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INVESTIGATING ENVIRONMENTAL VIBRATION COMPLAINTS - PRACTICAL ASPECTS

Ken Scannell

Industrial Noise and Vibration Centre, Slough

1. INTRODUCTION

Vibration is a mechanical oscillation, the to-and-fro movement of any physical body. Oscillation is a word used in non-technical language, along with shake, tremor, wave, swing, sway, reel, rock, roll and many others that describe this to-and-fro movement.

Vibration can be the cause of discomfort, pain and annoyance to humans and damage and destruction to sensitive equipment or buildings. We have all sensed vibration at some stage, whether it is travelling over a bumpy road in a car, meeting turbulence in an aircraft, the effect of heavy waves in a ship, using hand tools such as an electric drill or lawn mower or just walking over a springy bridge or floor. However, not all vibration has a negative effect. In fact without vibration we would cease to exist. We need the vibration of the beating of the heart and the to-and-fro motion of the lungs which pumps the air we breathe.

We use vibration as the basis for clocks and watches. In industry we use vibration for sorting, mixing, welding or moving components. Vibration is used for medical purposes and as a means of giving pleasure. For example new born babies are comforted by being rocked in the arms of their parents, teenagers are attracted to oscillating fairground rides while the older generation prefer the gentle oscillation of a rocking chair.

The earth on which we live is in a constant stage of vibration even through this is usually far below human sensitivity and can only be recorded with specialist equipment.

Vibration can be the cause of dynamic loading on buildings which could be the result of damage, ranging from hairline cracks in plaster to major impairment to the building superstructure. In extreme cases vibration can be the cause of building collapse. Secondary effects of vibration, such as foundation settlement can also be the cause of major damage to buildings.

2. MAN MADE VIBRATIONS

Although earthquakes are a major cause of destruction and death, man made vibration can be the cause of concern. This vibration is generated, for example, from:- Piling, demolition, compaction, blasting, drop forging, trains, motor vehicles and rotating machinery.

People are very sensitive to vibration and when it is perceived in buildings their usual first reaction is (understandably) about the structural damage to the property. Often the magnitude is far below any reasonable risk of damage and a vibration assessment and reassurance by an experienced and competent person, on occasions, is all that is required to alleviate the concern - see Scannell 1993 [1].

Before the damage risk can be evaluated it is useful to have an understanding of the basic physical principles involved.

Damage to buildings, such as cracking, can occur as a result of dynamic stresses and strains on the structure. However, history has shown that one of the main causes of building collapse is due to poor design and man made error - see Levy and Salvadori, 1992 [2].

Dynamic strains are directly related to the peak particle velocity, which is the parameter that is normally measured. The natural frequency and the degree of damping of the building and building element can also have an effect.

3. STRUCTURAL DAMAGE CRITERIA

It is not possible to define universal criteria that could be used to predict structural damage to buildings because of the many variables that are involved.

These include:-

(i) the condition, dimensions, foundation details and natural frequency and damping of the building;

(ii) the amplitude and frequency of the vibrating source;

(iii) the intervening geological strata (e.g. the soil type).

The criterion, therefore, must be site specific, based on the knowledge of many factors given above and the experience of previous case history data.

However, a guide to damage criteria for vibration is given in the British Standard BS 7385 : Part 2 (1993) [3] and for piling vibration criteria is given in British Standard BS 5228: part 4: (1992) [4]. (Unfortunately the criteria in the two Standards are at variance as shown in figure 1). Guideline values have also been issued by, German [5], American [6] and Swiss [7] Standards. The British Standard BS 7385 : 1990 (ISO 4866) [8] covers the evaluation and measurement for vibration in buildings. Part 1 of the Standard provides a guide for the measurement of vibration and a useful method for the classification of buildings according to their probable reaction to mechanical vibration given in Annex A (unfortunately these cannot be linked to criteria). While Part 2 (1993) provides a guide to simplified criteria as shown in table 1 and figure 2.

These Standards give guideline values, in terms of peak particle velocity, which are dependant on the type of structure and the frequency as shown in the table below.

