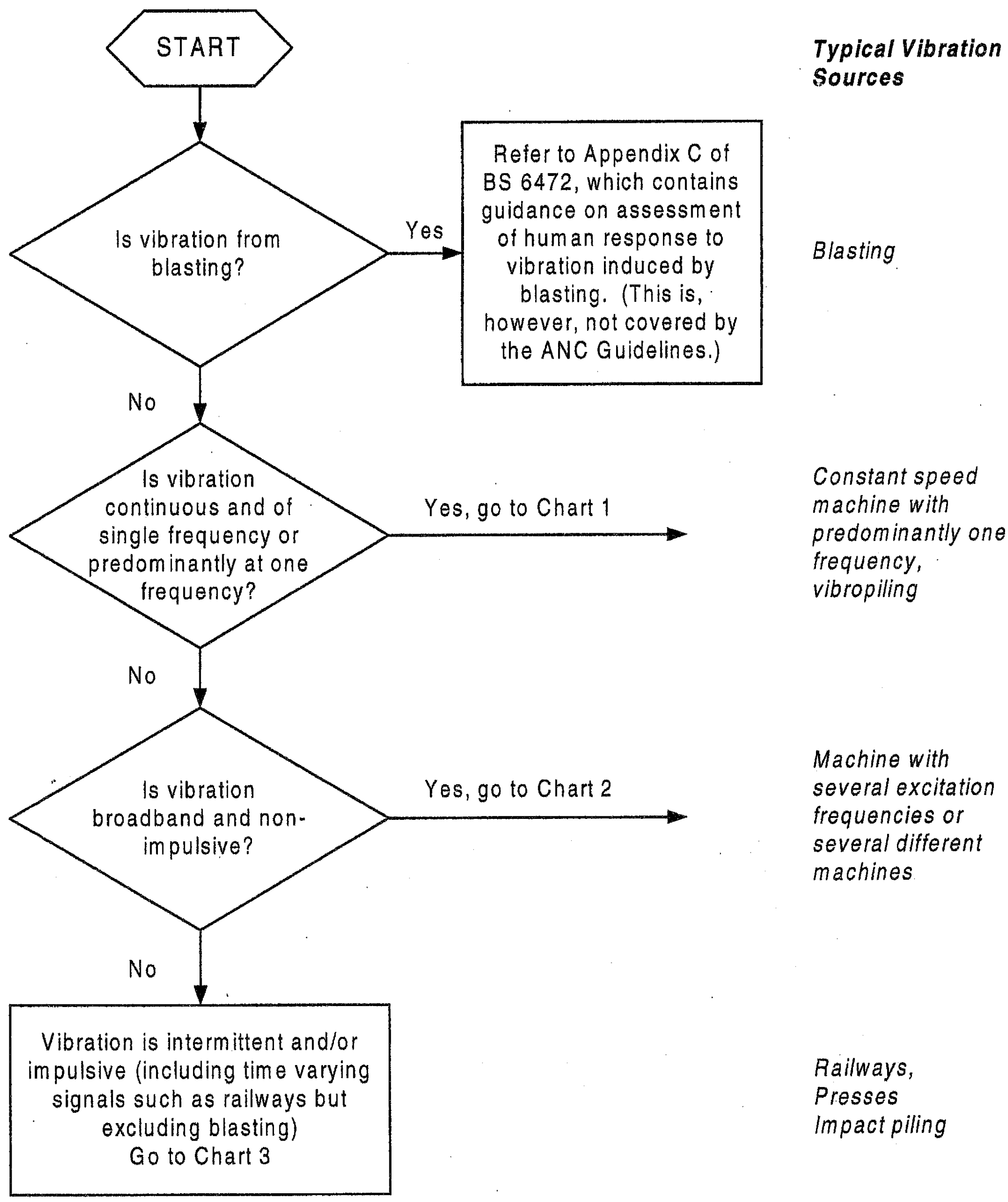
4 BS 6841:1987, Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.

5 ISO 2631-1:1997, Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – general requirements.

6 BS 7385-2:1993, Evaluation and measurement for vibration in buildings – Guide to damage levels from groundborne vibration.

7 BS 5228 Part 4:1992, Noise control on Construction & Open Sites. Code of Practice for Noise and Vibration Control Applicable to Piling Operations.

