Key Engineering Materials Vols. 245-246 (2003) pp. 467-474
online at http://www.scientific.net

The Role of Surface Waves in Assessing Structural Damage

P.R. Armitage[a] and J.M. Horwood[b]

School of Engineering and Computer Science, University of Exeter, Devon, UK
[a]p.r.armitage@exeter.ac.uk, [b]J.M.K.Horwood@ex.ac.uk

Keywords: Concrete Testing, Gauge Corner Cracking, Rail Testing, Rayleigh Waves

Abstract.
The properties of the various sound waves that propagate in solids are discussed, with a particular interest in the characteristics of surface waves and how they may be used to detect defects in a material. Experimental measurements are given of surface acoustic waves propagating over concrete test samples and how the properties of the surface wave can be separated from the waves due to reflections from internal objects. An investigation is made of the surface waves propagating over a steel railway line, and a comparison is made of the spectra of surface waves over a sample of good rail to that of a defective rail (gauge corner cracked).

Introduction

Over the years considerable research has been carried out in the use of sound waves to detect various defects that occur in materials. The early work concentrated on using sound wave reflections at high frequencies to resolve small defects. Later, transmission methods were used to examine changes in attenuation and velocity to determine the presence of faults along the sound wave's path. Over the past few years the impact echo method [2] has found extensive applications, particularly for testing concrete structural integrity. This technique entails transmitting a sound pulse at the material's surface and measuring the frequency of multiple reflections that occur between the surface and an internal defect.

Recent interest has involved the applications of sound waves that propagate over the surface of a material as a means to detect defects. This paper shows the results of sending a short low frequency sound wave over a material's surface and investigating what changes will occur due to the presence surface and near surface defects.

Sound waves in materials and over surfaces

There are only two types of sound wave that can propagate within the bulk mass of a homogeneous unbounded material, these are known as P-waves and S-waves. If the material has a boundary, such as a surface, then at this boundary, other types of sound wave propagation can occur. One of these wave types is called a Rayleigh wave, named after its discoverer.

P-waves (compressional, pressure waves)

Compressional waves involve displacements and dilatation in the direction of propagation, they occur within the bulk of a material and the velocity of wave motion, **Vp,** is provided by:-

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E(1-v)}{\rho(1-2v)(1+v)}} \quad (1)$$

where: λ and μ = lame's constants, ρ = density, **E** = Young's modulus and **v** = Poisson's ratio

S-wave (shear, transverse waves)

Shear waves involve displacements orthogonal to the direction of wave motion, occurring within the bulk of the material. The velocity of this wave motion, **Vs,** is given as follows:-

$$V_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1+v)}} \quad (2)$$

Bounded medium

The P and S waves described above involved wave motion in an unbounded medium.
If the dimensions of the material are of finite extent (bounded) then other modes of wave propagation can exist. In a rod (or thin bar) where the dimensions are small compared to the wave length of the sound wave, the velocity, **Vp,** of a compressional wave travelling along the rod is given by the following:-

$$V_p = \sqrt{\frac{E}{\rho}} \quad (3)$$

In thin plates, another type of wave propagation can occur called Lamb waves. These are acoustic waves that are guided by the geometry of the plate structure, usually when the plate is less than three times the wavelength. The displacements occur throughout the thickness of the plate. The velocity of propagation is dependant upon the material, the geometry and the wavelength.

In a thin plate bonded to a stiff material another wave motion can be found called Love waves. These waves consist of a displacement across the plate at right angles to the direction of propagation. They are usually associated with earthquake seismology, but are finding applications in material testing.

If a material is unbounded in the x and y direction, and half of the z plane illustrated in figure 1, then a wave motion confined to the surface can occur, this is called a Rayleigh wave.

