RECENT DEVELOPMENTS IN CONCRETE NONDESTRUCTIVE EVALUATION

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ABSTRACT

Concrete is a multi-phase composite material which is difficult to inspect using conventional ultrasonic techniques, including those that work well on relatively homogeneous materials such as metals. This paper summarizes recent research that makes use of signal processing techniques to overcome ultrasonic inspection difficulties in concrete. Basic findings from several new laboratory-based NDE techniques for concrete are reported. First, the application of split spectrum processing (SSP) is described. The SSP techniques obtains a frequency-diverse ensemble of narrowband signals through a filterbank and recombines them nonlinearly to improve the target visibility. Examples that demonstrate the capability of SSP to reduce coherent noise (clutter) in ultrasonic signals collected from concrete samples are presented. Next, a self-compensating procedure for practical one-sided surface wave transmission measurements on concrete structures is described. The utility of the technique is demonstrated by sensitivity to surface-opening crack depth in concrete slabs. Finally, an approach by which the setting process (stiffness change) in concrete is nondestructively monitored is described. The reflection factor of shear wave pulses at a steel-concrete interface is measured, from which the stiffness change (setting) of the concrete is inferred.

1. INTRODUCTION

Due to the complex nature of its microstructure, nondestructive testing (NDT) of concrete inherently imposes many challenges, which can cause severe limitations to both the resolution and sensitivity of the observed signals. With the advent of inexpensive and relatively powerful desk-top computers, digital signal processing techniques have become an integral part of non-invasive medical and industrial applications. In this paper we will examine several key signal processing techniques that have been applied successfully to the inspection of concrete. The initial results obtained from such applications point to the potential for development of more effective means for inspection of concrete in future applications.

2. SPLIT SPECTRUM PROCESSING

The use of high-frequency ultrasound is desirable in many areas of testing because of its superior beam directivity and lateral resolution characteristics. However, concrete testing is usually restricted to frequencies of $150KHz$ or less to avoid high levels of coherent (microstructure) noise, which can often mask the target signals. This type of coherent noise cannot be reduced by conventional techniques such as time averaging. However, the interference pattern characterizing ”structural noise,” which is comprised of echoes from many unresolvable reflectors, is highly sensitive to changes in the transmitted ultrasonic frequency. Whereas, the echoes from targets that are larger than the ultrasonic wavelength are far less sensitive to such frequency shifts, which allows for the dramatic improvement in target visibility when the resulting frequency diverse signals are appropriately combined.

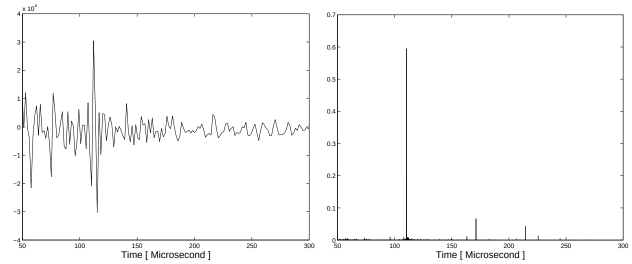
One implementation of this principle is the Split Spectrum Processing (SSP) technique [1], where the spectrum of the wideband ultrasonic backscattered signal from the test sample is decomposed into an ensemble of narrowband spectra by n equally spaced Gaussian bandpass filters. The inverse FFT of the n narrow band spectra yields a time-domain frequency-diverse signal ensemble. The process of splitting the wideband spectrum is equivalent to using n different narrow-band transducers spanning the passband of the transducer. Subsequently, the ensemble of narrow band signals are re-assembled using appropriate algorithms to form a single output signal. If a sufficient number of filters over a proper range of frequencies are used, the splitting process effectively decorrelates the ”structural noise” components, while retaining the phase coherence of the dominant reflectors such as voids and cracks. Thus, proper reassembly of the signal ensemble suppresses structural noise with respect to the target echo, resulting in signal-to-noise ratio enhancement. The recombination of the frequency-diverse ensemble can be achieved by a variety of schemes [1] [2], of which the minimization and polarity thresholding algorithms were found to be the most effective. The minimization algorithm selects, at each time instant t, the minimum absolute value from the ensemble of decorrelated signals, with magnitudes normalized to unity; i.e.,

