The detection of micro-cracks in concrete by the measurement of ultrasonic harmonic generation and inter-modulation

P.R. Armitage [1] L.V. Bekers [2] M.K. Wadee [3]

ABSTRACT.

The ultrasonic testing of concrete structures has posed many problems. Conventional methods such as pulse echo and pitch catch are of limited use due to its composition, aggregates will cause scattering and multiple reflections. Alternative ultrasonic methods have been recently investigated that examine the shape of the waveform as it traverses through a complex material, the idea being not to located a single defect but to determine the overall mechanical properties within a certain region.
In damaged materials, particularly ones that have micro-cracking, the stress-strain relationship does not obey Hooke's Law of elasticity, stress is not proportional to strain, it is not linear, resulting in distortions to a pure ultrasonic sine wave traversing through it. The degree of this distortion is measured by examining the spectral content of the waveform, second, third and higher harmonics will be present and are related to the degree of micro-structure damage. Additional practical advantages in detecting non-linearity may be achieved by transmitting the sum of two ultrasonic sine waves into a material from one transducer and examining the spectra for inter-modulation products. This paper details experiments on small samples of concrete using both harmonic and inter-modulation spectral analysis.

KEYWORDS.

Concrete, testing, non-linear, ultrasonic, harmonics

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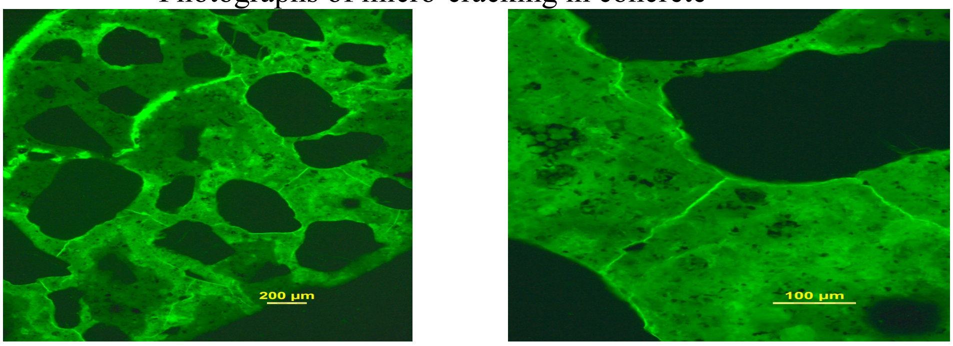
INTRODUCTION

The testing of concrete structures has posed many problems. Conventional ultrasonic transmission and pulse echo methods have limitations due to the nature and composition of concrete since they cause multiple reflections and non-direct ray paths. Alternative ultrasonic methods have been recently investigated that examine the shape of the waveform as it traverses through or over a complex material, the idea being not to located a single defect but to determine the overall mechanical properties within a certain region. These methods are known as Nonlinear Elastic Wave Spectroscopy (NEWS), Lacouture[1] details a NEWS method to monitor the curing process of concrete, by means of transmitting and receiving a 8 kHz sine wave signal through the setting concrete. Van Den Abeele[2] outlines various NEWS techniques to measure micro-scale damage in building materials, including concrete. In one of the NEWS methods two different frequencies are transmitted into the material via two separate transducers and third transducer used as a receiver.
Non-linear acoustic methods seek to determine how an ultrasonic waveform changes when it propagates through or over the surface region of a medium. These changes are directly related to the stress-strain relationship and the hysteretic properties of a material and are not unduly effected by the ray path. In damaged materials, particularly ones that have micro-cracking, the stress-strain relationship does not obey Hooke's Law of elasticity, stress is not proportional to strain, it is not linear. In addition these materials often have a stress-strain relationship that is non-symmetric, that is the reaction to compressional forces will have different properties to that of tensile forces, this is a result of the cracks opening and closing under a tensile or compressional loads. Figure 1 shows two photographs of sectioned micro-cracked concrete samples, the cracks having been formed by chemical degradation and mechanical damage. These photographs, provided by Geomaterials Research Services Ltd, were taken using epifluorescence illumination with a Zeiss Axioskop polarizing photomicroscope.