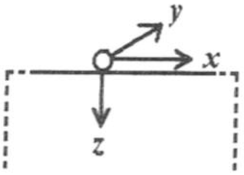

Figure 1. Surface wave motion

Kolsky[1] provides a comprehensive analysis of this wave, and the velocity of propagation can be found by determining the real, positive roots to the following:-

$$C^{6} - 8\,C^{4} + (\,24 - 16\,a\,)\,C^{2} + (\,16\,a - 16\,) = 0 \tag{4}$$

where C is the ratio of the Rayleigh wave velocity(Vr) to the shear wave velocity(Vs), C = (Vr / Vs) and the constant a, is related to the possion's ratio(v), by a = (1-2v) / (2-2v). If Poisson's ratio is known then the equation may be solved numerically. For steel with v = 0.29, C will be 0.9258 giving a Rayleigh wave velocity of 2980 m/sec. For a good quality concrete the Rayleigh wave velocity is typically about 2800 m/sec.

The rate at which the amplitude of the vibration parallel to the surface (A_p) attenuates with depth **z** is given by the following:-

$$\frac{dA_p}{dz} = e^{-qz} - 2qs\,(s^2 + f^2)^{-1}\,e^{-sz} \tag{5}$$

where q and s are attenuation factors and f = 2π / wavelength.

In steel the amplitude of the vibration diminishes rapidly to zero at a depth of about 0.25 wavelengths. At depths greater than this the amplitude starts to increase and the particle motion reverses. At 0.5 wavelengths a maximum amplitude is reached of 0.15 its value at the surface; it then decreases asymptotically with greater depth.

The rate at which the amplitude of vibration normal to the surface (A_n) attenuates with depth **z** is given as follows:-

$$\frac{dA_n}{dz} = e^{-qz} - 2f^{2}\,(s^2 + f^2)^{-1}\,e^{-sz} \tag{6}$$

In steel the amplitude of the vibration first increases with depth below the surface, reaching a maximum at about 0.1 wavelengths. It then decreases asymptotically. At a depth of one wavelength the amplitude has fallen to 0.2 of its value at the surface. The particle motion is elliptical. In hetrogeneous materials the energy of the wave can be converted to different wave propagation modes, at the material boundaries compressional waves or shear waves can be formed.

The Rayleigh wave

Characteristics

- The propagation involves only a limited depth equal to about one wavelength;
- 70% total energy released by a point source is transmitted by Rayleigh waves;
- The attenuation with distance is less than other waves.
- Over extensive, homogeneous materials, they are non-dispersive.

Applications

- Earthquake analysis (seismology)
- Soil characterization (geophysics)
- Concrete analysis(civil engineering)

- Metal defect detection (mechanical engineering)

Examples of surface waves in concrete

Fig 2. shows the signals received by a small wide band transducer, at various locations along the surface of a concrete test slab. The transmitted waveform was a single cycle at 190 kHz. This figure shows that the aggregates in the concrete have scattered the sound wave to a very large degree, mode conversions at the surface occur, and the resulting waveform is stretched. The amplitude of the signal attenuates significantly with distance, from 100mV peak (trace A) to 28mV peak (trace G). The Rayleigh wave is not observed in this example, the near surface p-wave being too dominant and travelling at 4.6km/sec. With some types of concrete mix, containing very small aggregates, the Rayleigh wave may be distinguished as it propagates at a slower velocity, usually between 2km/sec and 2.9km/sec. This wave is observed as a large amplitude signal progressing down through the traces at a shallower angle to that of the p-wave.