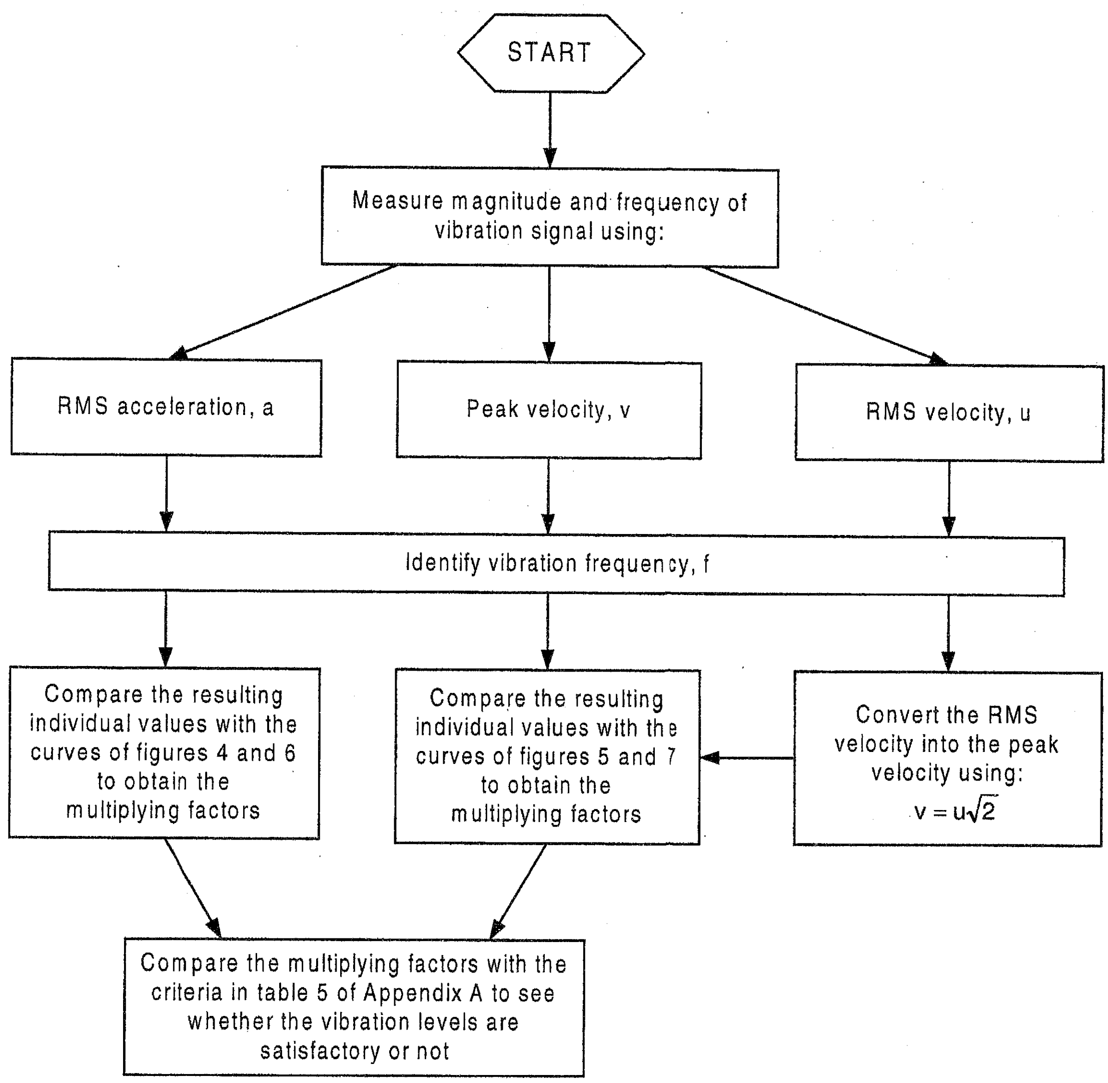
Chart 0 Guide to use of Charts 1 - 4



Notes

1. See Chart 4 for exposure correction.

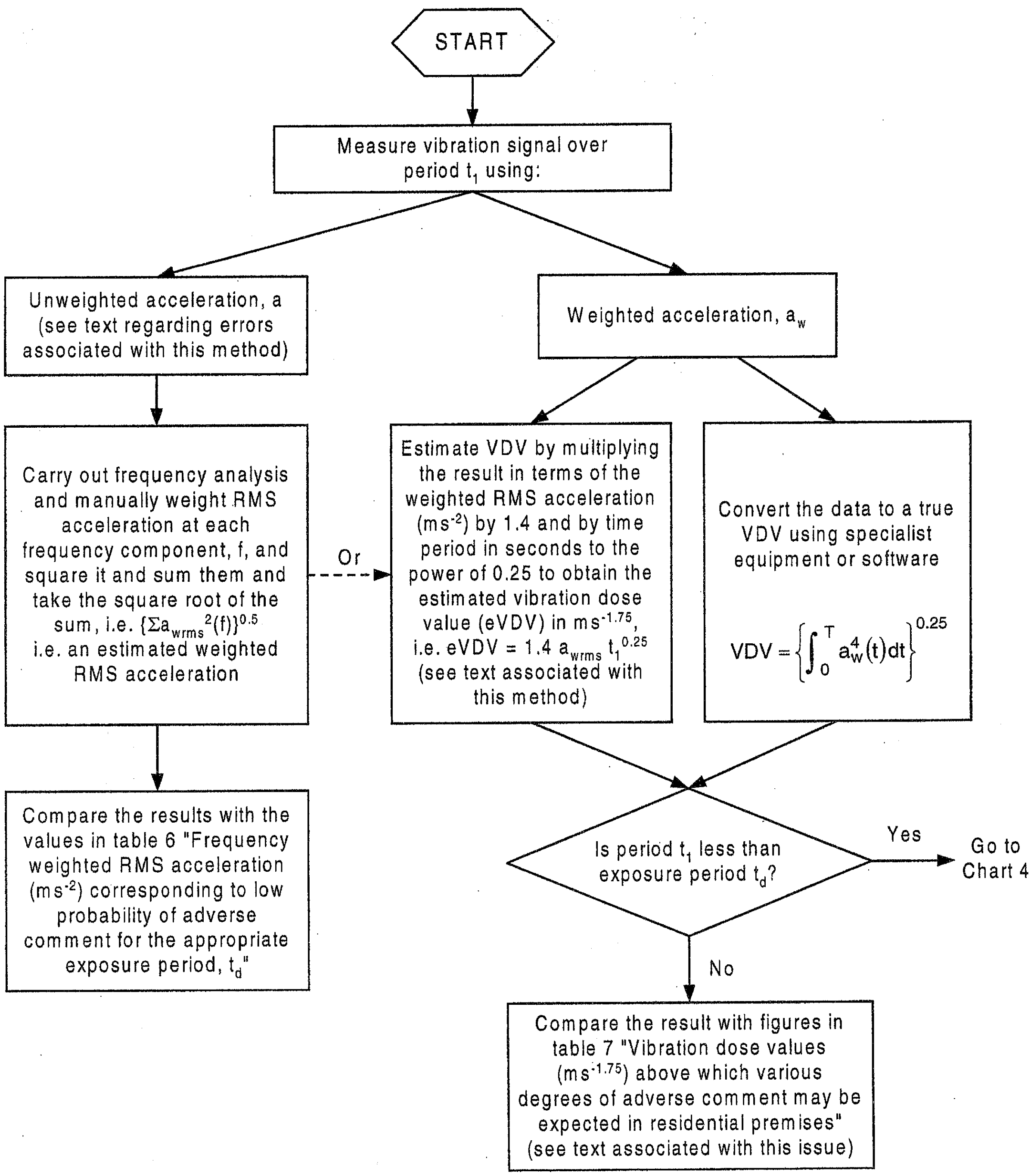
Chart 1 Continuous vibration of single frequency or predominantly at one frequency



<u>Notes</u>

1. For single frequencies (sinusoidal vibration) unweighted RMS acceleration, a is given by: $a \cong \omega u \cong \omega v/\sqrt{2}$, where $\omega = 2\pi f$
2. This includes signals where vibration energy is predominantly within a single 1/3 octave band or less.
3. Figure and table numbers refer to those in BS 6472: 1992

