Institute of Acoustics
Main Menu

GROUND VIBRATION PREDICTION AND ASSESSMENT

R.M. Thornely-Taylor Rupert Taylor Ltd

1. INTRODUCTION

Vibration is often grouped with noise and regarded as a kindred topic. Noise, after all, begins as vibration, and vibration is as much a part of acoustics as is noise.

By comparison, though, noise is simple. It always occurs in air, and except in special circumstances (e.g. in reactive near fields) the characteristic impedance of air is more or less always the same. So much so that we have standard methods of measuring sound power based on the measurement of sound pressure. The biggest complexities arise with velocity gradients in long distance propagation. Airborne sound almost always propagates as a compression wave, and the speed of sound is about the same at all frequencies. Damping due to air viscosity and boundary absorption is reasonably well understood. Only at very high intensities does airborne sound propagation become non-linear.

Vibration, by contrast, occurs in media ranging from rock or solid concrete, through water and soil to lightweight panels. It can propagate as a compression wave, a shear wave, a variety of surface waves, bending waves, torsional waves, either separately or together. It can propagate in two different media at the same time (e.g. water contained in porous rock and the rock itself). The propagation velocity of bending waves is frequency dependent. Damping can occur either through viscosity, or because of hysteresis or because of relaxation effects in solids and the mechanisms are not all properly understood. Sources of vibration such as machinery out of balance, moving loads and discontinuities are capable of moderately straightforward

mathematical description and manipulation. Transmission of vibration, and reception at the point of interest is beset with complexities and uncertainties.
To minimise the uncertainties, much more detailed prediction and modelling methods are required than is the case with airborne noise, and complex assessment methods are required.

2. CONSIDERATIONS IN PREDICTION

Receiver
Usually the most sensitive receptor is the human body. Whereas we have but two ears, we can sense vibration in any part of the body, and our response is dependent on direction. What may be x-axis vibration becomes y-axis or z-axis vibration by the simple act of a human receptor lying down. Going to bed does more than change the axis, because the impedance of the bed is very different from the impedance of the floor. Even the impedance of the floor varies according to location. Standing on the floor changes its impedance. Apart from the problem of axis changes, the human body though dynamically complex is a load impedance. The magnitude of a vibration signal transmitted into the body depends not only on the amplitude (displacement, velocity or acceleration) but also on the impedance of the system as seen from the point of contact with the body.
The significance of the effect of the body on vibration reception from a surface varies according to the impedance of the system. A concrete slab is more or less a constant-current source and the input to the body can be determined by the vibration amplitude of the slab without the presence of the body. The vibration of the surface of a mattress gives little direct indication of the vibration of a body that might lie on it.
BS 6472:1992 advises that “measurements of vibration should normally be taken on a building structural surface supporting a human body. In some circumstances, measurements may be made outside the structure, or on some surface other than at the point of entry of vibration to the body. Where measurements are made other than at the point of entry of vibration to the body an allowance should be made for the transfer function between the measurement point and the point of entry to the body.”
Figure 1 shows the impedance of the human body [1]. This can be idealised as a system of lumped parameters [2] with five degrees of freedom.

