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DETAILED FEATURE EXTRACTION FROM CONCRETE MEDIA USING MEDIUM FREQUENCY ULTRASOUND AND DIGITAL SIGNAL PROCESSING METHODS

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ABSTRACT

This paper describes the manner in which ultrasonic pulses travelling through concrete are generated, received and processed using piezoelectric transducers and digital data acquisition apparatus. Because of the highly attenuating nature of this medium and its differential effects on the frequency composition of broad-band signals, time domain analysis alone cannot provide sufficient information regarding the properties of the specimen under test. By partitioning the signal into discrete windows in the time domain, corresponding to the emergence of individual wave phenomena within the medium, and by then transforming these windows to the frequency domain, wave components relating to specific processes may be isolated and examined. Experimentation suggests that the emergence and decay of discrete frequency bands depends both upon the nature of the concrete, termed the resonance phase, and its external geometry, termed the geometric phase. The findings of this work have considerable importance with respect to the ultrasonic inspection of concrete.

1. INTRODUCTION

Ultrasonic inspection of concrete has traditionally been limited to simple measurements conducted in the time domain, such as the time required for a pulse to travel through a known distance or depth of the material. Since the velocity is related to the strength of concrete, the pulse-velocity technique has been established as possibly the only standard technique of non-destructive testing of concrete using ultrasonic methods. Pulse-echo techniques, which provide detailed information regarding the internal defects in materials whose composition is homogeneous with respect to the wavelength, are unsuitable for use with concrete [1]. Concrete is so inhomogeneous in its composition that the scatter of ultrasonic waves normally precludes the use of frequencies extending beyond 150 kHz. These low frequencies cannot provide sufficient spatial resolution for conventional imaging purposes.

However, the need to develop an ultrasonic inspection system capable of providing information not only with respect to the internal integrity of the concrete but also the condition of any steel reinforcing components, led to the detailed analysis of the waveforms that were received having travelled through concrete samples and structures of various types. Here we describe the methods that were used to insonate the concrete specimens, the manner in which waveforms were processed to reveal the contributions of the different mechanisms responsible for the changes to the original signal, and the way in which the spectral components were interpreted to reveal the presence of defects within the specimens.

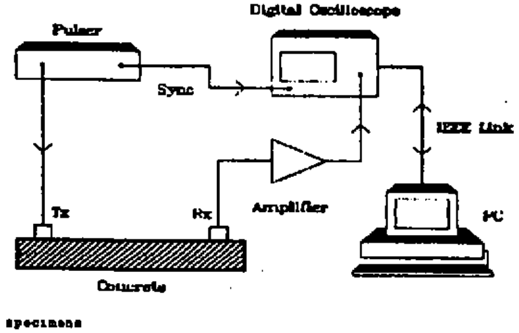

Figure 1 Experimental configuration used to inspect concrete specimens

2. EXPERIMENTAL SYSTEM

The experimental configuration that was adopted to acquire the ultrasonic signals varied according to the test being conducted, but a typical arrangement is shown in Figure 1. Here, a piezoelectric transmitting transducer was coupled to the surface of a concrete specimen using a medium-grade petroleum based grease. The transducer was excited to resonance by a Steinkamp pulser unit, having an excitation voltage of 600 V and a pulse repetition frequency of 1 Hz. The receiving transducer was connected to a low-noise amplifier and thence to the input of a Schlumberger 5602 digital storage oscilloscope. The oscilloscope was triggered to sample the data by a synchronization signal generated by the pulser, which coincided with the probe excitation pulse. In order to improve the signal-to-noise ratio, especially where weak signals were concerned, waveform averaging was performed. Once digitized, the data were transferred via an IEEE interface to a microcomputer for processing and storage. This kind of experimental configuration has been used by several researchers for similar purposes [2,3]. In later experiments, the oscilloscope was replaced by an Analogic 6100 waveform analyzer, which also performed the signal analysis. In this case, the PC was used as a system supervisor and storage unit, but the method of analysis remained essentially the same. The use of this processor did, however, greatly improve the speed of the system.