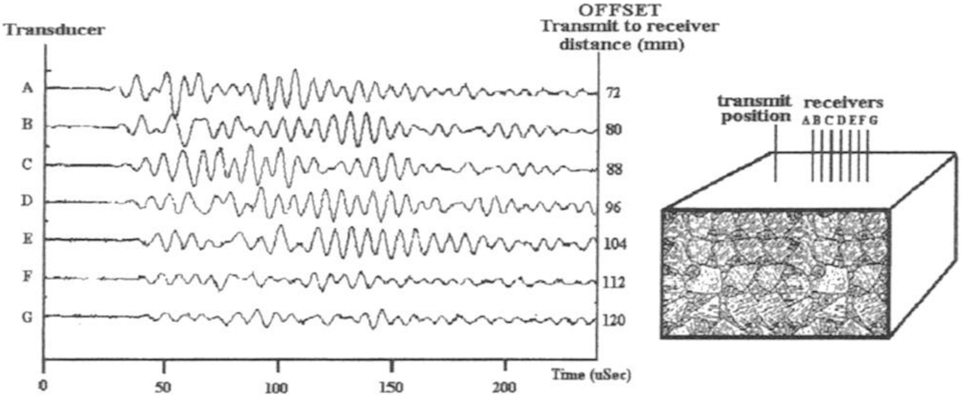

Figure 2. Sound waves propagating over a concrete surface

Serious defects, such as large deep cracks in the surface of the concrete, will attenuate this surface wave sufficiently to be observed. Spectral analysis and examining the velocity of propagation of p-waves through concrete samples have found useful applications, particularly in characterizing concrete mixes and the setting process, Garnier [4]. Further research will be required to determine if the surface waves are able to provide similar information. Carino [2] describes the use of an impact echo sounding method with spectral analysis to identify small cracks or voids within the concrete. This technique measures the resonant frequencies resulting from multiple reflections between the surface and an internal defect. It is possible to detect internal defects directly from their reflections and techniques exist that separate surface wave effects from the reflected waves.

Fig 3. shows a concrete test block that has a hollow steel duct at a depth of 100mm below its surface. The transducers are Andrews [3] design, these are wide band and are mortar coupled to the test block.

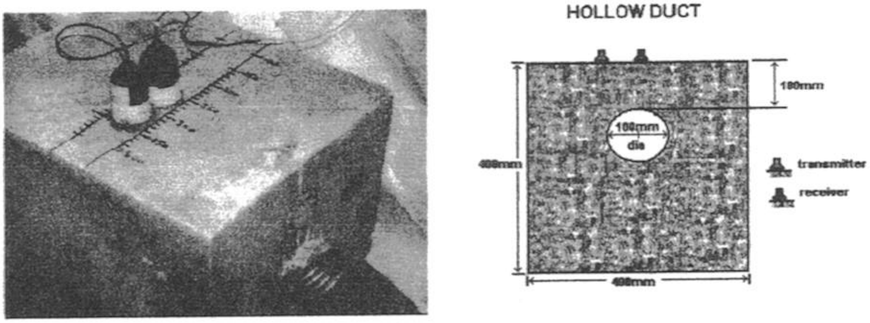

Figure 3. Concrete test block with hollow duct

Fig 4a shows the signals measured at various points over the surface. The transmitted signal was a 5 micro second pulse. A surface wave travelling at 4 km/sec can be clearly seen, again this is a near surface p-wave, the Rayleigh wave is absent. The reflection off the duct can also be observed, indicated in this figure, and forms an alignment between traces that is almost vertical.

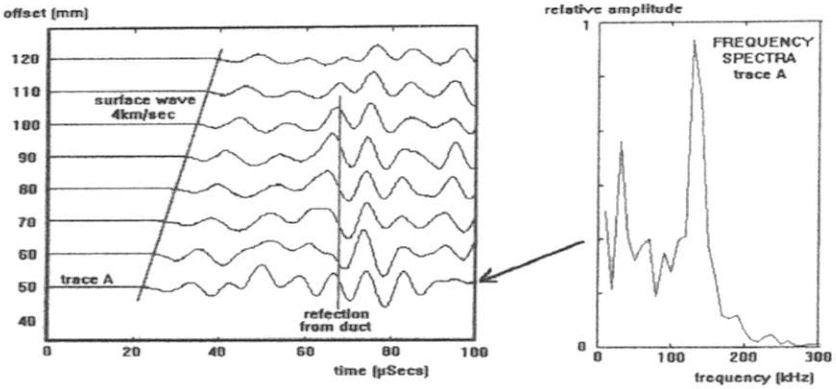

Figure 4a and 4b. Waves propagating over a concrete test block (with hollow duct)

Fig 4b shows the frequency spectra of trace A. Two dominant peaks are observed, one at 25 kHz and the other at 125 kHz. The method does not indicate whether the peaks result from reflections and resonances due to internal defects or from the properties of the surface wave.