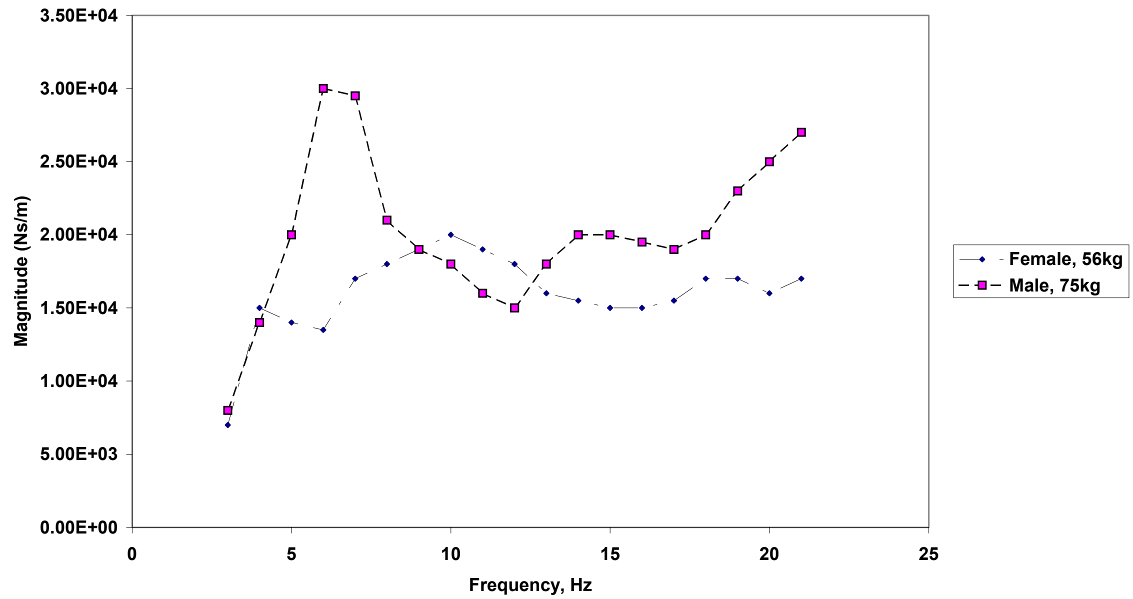

Figure 1 Driving-point impedance (z-axis) of seated human body

Path

Uncertainties associated with the relationship between floor vibration and vibration perceived by a human recipient are compounded by the variable response of different parts of the building structure. Vibration in the ground will not be coupled simply to the building foundations, and the local response of the building will depend on the impedance of building elements.

A monolithic "building" with a raft foundation on soil is in fact a mass-spring system itself. The spring constant of the soil, the damping ratio and added mass are given by the following expressions [3]:

	Spring Constant	Viscous damper	Added Mass
Vertical	$K \equiv 4Gr/(1-\nu)$	$1.79\sqrt{(K\rho r^3)}$	$1.50\ \rho r^3$
Horizontal	$18.2Gr(1-\nu^2)/(2-\nu)^2$	$1.08\sqrt{(K\rho r^3)}$	$0.28\ \rho r^3$

Where r = radius of plate; G = modulus of rigidity; ν = Poisson's ratio; ρ = mass density

There are also rocking and torsional degrees of freedom. The mass-spring behaviour of such a building influences the soil-structure interaction and the coupling loss factor between the soil and the building.

Floors in the building have natural frequencies, which if the floor is assumed to be either a plate with hinged edges or clamped edges, solutions for which are available [4]. At any one of those natural frequencies the floor impedance would be very low and controlled largely by damping, such the vibration amplitude would rise to very high levels for a continuous input signal.

Propagation through a building, from the ground upwards is such that losses in power transmission occur at each discontinuity, i.e. at each floor, but whether on not amplitudes increase or decrease depend on the impedances of the building elements. A suspended first floor may have higher vibration amplitudes than a ground floor slab, even though the power in the system is less, at frequencies where the suspended floor has low impedance. However, a higher amplitude due, not to higher power, but to lower impedance, may or may not result in higher received vibration in the receptor. Received vibration will depend on the extent of the match between the impedance of the system supporting the receptor and the receptor's driving-point impedance.
Propagation of vibration through the ground can in some cases be comparatively simple [6], if the source is deep below ground and the soil is homogeneous and isotropic. However, the characteristics of wave propagation though an elastic medium are such that linear distance laws do not apply. For example, for a spherical source in an elastic medium, the radiation impedance expressed as the magnitude of the ratio of the impedance in Ns/m to the impedance of a plane wave (product of density and wave speed) becomes very large at radiuses small compared with the wavelength as shown in figure 2. This effect can give rise to error in, for example, field trials to discover vibration propagation characteristics by simultaneous measurement of vibration close to a source signal such as an explosion or impact in the base of a borehole, and at a remote location.