Transducers normally employed for the inspection of concrete generate frequencies that are too low to provide detailed information with respect to the internal composition of the material. Typically, concrete propagates longitudinal waves at a velocity of approximately 4,000 m/s (although this will vary according to concrete properties), and at 100 kHz, the wavelength is 40 mm. By comparison, the inspection of steel components is normally carried out using wavelengths lying between 1.2 and 0.6 mm. For this reason it was decided that ultrasonic probes with frequencies extending to 500 kHz would be used. Although at these frequencies attenuation plays a dominant role in limiting the signal-to-noise ratio, sophisticated analysis and filtering enabled useful information to be extracted. A considerable amount of preliminary experimental work was conducted in order to determine the optimum choice of transducer. A range of transducers was investigated, having centre frequencies ranging from 40 to 500 kHz. With the exception of a pair of rolling transducers which had essentially point-contact with the concrete surface, all of the probes were disc-shaped with radii ranging from 10 to 20 mm None of the transducers oscillated monotonically; instead they generated a range of frequencies about a centre frequency whose value was governed by the nominal resonance of the crystal, by the backing material and by the filtering effects of the concrete.

3. LOSS MECHANISMS: SCATTERING AND ABSORPTION

In addition to the losses arising from divergence, a signal will experience attenuation as a result of absorption and scatter, these being frequency-dependent phenomena. Ultimately, attenuation losses are thermal in nature, and for a given medium and frequency the general function which describes the pressure, p_t, at a distance is given by:

$$p_t = p_0 e^{-\alpha x} \quad (1)$$

where α is the coefficient of attenuation [4]. Signal scattering is a highly complex process, depending upon mean particle diameter in relation to the wavelength, the number of particles per unit volume of the medium, and the acoustic properties of these particles which distinguish them from the medium. When the diameter of the particles is small in comparison to the wavelength, Rayleigh scattering occurs [5] whereby each particle acts as a spherical radiator. In this case, the scattered amplitude is proportional to the fourth power of the frequency, and the coefficient of attenuation becomes:

$$\alpha = 0.4\left(k\overline{D}\right)^4 \pi \overline{D}^2 N \quad (2)$$

where k is the wave number, given by $2\pi/\lambda$, D is the mean particle diameter, and N is the number of particles per unit volume.

In the Rayleigh region however, the absorption coefficient increases linearly with frequency. Hence the total attenuation coefficient is given by the general relationship:

$$\alpha(f) = a_1 f + a_2 \overline{D}^3 f^4 \quad (3)$$

where a_1 is the absorption coefficient and a_2 is the scattering coefficient.

In the stochastic region, where the particle size is approximately equal to the wavelength, the scattering is proportional to the square of the frequency:

$$\alpha(f) = b_1 f + b_2 \overline{D}^2 f^2 \quad (4)$$

Finally, in the diffusion region where the wavelength is much smaller than the mean particle size, the scattering coefficient is given by:

$$\alpha(f) = c\overline{D}^{-1} \quad (5)$$

In concrete, all forms of scattering mechanisms occurred in the tests since the frequencies examined ranged from near DC to several hundred kHz, with grain sizes ranging from less than 1 up to 25 mm.

4. TIME AND FREQUENCY DOMAIN SIGNAL PARTITIONING

Given that ultrasonic pulse-echoes systems are unsuited to the inspection of concrete structures, there is nevertheless a great deal more information that can be extracted than simple time-of-flight measurements. Heuristic models developed by Saniie and Bilgutay [5], which characterize the back-scattering contributions from Rayleigh scatterers, show how the signal can be segmented into discrete units relating to both time and depth. Although we are concerned here with not just Rayleigh scattering but also with stochastic and diffusion mechanisms, the principle is still wholly applicable. Furthermore, it can be applied not only to back scattered but also to forward scattered signals. Assuming that the beam spread is much greater than the particle size, and that the scatterers lie in the far field region, then the received signal $r(t)$ can be partitioned into fixed time intervals $r_j(t)$ corresponding to fixed spatial intervals, ie, lengths, within the sample:

$$r(t) = \sum_{j=1}^{q} r_j(t) \quad (6)$$

where $r_j(t)$ represents the signal corresponding to the jth region and q is the number of regions. Similarly, it can be shown [6] that the summation of the discrete-time counterpart of the unit impulse function, $d[n]$, can be used to build *any* discrete signal. Thus the term $r_j(t)$ in Equation (6) can be expanded to:

$$r_j(t)=\sum_{k=1}^{n} r_j(k)\delta(t-k) \qquad j=0,1,2..q \tag{7}$$

In this form the signal $r(t)$ is determined by the spectral characteristics of the transducer and the filtering effects of the medium. In our work we have shown that the composite signal detected consists of two quite distinct phases, which we have termed:

1. the resonance phase, characterized by the original output and the effects of the internal conditions of the medium on the signal, ie, $r(t)$; and
2. the geometric phase, $g(t)$, in which the frequencies generated are governed by the dimensional properties of the specimen.