In order to find out the source of these resonant peaks, a two dimensional Fourier Transform is performed on all these traces. The result is a conversion from a time-distance plot to a frequency-wavenumber plot, shown in Fig 5.

Fig 7. shows the signals received from a wide band transducer placed over a sample of steel railway line that has gauge corner cracking over part of its surface. The transmitted wave form was one single cycle at 140KHz. Again the surface Rayleigh wave can be clearly seen as a high amplitude wave, and propagates at 3km/sec, however in the region of worst cracking (positions E and F) there is observed additional noise after the main part of the Rayleigh wave has passed. This may be result of the scattering caused by the presence of these cracks in the vicinity of the receiving transducer.

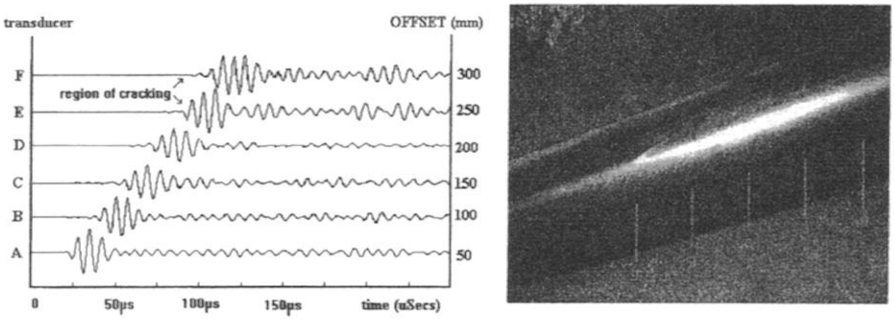

Figure 7. Surface waves on a defective railway line

Fig 8., Shows a comparison of the frequency spectra of trace F (good rail, fig 6) and trace F (cracked rail, fig 7). The good rail shows a normal distribution of frequency components centred on 140kHz, following closely to the signal that was transmitted into the rail. The cracked rail's spectra shows distinctive peaks and troughs within the 110kHz to 190kHz band. The cause of this is under investigation, it is probably due to various frequency components being absorbed or lost due to destructive interference. The cracks have appeared to act as a local filter removing certain frequency components within the Rayleigh wave. The two large frequency troughs in this example occur at 127kHz and 138 kHz, corresponding to a Rayleigh wavelength of 23 and 21 mm, comparable to the size of the cracks in the rail, which were measured to be approximately 7mm deep and 20mm wide.