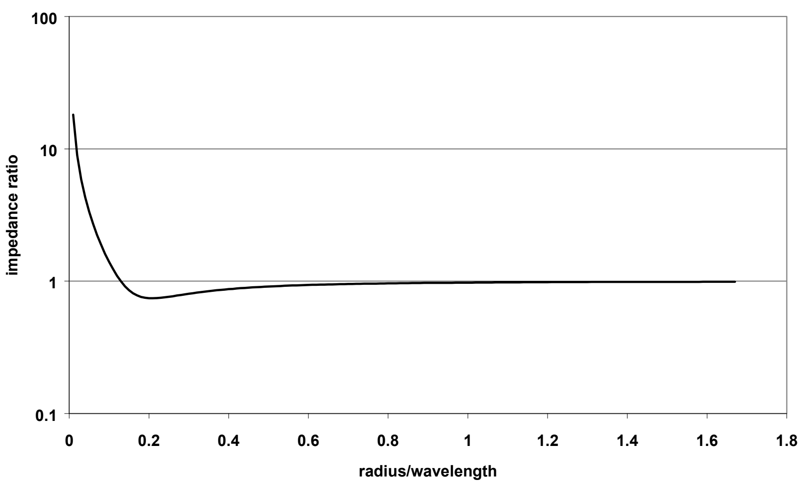

Figure 2 Impedance ratio of spherical source in elastic medium for Poisson's ratio=0.3

In a homogeneous isotropic medium, attenuation due to geometric spreading depends on the wave type. Compressive or body waves from a point source decay, in the far field, in inverse proportion to the distance, and some shear waves decay as the square of the distance. Where discontinuities occur, such as a ground surface, 2-dimensional waves such as Rayleigh waves arise which decay in inverse proportion to the square root of the distance. For line sources the rate of decay with distance is less, depending of the degree of coherence in, and length of, the source.
Where clearly defined interfaces between, for example rock and clay, partial transmission and reflection occur. In the special case of normal incidence, the reflection and transmission factors are a simple function of the characteristic impedances of the media, but for the more usual case of incidence other than normal,

the effect is more complex. Conversion between body waves and shear waves occurs, and it is necessary to differentiate between horizontal and vertical shear waves. In some circumstances total reflection of shear waves takes place. The more usual case involves a progressive change in soil characteristics with increasing depth. This will cause curvature of propagation paths towards the ground surface.

In rock, geometric spreading is the main means by which amplitude reduces with distance, but in many soils such as clay, gravel, and sand, dissipative effects, also known as material damping, are important. This is the largest source of uncertainty in prediction of vibration transmitted through these soils. The literature contains rudimentary figures for loss factor, but the effect of the loss factor depends on the type of damping assumed. A viscous damping model produces very large attenuations at higher frequencies over distances of tens of metres. Other damping models produce much lower attenuations and the potential error can be reckoned in factors of ten. At frequencies below 10Hz the loss factor $Q^{-1}(\omega)$ appears to be essentially constant [5], but may be dependent on frequency above 10Hz. This loss factor is defined as

$$Q^{-1}(\omega) = - \Delta E(\omega)/(2\pi E_o(\omega)) \qquad [1]$$

where $\Delta E(\omega)$ is the energy loss per cycle at angular frequency ω and E_o is the stored elastic energy. However, for shallow propagation in the range 10-60Hz a constant Q^{-1} model has been found [5] to give a good explanation of observed amplitude loss.

Source

Sources of vibration include rotating machinery, moving vehicles (particularly trains) and impulses from industrial machines such as presses, together with construction processes such as percussive piling.

Predicting source vibration from machinery is made difficult by the lack of an effective equivalent to sound power level in the vibration context. Knowing the vibration measured at the base of a machine is only relevant if the impedance of the foundation is known, or is effectively the same as the foundation for which the predictions are required. Measuring vibration in machine supports when they are placed on soft springs such that the foundation impedance is dominated by the springs, and can readily be estimated, is one of the few ways of discovering the source power of a vibrating machine at frequencies where calculation of all the out-of-balance forces across the spectrum is impractical.

Techniques for predicting the source term in the case of moving rail vehicles, dependent on the vehicle and track dynamic parameters are available [7]. The source power is dependent largely on the unsprung mass, the roughness of the wheel/rail interface and on the receptance of the track.

For sources such as percussive piling, the source strength is related to the energy per blow and the numbers of blows per minute. The impulse is transferred to the ground, and modified in shape and amplitude (and therefore in frequency content) by skin friction in the pile and by tip resistance. Skin friction and tip resistance depend on the size and shape of the pile, and on the soil characteristics. Some energy is lost through overcoming skin friction and tip resistance, and that which remains is propagated

largely from the region of the tip. Empirical methods exist for estimating source strength based on energy per blow [8].
Empirical data in all cases need to take account of the impedance of the ground which is supporting the source and through which propagation from the source to the measuring location takes place.