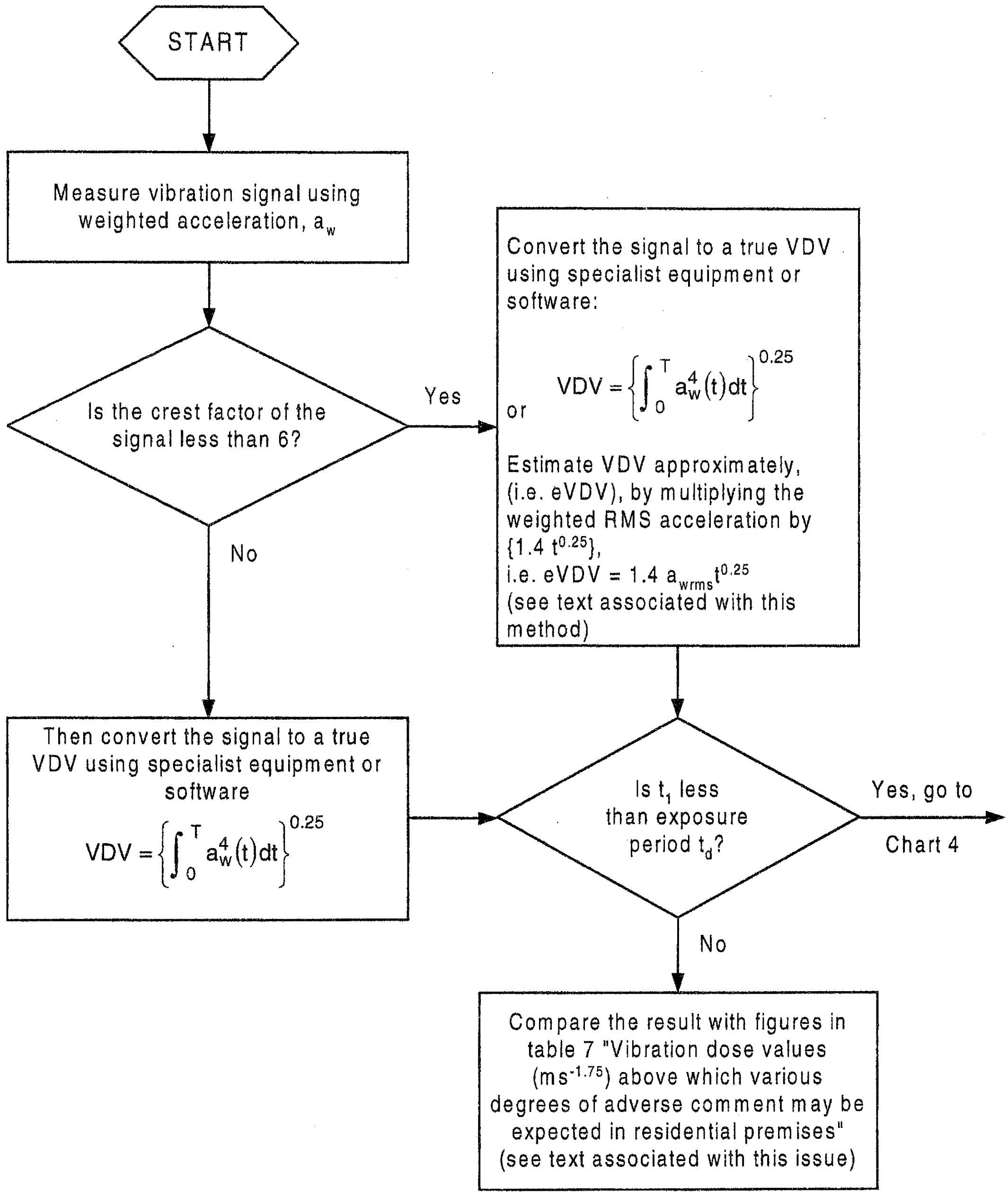
Chart 2 Broadband and non-impulsive vibration



Notes

1. For information on weighting curves see BS 6841: 1987
2. Table numbers refer to those in BS 6472: 1992
3. t_d = exposure period (in s). This is the length of time over either day or night that the vibration occurs. The exposure period may be equal to or less than the total day or night-time periods.
   Example (1): The vibration continues all day: the value of t_d = 16x60x60 = 57,600 s.
   Example (2): The vibration continues all night: the value of t_d = 8x60x60 = 28,800 s.
   Example (3): The vibration occurs for 4 hours of a day or night: the value t_d = 4x60x60 = 14,400 s.
4. a = unweighted RMS acceleration
   a_{wrms} = frequency weighted RMS acceleration, measured over period t_1
   $a_w(t)$ = instantaneous time varying value of the weighted acceleration.

Chart 3 Intermittent and/or time-varying vibration



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   Example (3): The vibration occurs for 4 hours of a day or night: the value t_d = 4x60x60 = 14,400 s.
3. a_{wrms} = frequency weighted RMS acceleration, measured over period t_1
   $a_w(t)$ = instantaneous time varying value of the weighted acceleration.

Chart 4 Exposure correction

From Chart 2 or Chart 3 → START

Where vibration conditions are constant (or regularly repeated) throughout the day, only one representative period, in seconds, (of duration t_1) need be measured. If the measured vibration dose value is VDV_1, the total vibration dose value for the day, (VDV_d) will then be given by the following equation :

$$VDV_d = (t_d/t_1)^{0.25} \times VDV_1$$

where:

t_d is the duration of exposure per day (in s).(Note 2)

If, in a day, there is a total of N periods of various durations with vibration dose value, VDV_n, the total vibration dose value for the day is given by:

$$VDV = \left(\sum_{n=1}^{n=N} VDV_n^4 \right)^{0.25}$$

or if all events have the same dose value

$$VDV = (N)^{0.25} \times VDV_1$$

↓

Compare the result with figures in table 7 "Vibration dose values ($ms^{-1.75}$) above which various degrees of adverse comment may be expected in residential premises" (see text associated with this issue)

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   Example (3): The vibration occurs for 4 hours of a day or night: the value t_d = 4x60x60 = 14,400 s.
3. Figure and table numbers refer to those in BS 6472: 1992
4. The above also applies to eVDV