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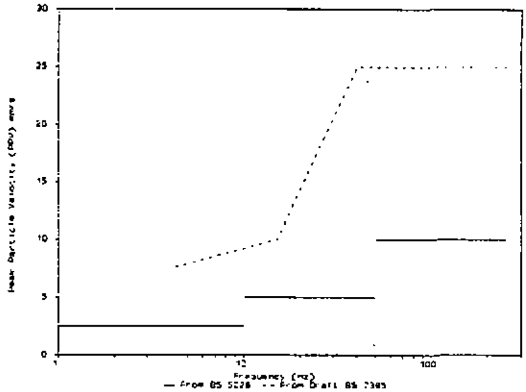

Figure 1. A comparison of guideline values given in BS 5228 Part 4 (1992) and BS 7385 Part 2 (1993) for continuous pile driving vibration in residential buildings. Below these valves even minor (cometic) damage is unlikely to occur.

TABLE 1 TRANSIENT VIBRATION GUIDE VALUES FOR COSMETIC DAMAGE (FROM BS 7385: Part 2: 1993).

Line	Type of Building	Peak Particle Velocity (mm/s) in Frequency Range of Predominant Pulse	
1	Reinforced or framed structures. Industrial and heavy commercial buildings	50 @ 4 Hz and above	
2	Unreinforced or light framed structures. Residential or light commercial type buildings	4 Hz to 15 Hz	15 Hz and above
		15 @ 4 Hz increasing to 20 @ 15 Hz	20 @ 15 Hz increasing to 50 @ 40 Hz and above

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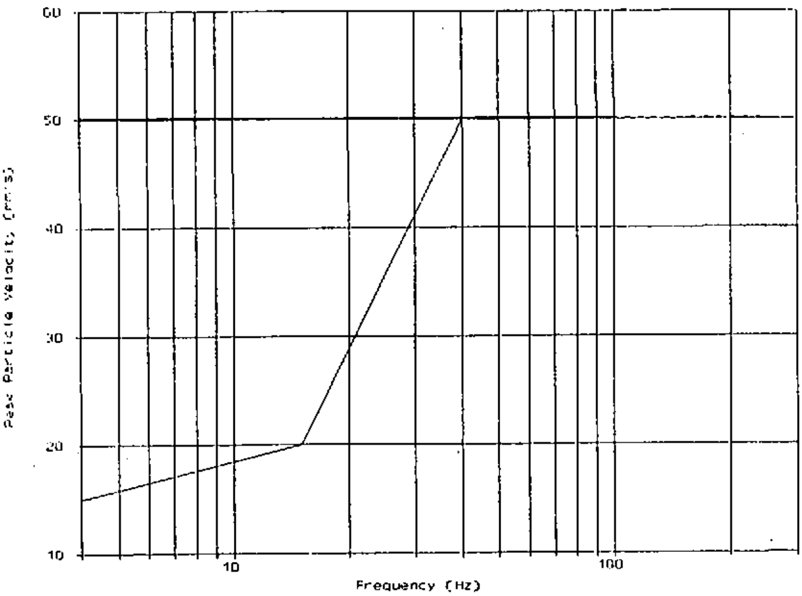

Figure 2. Transient Vibration Guide Values for Cosmetic Damage as given in BS 7385 1993. The upper curve is line 1 and the lower curve is line 2 (see table 1).

3.1 The Effects of Repeated Low Level Vibration.

The degradation of materials or structures due to repeated vibration is known as fatigue. It is not usually practical to carry out fatigue tests in 'real' situations, as the time scale needed would be too long. Most of the evidence on the effects of fatigue comes from laboratory tests.

The U.S. Bureau of Mines, and the (then) Transport and Road Research Laboratory (TRRL), in the U.K. have conducted studies on full-size houses to determine the effects of fatigue.

The U.S. study involved a test house specifically constructed near a surface coal mine to investigate the effects of blasting (Stagg et al., 1984 [9]). The test house was framed in wood with paper-backed gypsum board interior walls. It was initially shaken in torsion at an acceleration of 2.5 m/s^2 at the structures's natural frequency of 7 to 8 Hz. This magnitude of excitation corresponds to an equivalent horizontal ground motion of approximately 12 mm/s. The first fatigue cracks occurred after 52,000 cycles. These 52,000 cycles correspond to approximately 10,000 blasts with five significant pulses each and would take over 30 years to accumulate at a rate of 300 blasts per year.