Figure 1 Photographs of micro-cracking in concrete



The stress-strain curve for non-linear behaviour is illustrated in Figure 2. The result of non-linearity is that any stress loading that is in the form of a pure sine wave will produce a strain that is distorted as it traverses the material. This is illustrated in Figure 3. The degree of this distortion is measured by examining the spectral content of this distorted waveform, second, third and higher harmonics will be present and are related to the amount of damage. Greater sensitivity to non-linear effects can be achieved by transmitting complex waveforms into the material, for example a waveform that is composed of the sum of two sine waves. Any non linearity will act to produce a multitude of frequency components in the spectra, called inter-modulation products. Considerable practical advantages can be made if only one transducer is used to transmit these complex waveforms. To achieve this, wideband transducers that are acoustically matched to the test material were developed that do not generate non-linear effects internally or at the point of contact with the concrete, these transducers were used in the experiments detailed in this paper.

Figure 2 Non-linear stress v strain

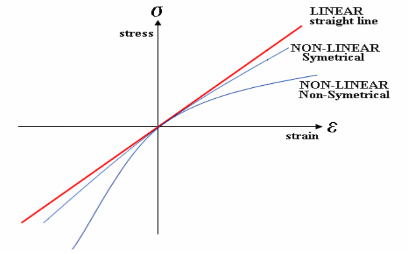
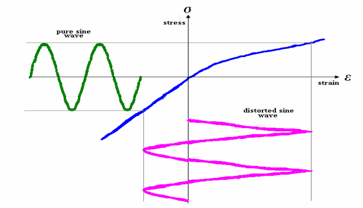


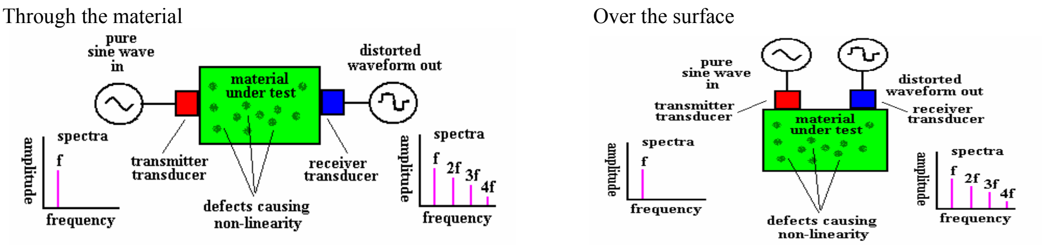
Figure 3 Waveform distortion



Harmonic generation

The simplest method in a practical system that measures non-linear effects in a material using acoustic waves is to measure the harmonics generated when a pure tone (pure sine wave) is transmitted through or over the surface of a material. This is illustrated below in Figure 4.

Figure 4 Harmonic generation



The harmonics are measured by examining the power spectra of the received signal. The transmitted frequencies (fundamental) amplitude is compared to that of the amplitudes of each of the harmonic frequencies. These harmonics are expressed in terms of decibels (dB) down from the fundamental, that is the number of decibels below the fundamentals amplitude. These values can be converted to a distortion factor that is expressed as a percentage.
Other non-harmonically related frequencies may also be generated by the sound wave, particularly in the presence of severe defects, these are called overtones and noise they result from acoustic emissions, hyteresis and other effects. Figure 5 below shows the photographs of two concrete test cylinders (size 300mm long, 150mm diameter).
Figure 6 below shows the results obtained by sending a 50 kHz sine wave over the surface of these two cylinders of concrete. The second harmonic generated in the severely cracked region is clearly visible and has a level of distortion above 1%. The third and fourth harmonics are not so prominent but have values above 0.5%. The undamaged concrete sample does not produce any clear harmonics and consists of noise predominately below 0.25%.