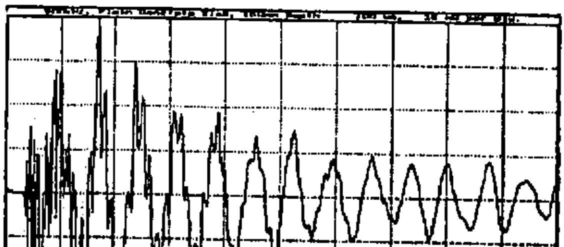

Figure 2a Signal transmitted and received by matched ultrasonic transducers propagating through a 150 mm thick concrete slab, 700 mm square

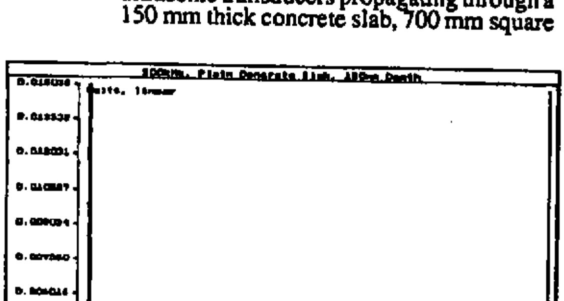

Figure 2b Fourier spectrum of signal shown in Figure 2a

As an example, Figure 2a shows the first 1,024 μs of a signal that was obtained when two matched transducers, with a nominal resonance of 500 kHz, were mounted centrally on either face of a concrete slab, measuring 700 mm square by 150 mm depth. The corresponding spectrum is shown in Figure 2b. It contains no high frequency harmonics of any significance, due to the strong attenuating and scattering effects of the concrete. However, Figure 2a also shows that the last 500 μs of the signal contain predominantly low frequencies, whereas the initial 50 s contain in addition higher frequencies. It is important to note that the low frequencies also extend to the initial phase of the waveform, ie, the high frequency harmonics are superimposed on the lower ones.

If we now partition the signal to include only the first 100 μs, the spectrum obtained is very different, as shown by Figure 3a. The high frequency band is clearly in evidence, and is now much stronger in relative terms, when considering the low frequency band at 14 kHz, which is nevertheless still present. This confirms that the low frequency phase extends for the duration of the signal. However, if the signal is partitioned to include only the remaining 400 s, then

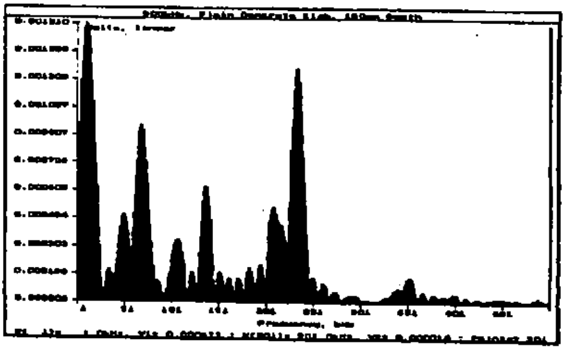

Figure 3a Fourier spectrum of first 100 μs of signal shown in Figure 2a - the resonance phase

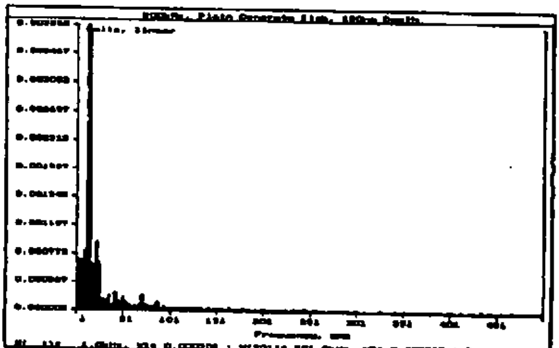

Figure 3b Fourier spectrum of last 400 μs of signal shown in Figure 2a - the geometric phase

the spectrum, shown in Figure 3b, shows only low frequency harmonics.