The study from the TRRL (Watts, 1987) [10] involved an 80 year old pair of semi-detached houses which were subjected to typical heavy goods vehicle vibration with a 1 second pulse waveform. The vibration was generated on a small area of road pavement approximately 5.2 m from the cellar wall of the house. The maximum amplitude of the vertical component, at the house foundation was 2.6 mm/s in the frequency range of 12 - 13 Hz. The structure was exposed to 888,000 pulses simulating the effect of over 3.5 million goods vehicle axles. Of the forty existing cracks that were monitored throughout the tests only five showed sustained change in width exceeding 0.1 mm and a small amount of additional cracking of plaster occurred.

4. HUMAN REACTION TO VIBRATION - BUILDING DAMAGE FEAR

Humans are extremely sensitive to whole body vibration, particularly in the low frequency range (1 Hz to 10 Hz). Although the perception magnitudes vary considerably, values as low as 0.1 mm/s peak particle velocity (at low frequencies) can be perceived by some individuals. Assessing and predicting annoyance from vibration is covered in the British Standard BS 6472 (1992) [11] and the International Standard ISO 2631-2 (1989) [12].

Practical experience indicates that, usually, the first complaints that arise are not from the direct effects of the magnitude of vibration on the human body, but from the fear of structural damage to the complainants property. Not unexpectedly, this is particularly true where the dweller is also the property owner.

Complaints can be expected from 'building damage fear' at any magnitudes over 0.2 mm/s peak particle velocity (New, 1986 [13]) even though the chances of damage (under almost any circumstances) from magnitudes up to ten times this value are negligible.

An assessment is usually required if a complaint is received about vibration however, the assessment is quite different depending upon whether the complaint was made due to the direct effect of the vibration or building damage fear as shown below:

4.1 Direct Effect.

If the complaint is regarding the direct effect of vibration on the human body, then a procedure is followed as given in BS 6472. The root mean quad of the acceleration of the vibration is measured at the point of entry to the human body (or the centre floor position). The procedure is covered in detail in section 5.

4.2 Building Damage Fear.

If, however the complaint concerns a fear of structural damage then an assessment procedure should be followed as given in BS 7385. The measurements are taken in terms of peak particle velocity at foundation level and the plane of the uppermost full story. Further details are given in section 6 of this paper.

The anxiety can be greatly reduced if the procedure given by Scannell [1] is adopted.

4.3. Monitoring cracks during vibration.

It is advisable to monitor the size of any cracks that have been recognized as having the potential for expansion. This can be done with the use of 'Demec' gauges or vernier callipers which required the adhesion of small studs or screws on either side of the cracks. The distance between them can then be accurately measured with the gauge. Alternatively 'Avongard' (or similar) tell-tales can be fitted across the cracks which enable direct readings in vertical and horizontal directions to an accuracy of 1.0 mm.

5. HUMAN REACTION TO VIBRATION - WHOLE BODY VIBRATION

It is accepted in the British Standard BS 6472 (1992) that human response to vibration in buildings can depend on many factors other than the magnitude of the vibration. These include:- the direction of vibration input to the body (i.e. whether foot to head or back to chest etc.),the frequency of the vibration, the place of occupation (i.e. whether residential, office or workshop etc), the temporal structure of the vibration (i.e. whether continuous, intermittent or impulsive).

5.1. Criteria.

For continuous vibration and blasting, criteria is given in table 2. This is an adaption of the table given in BS 6472 and gives frequency weighted vibration magnitudes. For intermittent vibration the preferred method is to directly measure or to calculate the vibration dose value (VDV) or the estimated vibration dose value. Further details on this procedure is given by Scannell (1990) [14].