Figure 5
Concrete test cylinders

Cracked concrete

Undamaged concrete

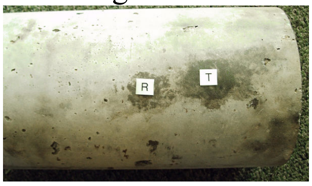


Figure 6
Harmonics generation over surface of concrete test cylinders

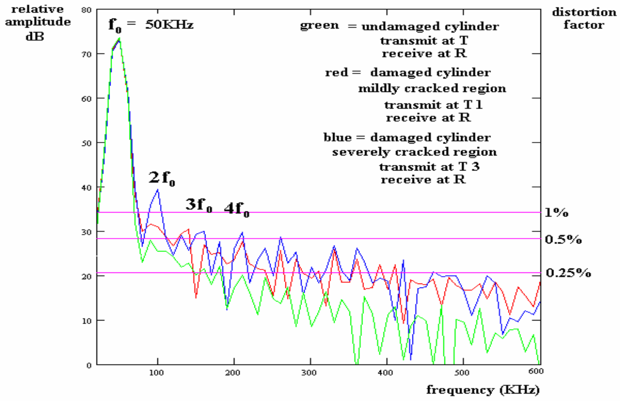
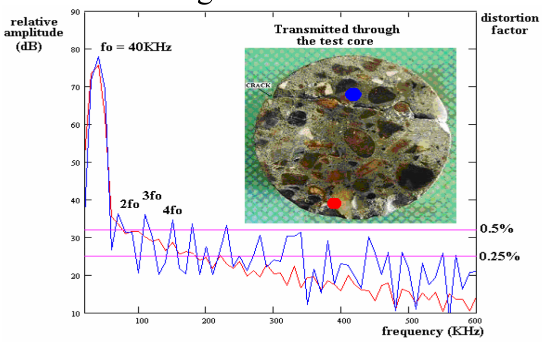


Figure 7

Transducers connected to a drilled core test sample

Figure 8 Harmonic generation-drilled core

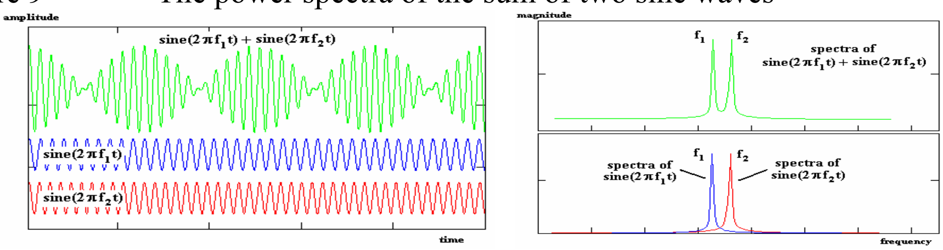


The photograph in Figure 7 shows a micro-damaged drilled test core with an ultrasonic transmitter on the right and a receiver on the left. The blue trace of the spectral plot in Figure 8 shows that transmitting and receiving in a line through the concrete close to the crack produces relatively high levels of 2^{nd}, 3^{rd} and 4^{th}, harmonics above 0.5%. Transmitting and receiving in a line away from the crack (shown in red) produces little harmonic content.

Inter-modulation.

If two sine waves of different frequency are added together the resulting power spectrum is unaltered, this is illustrated in Figure 9 below.

Figure 9 The power spectra of the sum of two sine waves



An ultrasonic wave composed of the sum of two sine waveforms of different frequencies, f1 and f2 with equal amplitude, can be represented by [sine(a) + sine(b)], where $a = 2\pi f_1 t$

and b = $2\pi f_2 t$. If this waveform is passed through a material that exhibits a square law stress-strain relationship. The resultant wave forms can be expressed as:-

$$\mathbf{A(t) = [\sin(a) + \sin(b)]^2}$$

by expansion this gives :-

$$\mathbf{A(t) = \sin^2(a) + 2\sin(a)\sin(b) + \sin^2(b)}$$

using the standard trigonometric identity formulae.... sin(a).sin(b) = ½ [cos(a-b) – cos(a+b)]
and noting that sine(a).sine(a) = ½ [cos(a-a) – cos(a+a)] = ½ [cos(0) – cos(2a)]
which becomes = ½ [1 – cos(2a)], since cos(0) = 1, then the expression for A(t) becomes:-

$$\mathbf{A(t) = \tfrac{1}{2}[1 - \cos(2a)] + [\cos(a - b) - \cos(a + b)] + \tfrac{1}{2}[1 - \cos(2b)]}$$

re-arranging

$$\mathbf{A(t) = 1 + \cos(a - b) - \cos(a + b) - \tfrac{1}{2}\cos(2a) - \tfrac{1}{2}\cos(2b)}$$

Figure 10 below shows a graphical representation of this process. Four distinct frequencies and one constant term are generated by this process, the frequencies are; the second harmonics of f_1 and f_2 that is ($2^* f_1$) and ($2^* f_2$). The sum and difference frequencies of f_1 and f_2, that is ($f_1 + f_2$) and ($f_1 - f_2$). The second harmonics are half the amplitude of the sum and difference frequencies. As there is a larger variation in the generation of the sum and difference frequencies these should provide greater sensitivity in the indication of non-linearity. If the sine wave sum is subject to non-linearity that is of a higher order than a square law stress-strain relationship then many other multiples, sum and difference combinations result, these will all appear in the spectra.