Alternatively, to demonstrate the concentration of different frequencies in different parts of the signal, the waveform shown in Figure 2a can be filtered in the frequency domain to leave only those harmonics above 200 kHz. Once the inverse transform has been obtained, a signal is derived which is shown in Figure 4a. In this case the high frequencies are concentrated towards the initial part of the waveform and decay rapidly with time. This signal represents that part of the waveform known as the resonance phase. By contrast, if the composite signal is filtered (again in the frequency domain) to leave only those frequencies below 30 kHz, the signal produced appears as in Figure 4b, ie, this constitutes the geometric phase.

Now a solid plate of thickness l and longitudinal wave propagation velocity c has a fundamental half-wavelength thickness-mode resonant frequency given by:

$$f = \frac{c}{2l} \qquad (8)$$

In this case, the concrete slab has a thickness of 150 mm and a value for c of 4,285 m/s. The f_0 value should therefore be 14.23 kHz, a figure which is very close to the value of 14 kHz shown by the dominant harmonic in the geometric phase spectrum. Although the geometric phase in this instance is characterized by thickness mode vibrations, the general nature of this low frequency signal will depend upon the dimensions and physical properties of the sample thus insonated. Sansalone and Carino [7,8] for instance, have reported the use of mechanical impact devices to generate acoustic frequencies which revealed the presence of laminar defects within concrete test slabs. However, what is of significance is that ultrasonic probes can be used for more than just this purpose, albeit with greater temporal precision. Time and frequency domain partitioning is a technique that has seen some application in the field of acousto-ultrasonics [9], and has yielded significant results in the analysis of laminates and reinforced composite materials. For the general case therefore, the signal in the time domain, given by $x(t)$, can be described by:

$$x(t) = r(t) + g(t) \qquad (9)$$

Each phase will decay over time, and the coefficients for the decay of the resonance and geometric phases are given by $e^{-\alpha t}$. If $R(t)$ represents the resonance phase in the absence of any decay, and $G(t)$

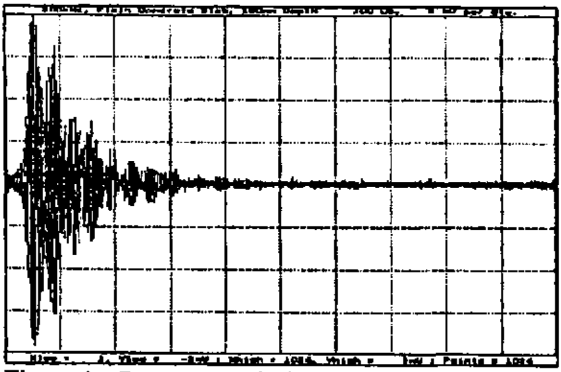

Figure 4a Reconstructed signal of Fourier-filtered signal shown in Figure 2a, leaving only harmonics extending beyond 200 kHz

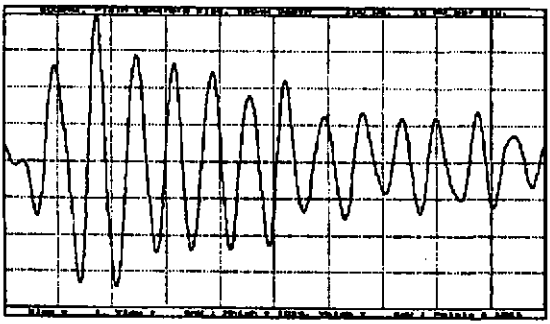

Figure 4b Reconstructed signal of Fourier-filtered signal shown in Figure 2a, leaving only harmonics extending below 30 kHz

represents the same for the geometric phase, the signal $x(t)$ is described by:

$$x(t) = e^{-a_r t}R(t) + e^{-a_g t}G(t) \qquad (10)$$

5. DEFECT IDENTIFICATION THROUGH SPECTRAL ANALYSIS: SYSTEM OPERATION

In practice, the system operates with 400 kHz rolling transducers which move long the surface of the concrete beam to be analyzed, firing and receiving pulses at regular intervals. Consider then a 5 m concrete beam, which is interrogated every 5 cm. One hundred waveforms will be acquired, ie, $x_1[n]$ to $x_{100}[n]$ (each waveform comprises 512 data points, ie,. $n = 1..512$). Each waveform is then transformed to the frequency domain and the energies in eight bands are calculated. The energy of a band in the frequency domain can be calculated using the equation:

$$E = t.\left(\tfrac{1}{2}\sum_{\omega=m}^{n}[X(\omega)]^2\right) \qquad (11)$$

where $X(\omega)$ is the amplitude at that frequency. The bands that are calculated are 50 kHz in width and range from 0 - 50 kHz, to 350 - 400 kHz. The energy for the first band of the first waveform we label $E_{1,1}$. The energy for the second band of the first waveform we label $E_{1,2}$ etc. Hence for each waveform, we calculate eight separate energy values. The way in which we combine the energies for each waveform determines the kind of defect that can be detected, since the scattering equations show that the amount of energy scattered (and hence received) is determined by the dimensional relationship of the wavelength and scatterer. For instance, if a major void was being sought, the energies in each band for a given waveform are simply multiplied together (an operation similar to cross-correlation), since all bands will show greater energy levels due to reflection. In this case, We wish to synthesis a new function Z(k), which represents the combined (multiplied) energies as a function of the scan position. Hence if k represents the scan number (from 1 to 100), and m represents the energy bands from 1 to 8, then we have the equation:

$$Z[k] = \prod_{m=1}^{m=8} E_{k,m} \qquad k = 1..100 \qquad (12)$$

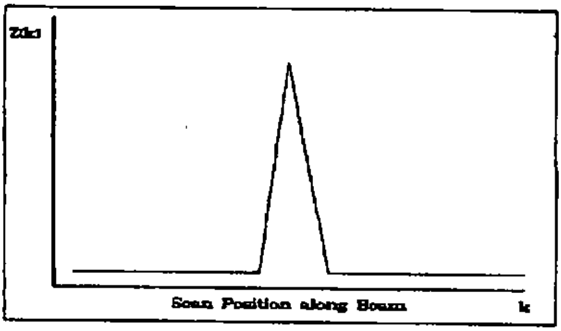

Figure 5 Typical processed signal returned from void-like defect in concrete

A major void in the middle of the beam, would be revealed by plotting $Z[k]$ against k, as shown in Figure 5. If smaller defects are being sought, such as areas of delamination due to the corrosion of steel reinforcing components, then experiment has shown that only high frequency components respond. In this case, we use the energies of the low frequency bands to correct for coupling variation, by taking the ratio in the following manner:

$$Z[k] = \frac{\sum_{n=p}^{n=8} E_{k,n}}{\sum_{m=1}^{m=p-1} E_{k,m}} \qquad (13)$$

Once the method of signal processing has been established, the computer based DSP was be replaced with a dedicated signal analyzer. In the final prototype, the analyzer performed the data acquisition and DSP, and the computer acted as system supervisor, informing the analyzer what operations it should perform and acting as a mass storage device for the data.

6. DISCUSSION.

Although concrete is a medium which attenuates ultrasound through a variety of scattering and absorption mechanisms, it is not attenuation through absorption (ie, thermal loss) but attenuation through scatter and divergence which precludes the use of pulse-echo systems. Furthermore, the wavelengths of frequencies that can be used are too long to provide sufficient spatial resolution for imaging purposes. This does not mean that no information can be obtained other than through ultrasonic pulse velocity measurements. We have established that the energy contained within the various frequency bands changes considerably according to the internal structure of the concrete. However, in order to detect this it is necessary to partition the signal into discrete time bands since the frequency content also changes with time.

Regarding the geometric phase of the signal, this is essentially transducer-independent and is by definition a function of the dimensional geometry of the specimen. In the tests that we have conducted, the geometries have been simple and the vibrational modes can be described by simple mathematics. In most cases however, the geometries will not be of this kind and as a result these vibrations would include a number of superimposed waveforms in the time domain. Fortunately, they would always correspond in wavelength to some multiple of the dimensions involved, and unless the sample was very small, a considerable difference in the frequencies of the resonant and geometric phases would be evident. In addition, It would also be expected that the geometric phase would extend for the duration of the signal, but the resonance phase would attenuate rapidly with time.

7. CONCLUSION

The manner in which the current system locates defects within the concrete matrix is based upon the knowledge that the received frequency spectrum of the material is dependent upon it internal structure; significant changes to the constituent parts of the spectrum in turn imply changes in that structure. Furthermore, by filtering the signal in the frequency domain it is clear that information can be obtained from high frequencies not normally associated with the inspection of this kind of material.

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