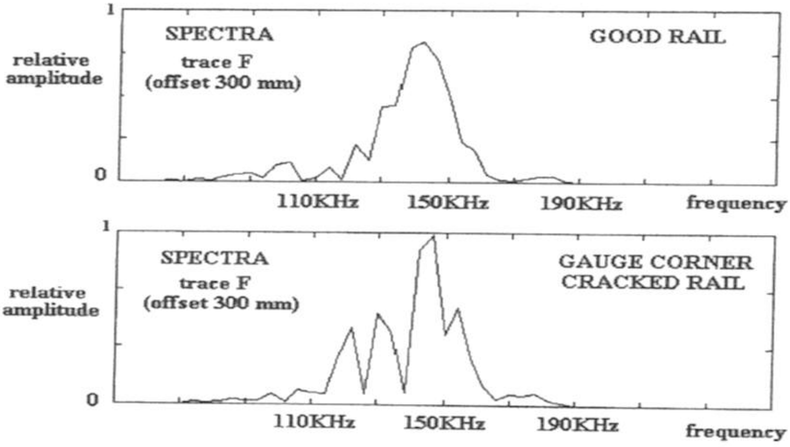

Figure 8. Spectral comparison of good and defective rail

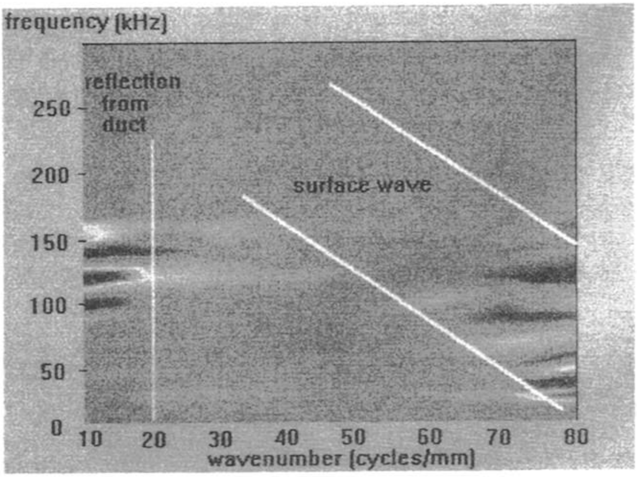

Figure 5. Frequency wavenumber plot of concrete test data

In the frequency-wavenumber plot Fig 5, the vertically aligned duct reflections are transformed to the far left, the surface wave is transformed diagonally from the top left to bottom right, as shown in the figure. The spectral content of the reflected wave has a maximum value at 125 kHz (shown in red), and the surface wave has a maximum value at 25 kHz (shown in red). The technique provides a method whereby the resonant properties of the surface wave are identified, giving an insight in to the composition of the aggregates.

Examples of surface waves in steel railway lines

Fig 6 shows the signals received from a wide band transducer placed over a sample of good quality steel railway line. The transmitted wave form was one single cycle at 140kHz. The surface Rayleigh wave can be clearly seen as a high amplitude wave, and propagates at 3 km/sec. Also observed on some of these traces are a very weak p-wave, seen as a small deflection before the large Rayleigh wave arrives at each transducer, propagating at a faster velocity of 5.1 km/sec. The velocity is the rod wave velocity, since at this frequency the wave length will be large compared to the dimensions of the rail. If the wave was not confined to the rail, but in an extensive steel medium, the p-wave would propagate at the higher bulk wave velocity of 5.9Km/sec.

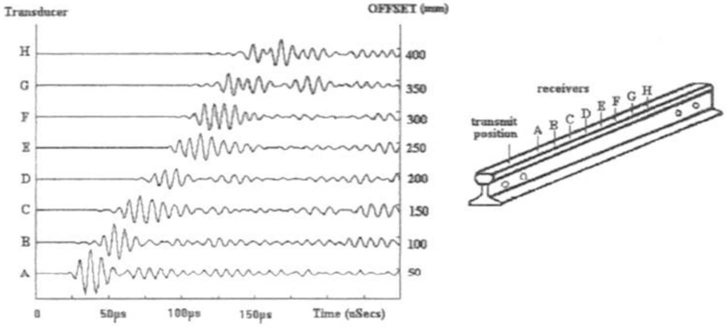

Figure 6. Surface waves on a steel railway line

Summary

The experiments outlined in this paper have shown that the surface wave propagating over concrete containing large aggregates is not a Rayleigh wave, since it has a velocity far greater than that expected. It appears to be predomanantly a near surface p-wave.

The research has shown that the surface wave can be troublesome when trying to identify refections from internal objects or defects, as it is " stretched " out over a long period of time, masking the reflected signals.. Techniques have been demonstrated that will enable the separation of the surface wave from the reflected waves, thereby allowing independant analysis to be carried out of these two signals.

The Rayleigh wave has been shown to exist over the surface of a steel railway line, even though it is confined by the dimensions of the rail. Examination of the frequency content of the Rayleigh wave in both good and defective rail (gauge corner cracked) has yielded the possibility of being able to use this wave as a means to detect surface and near surface defects.

References

[1] Kolsky H. Stress Waves in Solids, published: Clarendon Press Oxford 1953.

[2] Carino N. The impact echo method: An overview, Proceedings Structures Congress & Exposition, May 21-23, 2001,Washington, D.C., American Society of Civil Engineers.

[3] Andrews David and Hughes Angela: A novel ultrasonic transducer for inspecting concrete, IEEE Proceedings Ultrasonic Symposium 1991 Vol 1 p349 to 351.

[4] Garnier V: Non-Destructive evaluation of concrete damage by ultrasound.
Proceeding 15th World Conference on Non-destructive testing.
Roma (Italy) 15th to 21st October 2000.