TABLE 2 SATISFACTORY MAGNITUDES OF BUILDING VIBRATION WITH RESPECT TO HUMAN RESPONSE

Place	Time	Continuous Vibration (16 hr day, 8 hr night)		Blasting Vibration (up to 3 blasts per day)		Intermittent Vibration VDV
		m/s^2	mm/s	m/s^2	mm/s	$m/s^{1.75}$
Critical working Area	Day and Night	0.005	0.141	0.005	0.141	0.09
Residential	Day	0.01 to 0.02	0.28 to 0.56	0.3 to 0.45	8.5 to 12.7	0.2 to 0.4
	Night	0.007	0.2	0.1	2.8	0.12
Office	Day and Night	0.02	0.56	0.64	18	0.3
Workshops	Day and Night	0.04	1.12	0.64	18	0.7

Note: all values are frequency weighted - see BS 6472.

5.2 Vibration Dose Values.
The use of vibration dose values is given by Scannell [14].

5.3 Peak Particle Velocity.
The current practice for blasting assessments and for structural damage assessments is to measure the peak particle velocity (ppv) with a velocity transducer. This method can also be used as an alternative to VDV (or eVDV) if the magnitude/duration trade off in table 3 is used.

TABLE 3. THE TRADE-OFF BETWEEN PPV AND DURATION

PPV (mm/s)	Low Probability of Adverse Comment	Adverse Comment Possible	Adverse Comment Probable
1	5 min to 1 hr	1 hr to 16 hr	-
1.5	1 min to 15 min	15 min to 3.5 hr	3.5 hr to 16 hr
2	up to 5 min	5 min to 1 hr	1 hr to 16 hr
2.5	up to 2 min	2 min to 30 min	30 min to 8 hr
3	up to 1 min	1 min to 15 min	15 min to 3.5 hr
3.5	-	up to 7 min	7 min to 2 hr
4	-	up to 5 min	5 min to 1 hr
4.5	-	up to 3 min	3 min to 45 min
5	-	up to 2 min	2 min to 30 min
5.5	-	up to 1 min	1 min to 20 min
6	-	-	up to 15 min
6.5	-	-	up to 10 min
7	-	-	up to 7 min
7.5	-	-	up to 5 min
8	-	-	up to 4 min
8.5	-	-	up to 3 min

NOTES

(i) All values are frequency weighted in accordance with BS 6472 (1992).

(ii) Values are calculated from eVDV's given in BS 6472 (1992).

(iii) All times are rounded to the nearest 'sensible' figure.

(iv) Times below 1 minute or above 16 hours are not shown.

5.4 Blasting vibration.
Where more than three blasting events occur in a 16 hour day an alternative to the VDV approach may be used. This method also assumes a 'trade-off' between the magnitude of the vibration and the number of events multiplied by the duration of the events. To calculate satisfactory magnitudes ppv_s use the formula shown below:

$$ppv_s = \frac{14.45}{\sqrt{N} \times T^d}$$

for the z-axis and

$$ppv_s = \frac{41}{\sqrt{N} \times T^d}$$

for the x/y-axis.

Where:

N is the number of events in a 16 hour day (and $N > 3$);
T is the duration of the events in seconds;
d is zero for T less than 1 second
For T greater than 1 s, d = 0.32 for wooden floors
d = 1.22 for concrete floors.

The different magnitudes for wooden and concrete floors is thought to be due to the difference in the expected movements.

Despite the difference in origin between this method and the VDV method, the two produce remarkable similar results accept at the extremes.

6. VIBRATION MEASUREMENT TECHNIQUES

6.1 Instrumentation.
There is a wide range of instruments that are suitable for the measurements of ground vibration, vibration in buildings and vibration of building elements, however they all consist of at least:- a transducer (accelerometer or geophone), a signal processor, and a display or indicator.

6.2 Measurement Techniques - Structural Damage.
To evaluate the effect of the vibration on the superstructure of a building measurements of the peak particle velocity (in mm/s) as a function of time, must be obtained.

The measurements should be made at the foundation level and at the highest floor level (as shown in figure 4), in all three orthogonal directions (i.e. in the vertical direction and horizontal directions in the plane of the building length and width).

Although of prime interest are: the vertical direction (z) at the foundation for compressive and tensile strain, the horizontal directions (x and y) for the shear strain.