Figure 10 Inter-modulation products resulting from a sine sum waveform being subject to a square law distortion.

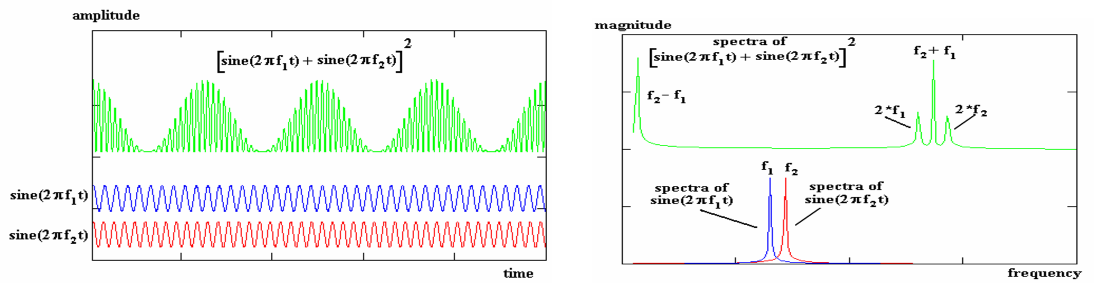


Figure 11 shows a photograph of the transmitter and receiver placed against a test sample cube of concrete (size 50x50x50mm). Two concrete test samples were selected and are shown in this figure, one has a crack running through its entire length, the other is undamaged. The transmitter comprises a single piezoelectric wide band actuator that is continuously sending the sum of two sine waveforms at pre-programmed frequencies.

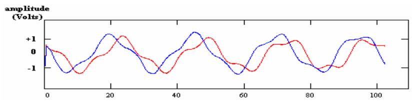
Figure 11

undamaged cube

damage cube

Figure 12

Dual frequency (40/120 kHz) spectra and time data plot of a good and damaged test cube



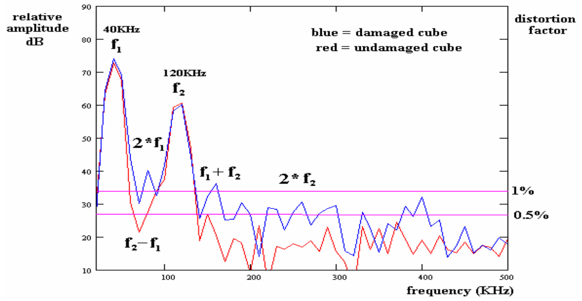


Figure 12 shows the time and spectrum plots for the received waveform having passed through each of the concrete test cubes. The difference in the amplitude of the two frequencies results from the ultrasonic attenuation of concrete being frequency dependent, losses are greater at higher frequencies.

The data for the damaged sample is shown in blue, and the good sample shown in red. The damaged sample shows clearly that harmonics and inter-modulation products have been generated by the crack. The upper side band ($f_1 + f_2$) at 160 KHz is below 0.5% for the good sample and rises above 1% in the damaged sample. The second harmonic of f_2 at 240 kHz changes from, -56dB (0.16%) in the good sample and rising above 0.5% in the damaged sample. The effect of the combinations of the harmonics and inter-modulation products are very noticeable in the frequency range 200 to 350 kHz. For example, $2f_2$ (240kHz), $2f_1+f_2$ (200kHz), f_1+2f_2 (280kHz) and $2f_1+2f_2$ (320kHz). The result is the formation of peaks and troughs within this range, corresponding to the interaction of their frequencies and phases, this effect can mask the changes between the good and bad samples. The correct choice of the two frequencies f_2 and f_1 is an important factor. Figure 13 illustrates this by showing the spectra resulting from two different frequency combinations, f_1+f_2 is reduced by the effect of the third harmonic of f_1 ($3*f_1$).