Conclusions on prediction
Vibration is best predicted using numerical methods where data concerning the input variables is known within ranges that enable overall uncertainties to be estimated. Algebraic prediction of vibration is a useful tool for predicting the likely upper bound of received vibration amplitude, provided care it taken to avoid the use of possibly inappropriate models (such as viscous damping in soil propagation). Empirical prediction is attractive, and is valuable when proper account is taken of differences between the site where the empirical data were obtained and the site to which they are to be applied.

3. CONSIDERATIONS IN ASSESSMENT

Vibration affects people, structures and machines. The assessment of vibration affecting the last class, vibration-sensitive machines, normally necessitates reference to the manufacturers of the machines for sensitivity criteria. General criteria are available in the literature [9]. The position is complicated by the fact that highly sensitive machines tend to be installed with local vibration-isolating foundations.
As far as structures are concerned, damage to the fabric, for example in terms of cracks, is the principal consideration and criteria appear in the literature [9][10].
The assessment of vibration affecting people is the most complex of the three considerations. This is partly because most people’s normal environment involves perception of vibration only in response to events such as footfalls and door slams, and in transportation environments. Any vibration from an extraneous source, above the threshold of perception, tends to give rise to indirect concerns about potential building damage, even though it is well-established [9][10] that amplitudes of vibration sufficient to cause even cosmetic cracks in buildings are many times higher than perception thresholds. Vibration below the threshold of perception can affect people through their sense of hearing if the vibration occurs at acoustic frequencies and is re-radiated as airborne noise by building surfaces.
Discounting unfounded fears of building damage, assessing the direct effects of vibration on people is made difficult by differences the standards that are in use. BS 6472 adopts weighting curves which differ from those in ISO 2631, and which are under review [9][11][12]. However, most weighting curves have the effect that human response is velocity-dependent above the region 8-10 Hz. The differences concern absolute sensitivity and sensitivity at frequencies below this region. Reference to figure 1 above shows that differences between the driving-point impedance of a human body in the sub-10Hz region are so large that time spent attempting to refine weighting curves in this region is somewhat futile given the large uncertainties which

exist according to weight and sex of the person concerned. In any event, use of velocity is unlikely to underestimate human response.

The second matter relates to the effect of duration and number of vibration events. In the UK, the vibration dose value, using the BS-specific W_g [11] weighting is used. This takes the fourth root of the duration and/or the number of events for use in a linear scale, which is therefore very insensitive to duration and number. VDV also appears in ISO 2631 [12] but using a different weighting curve.

In the UK, current practice is to follow BS 6472, the use of which is clarified in reference [9]. It is likely, however, to be several years before assessment of vibration reaches the internationally accepted status that has broadly been achieved in noise assessment.

REFERENCES

[1] Cheng, H., et al. AL/CF-TR-1994-0051, 1994

[2] Smith, S.D., Modeling Female Vs Male Whole-Body Vibration Response, Twenty-First Annual Meeting of the American Society of Biomechanics Clemson University, South Carolina, September 24-27, 1997

[3] derived from Newmark, N.M and Rosenblueth, E., Fundamentals of Earthquake Engineering, Prentice-Hall Inc., Englewood Cliffs, N.J., 1971, p.98

[4] Leissa, A, Vibration of Plates, Acoustical Society of America, 1993

[5] Kennett, B.L. Seismic Wave Propagation in Stratified Media, Cambridge University Press, 1983

[6] Thornely-Taylor, R.M. Predicting the propagation of ground vibrations from underground railways. Proc. Inst of Acoustics, Vol 20: Part 1 (1998)

[7] ISO DIS 14837-1 Mechanical vibration — Prediction of groundborne vibration arising from rail systems in tunnels — Part 1: General Guidelines

[8] BS 5228:part 4:1992 Noise control on construction and open sites Part 4. Code of practice for noise and vibration control applicable to piling operations.

[9] ANC Guidelines, Measurement & Assessment of Groundborne Noise & Vibration, Association of Noise Consultants, 2002

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

[11] BS 6472:1992, Guide to Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz).

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