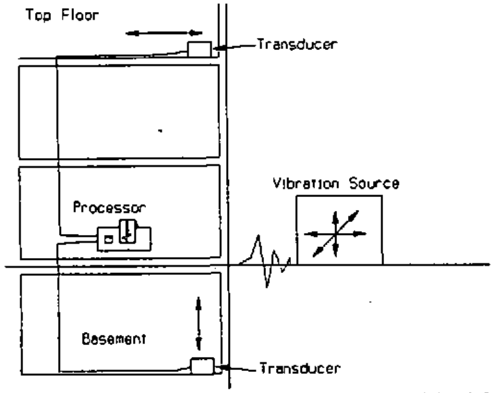

Figure 4. The measurement positions (as preferred by BS 7385 : 1990 and DIN 4150 : 1986)

When measuring vibration at the foundation, the transducers should be placed on the lowest storey of the building, close to an outer wall or in a recess of the outer wall. For buildings with no basement, the point of measurement should lie not more than 0.5 m above ground level. The measuring points should be located on the side of the building facing the source of the vibration.

When measuring the horizontal direction in the upper-most storey, the transducers should be placed close to the outer wall with one direction of measurement parallel to the side of the wall facing the source of the vibration.

If a multi-storey building is subjected to steady state harmonic vibration, simultaneous measurements should be made at all storeys where practicable and at least every 4 storeys (approximately every 12 m). This is because at higher 'modes' of vibration than the fundamental, much larger vibration magnitudes could occur at intermediate floor levels.

Where the building is more than 10 m long measurements should be taken at horizontal intervals of approximately every 10 m.

When potential damage to building elements (i.e. floors, walls, ceilings, window panes) is to be monitored, lightweight transducers are mounted in a central position on the element. Although sometimes severe (the author has measured ppv's up to 100 mm/s without damage occurring) these vibrations are usually unrelated to structural integrity (Siskind et al 1980) [15].

In the case of complaint it is often useful to take measurements where the complainant states that the vibrations are strongest.

6.3 Measurement Techniques - Whole Body Vibration.

6.3.1 The position of transducers
The vibration should be measured at the point of entry to the human body. If a complaint is made about vibration at a specific place (e.g. when the complainant is seated) then the measurement should be carried out at that body-environment interface. The accelerometers must move with the interface, they must not alter the dynamic properties of the body or the seat and they must offer little impedance to movement over the frequency range of interest. The seat must be occupied by the complainant. The same rule would apply for complaints from people lying in bed. For many of these type of measurements a 'semi-rigid' interface device, defined by the Society of Automotive Engineers (SAE) (1974) [16] will prove, suitable. This device is shown in figure 5, see also ISO 7096 (1982) [17].

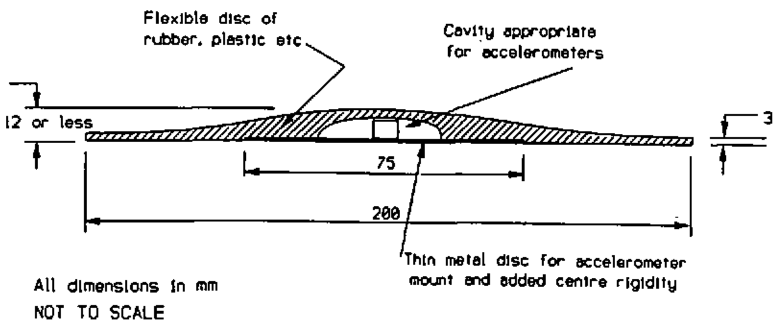

Figure 5. An example of an accelerometer mount for measuring on soft seats from SAE (1974).

However, it is often found that the complaint is not specific but more general, stating vibration occurs throughout the house. In this case the vibration should be measured at the point in the building where the highest vibration magnitude, that could be responsible for whole body vibration, is obtained. If the vibration source is restricted to the day time then the floor of the living areas would be the appropriate place to measure. The bedroom areas may provide the highest magnitudes but it is only reasonable to obtain measurements here if the vibration is expected to be generated at night.

In principle, vibration should be measured in all three orthogonal directions at a number of points in a building and the measurement results from the point and the direction where the highest range of magnitudes are found should be acted upon. It is often possible, on the basis of a survey or guided by experience to select a few measurement positions and directions where the highest range of magnitudes occur.

In many cases the magnitude of vertical vibration is higher than the horizontal vibration. The highest magnitude of vertical vibration is usually found in the unsupported centre of the beams with the longest span across the floor as shown in figure 6.