Figure 13 Dual frequency (40 / 95 kHz)

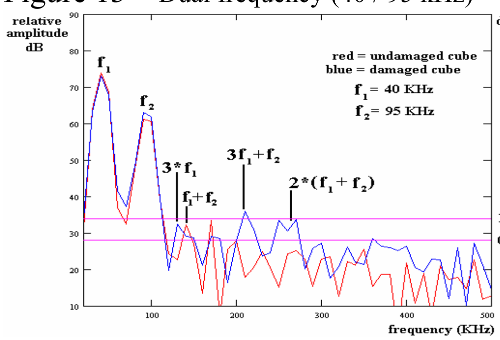


Figure 14 Dual frequency (40/70 kHz)

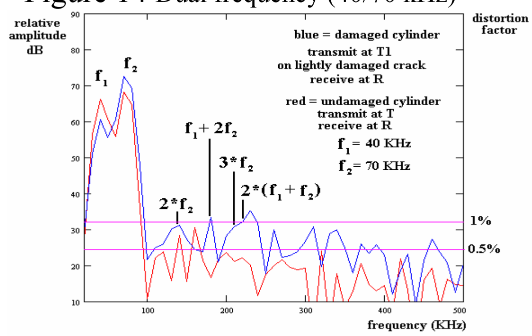


Figure 14 shows a spectral plot taken over the surface of a mildly damaged region of the concrete test cylinders, shown previously in Figure 4. This test was performed at the two frequencies 40 and 70 kHz. The two fundamental frequencies are not sufficiently separated to form clear spectral peaks, however the inter-modulation products and in particular the second multiple of f_1+f_2 that is $2*(f_1+f_2)$ shows a very clear peak above 1% distortion in the damaged region.

Figure 15 shows a dual frequency being applied to the micro-damaged drilled core. The dual frequency ultrasonic waveform was transmitted through the sample at two locations, one along the crack, shown in blue and the other away from the crack shown in red. The difference between the two locations is very clear. The cracked region produces harmonics and inter-modulation products well above 0.5% distortion factor and f_1+f_2 is above 1%. The less cracked region has all levels below 0.5% and for frequencies above 250 kHz is below 0.25%.

Figure 15 through test core

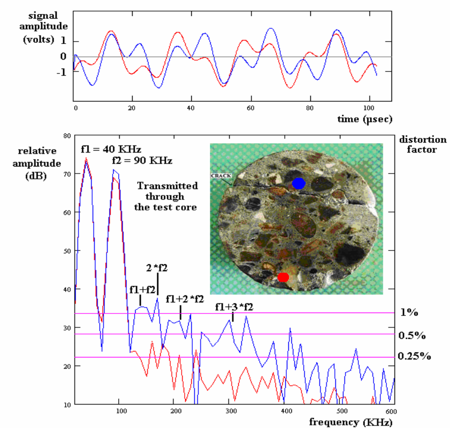


Figure 16 over surface of test core

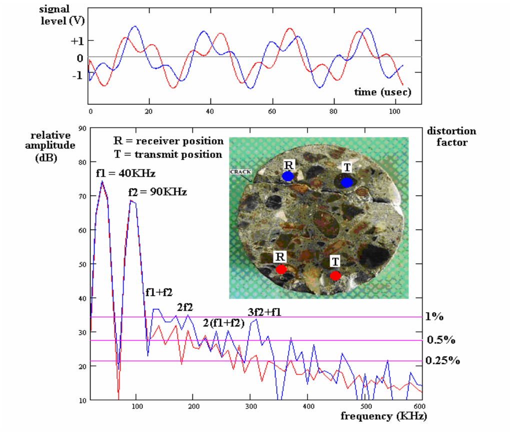


Figure 16 shows the same core but this time tested on one side only, the receiver positions are indicated by the letter R and the transmitter positions by letter T. The red trace corresponds to a position away from the crack and the blue near to the crack. There is less difference between the two positions at low frequency however at higher frequencies, above 300 kHz, the cracked region does produce a significantly higher levels of inter-modulation produces particularly at $3f_2+f_1$ (310 KHz).

CONCLUSIONS

Utilizing just two transducers, measurement of harmonic generation together with the production of inter-modulation products resulting from the transmission of an ultrasonic wave or the sum of two ultrasonic waves of different frequency, through or over the surface of a concrete test sample has shown to have the ability to detect cracks and micro-cracks.The method indicates that it can provide a quantitative measurement of the non-linearity of the concrete and thereby giving a measure of the degree of damage.

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