imperfections such as bumps or potholes. A perfectly balanced engine driving a vehicle along a perfectly smooth road would not produce any vibration.

The main parameters determining the magnitude and frequency of traffic vibration are : road surface profile, vehicle mass and road speed, and the characteristics of the vehicle suspension system, and in particular its natural frequency.

Vibration from trains.

The vibration producing mechanisms are not fully understood, but it is believed that the main source of ground vibration from trains is the variability in the interaction between wheels and rails, arising from imperfections, irregularities and roughnesses in the surfaces of both. Irregularities in the track system supporting the rails may also cause vibration. The important parameters are rail and wheel profiles, vehicle mass, speed and suspension characteristics.

Wind induced vibration

Variability in the wind loading forces on buildings cause vibration, and this is particularly important for tall buildings. Steffens states that serious vibration in tall buildings is likely if the natural frequency of the building is less than the frequency of vortex shedding at the maximum wind velocity, and gives a method for calculating both quantities.

Other sources

Other sources of vibration in buidings include earthquake s, blasting operations, pile-driving, acoustic excitation eg from blasting, road and rail traffic and aircraft, machinery of various kinds, and human activities such as walking and door slamming. BS7385 Part 1 indicates the characteristics of vibration produced in buildings by various sources.

Steffens gives a fascinating and comprehensive account of vibration produced by a wide range of sources, including bell ringing, church organs, industrial knitting machines and door slamming, as well as all the sources mentioned above.

Vibration from pile-driving

There are many different methods of pile-driving, and these may result in vibration which is either continuous, or intermittent, or impulsive in nature.

BS5228 Part 4 (Appendix A) gives a detailed account of the characteristics of vibration associated with various types of pile-driving operations and a wide range of case study data.

Vibration from machinery

The motion associated with the operation of reciprocating machi nes (eg internal combustion engines) inevitably causes vibration.Rotating machinery (such as pumps, motors, fans) also causes vibration because there will always be some ’out of balance’ forces associated with the rotary motion, although in principle the perfectly balanced rotating machine would not produce any vibration.

Vibration is also produced as a by-product of the 'working forces' associated with various types of machine including , for example : cutting, pressing, pumping, abrading and polishing, electrical forces in rotating machinery, combustion forces, aerodynamic and hydrodynamic forces in fans and pumps, forces in bearings, gear meshing forces, and impact forces.

Vibration is also produced by the imperfect operation of machinery caused by wear, looseness and mis-alignment of parts, and imperfect balancing. It is for this reason that good maintenance procedures are so important in minimising vibrationand noise from machines.

Since most machinery operates on a cyclic basis of either rotational or reciprocal movement the frequency spectrum of machine vibration usually consists of a series of pure tone components (fundamentals and harmonics) associated with the repetition rates of the various cycles, (and with frequencies therefore dependent on machine speed), superimposed upon a broad band spectrum of raNDOM VIBRATION caused by impacts, wear, and irregularities in the machine motion. The narrow band component of the spectrum, or 'vibration signature' as it is sometimes known, can be used to diagnose the source of a particular noise or vibration frequency, eg to identify a particular set of gears, or fan or bearing. For a particular machine the spectrum can also be used to identify the vibration producing mechanism, such as 'out of balance' or 'misalignment' and this knowledge forms the basis of vibration monitoring of machinery in order to give early warning of malfunction.

## THE TRANSMISSION OF VIBRATION

### THE PROPAGATION OF VIBRATION IN UNIFORM MEDIA

There are two sorts of elastic waves which can travel in an infinite, ie unbounded homogeneous solid elastic medium : longitudinal compressional waves, often called P waves, and transverse shear waves, often called S waves. Only the P waves can be propagated in a fluid such as air or water. In bounded solids, such as plates, beams, rods and bars (such as in the elements of a building) there are in addition a number of other types of waves, such as flexural and torsional waves, which are combinations of the two main types. Also in bounded solids and fluids surface waves are transmitted, but, as the name suggests, only on and at limited depths below the surface. Surface waves in solids are also known as Rayleigh waves.

NB Homogeneous means having the same properties throughout the medium, ie 'being the same everywhere'. Isotropic means having the same properties in every direction

### Propagation of ground-borne Vibration

Ground-borne vibration is, then, transmitted by P, S, and, near the surface, by Rayleigh waves. The velocity of shear waves in soils ranges from approximately, 30 $m.s^{-1}$ to 300 $m.s^{-1}$ , and for rock it is about 1000 $m.s^{-1}$ . The velocities of compressional waves is about 2.5 to 4 times higher than for the shear waves, and the Rayleigh waves travel at speeds slightly lower than shear waves. The amplitude of surface waves reduces rapidly with depth below the surface, so that they are confined within a wavelength or so of the ground. Because of this Rayleigh waves are subject to less spreading loss than P or S waves, and especially in lightly damped soils or rock, they can travel greater distances with less attenatuion.