It is often practical to measure horizontal vibrations on structural walls as close to the floor as possible, rather than the floor itself. Care should be taken not to take measurements on lightweight or loose wall coverings or nonload-bearing partitions or columns.

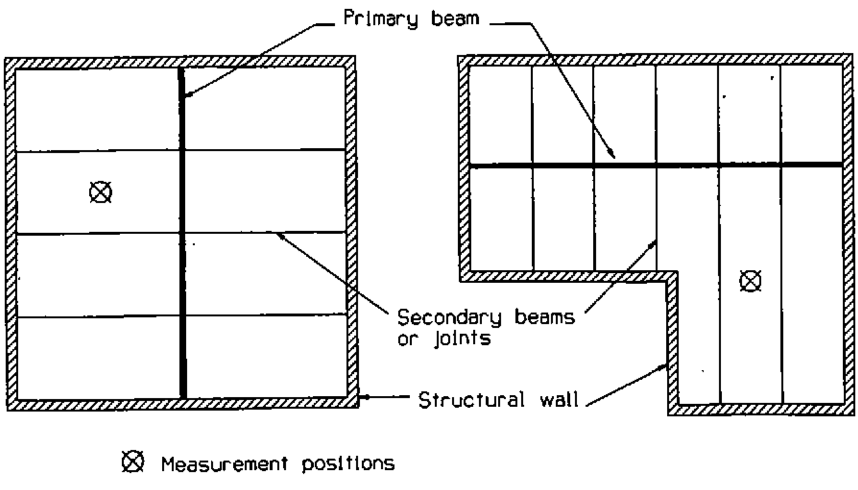

Figure 6. Examples of measurement points, where the highest magnitude of vertical vibration may be expected (from Danish Acoustical Institute 1987) [18].

6.3.2 Mounting the transducer.

For measurements on a solid and rigid floor or structural wall the transducer can be fastened with double sided adhesive tape or similar. If the floor is covered with a non-removable carpet or the like, the transducer shall be mounted with solid contact to the floor, i.e. on a device as illustrated in figure 7. This device is supported at three points. When placing the device, it must be ensured that the supporting pins fully penetrate the carpet and rest on the solid floor beneath. This will not cause damage as carpets are an open weave construction. It must be ensured that the mount cannot rock. Measurement of horizontal vibration must not be made with this device.

A transducer to measure horizontal vibration of a structural wall can be fixed with bees' wax or double sided adhesive tape if the transducer is light enough to be held firmly in position in this way. Alternatively, a heavier transducer can be secured to a mounting stud, which is glued to the wall, or attached with a bolt fixed in the wall by an expanding plug.

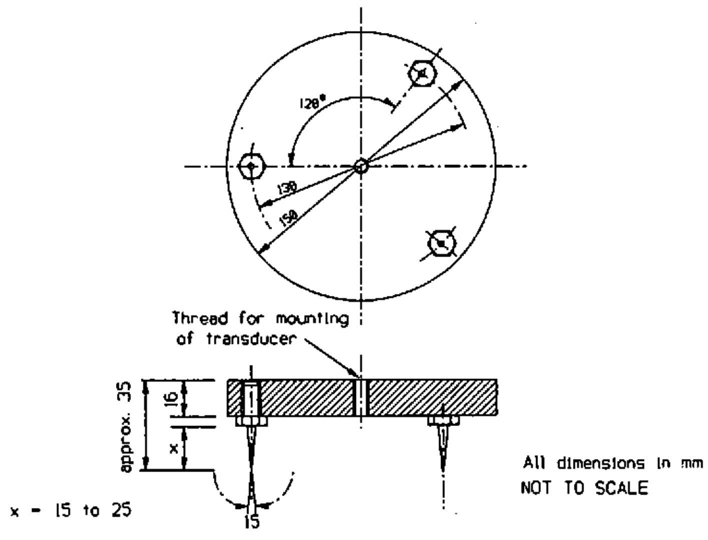

Figure 7. Mounting device for measurement of vertical vibration on carpet-covered floors. The combined weight of the device plus attached transducer should be about 1.5 kg.

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