$$y(t) = min\{|r_i(t)|; i = 1, 2, ..., N\} = r_{min}(t) \qquad (1)$$

Since the echoes from the randomly distributed scatterers are now decorrelated (i.e., large amplitude variance) while target echoes remain correlated (i.e., small amplitude variance), low $y_{min}(t)$ values at time instants t indicate the likely presence of noise, while large $y_{min}(t)$ values are likely to be target signals not reduced significantly by frequency change. The polarity thresholding algorithm is based on the principle that at time instants where target signal is present, the corresponding SSP data set will not exhibit any polarity reversal since the flaw signal will dominate the microstructure noise (i.e. all the elements of the corresponding column will have the same polarity). However, if the data set contains only microstructure noise, which is zero-mean, then it is likely that the data will exhibit polarity reversal. Therefore, by setting the amplitude of the processed signal to zero at time instants where polarity reversal occurs, while maintaining the original value of the unprocessed wideband signal when the data has identical polarity, the microstructure noise level may be reduced significantly.

The critical processing parameters are the bandpass filter bandwidth and spacing, and the spectral range spanned by the filters. The set of parameters that produce optimum or near optimum re-assembly for a given sample and test conditions are obtained initially by repeated trial-and-error. Although this process yields good results, it is highly desirable to develop adaptive techniques, which can determine the processing parameters automatically, thus requiring little expertise on the part of the user.

Application of SSP using both the minimization and the polarity thresholding algorithms have produced significant enhancement in target visibility in titanium and stainless steel samples. More recently, SSP has also been applied successfully to test concrete. Although some excellent experimental results have been obtained with concrete, in general the relatively severe attenuation of high frequencies in concrete compared to metals imposes a higher limitation on the expected improvement in signal-to-noise ratios. Due to the composite and viscoelastic nature of concrete [3], the optimization of the SSP parameters is more difficult. Our experimental work with concrete has led us to the following findings: the variation of components in concrete is greater compared to metals; the structural dimensions vary to a greater extent; due to limited signal bandwidth, decorrelation of structural noise is more limited in concrete; and the optimal SSP parameters are dependent on the type of concrete.



(a) (b)

Fig. 1. (a) Unprocessed Signal. (b) Minimization Output.

2.1. Experimental Result

The experiment presented here was performed to examine the thickness of a mortar prism whose dimensions are $203 \times 203 \times 95$ mm^3. The aggregate cement mass ratio is 8 with 4.5 mm maximum particle size. The density of the concrete is approximately 2.0 g/cm^3. Moreover, the aggregate is concrete sand with quartz and the wave velocity is experimentally determined as 0.36 cm/μsec. Experimental result is obtained in the pulse-echo mode in the longitudinal direction using contact transducer with 0.9 MHz center frequency and 1.00 inch diameter. Each A-scan is obtained using a sampling frequency of 12.5 MHz and is time averaged 1000 times. 14 sets of data are collected from different locations on the sample in order to achieve spatial diversity. Our goal is to achieve both spatial diversity and frequency diversity, which will further improve the results. Consequently, each data set is processed using split spectrum processing technique and minimization outputs are obtained for each data set. The SSP filtering is achieved in the first half of the spectrum, and the filter spacing is set to the minimum value. The optimization of the filter bandwidth required only couple of trials. The individual SSP minimization results were combined by using minimization technique on the spatially diverse data. Fig. 1(a) shows the received signals before processing, while the final minimization output is shown in Fig. 1(b).

The thickness of the specimen can now be obtained accurately from the corresponding time of flight measurement, which is 113 μsec. This process suppresses the scattering noise from the aggregates, while the backsurface echo gets stronger.

3. SELF-COMPENSATING SIGNAL TRANSMISSION MEASUREMENT

A one-sided, self-calibrating surface wave transmission technique for detection of cracks in concrete is now described. This technique eliminates some of the problems that were encountered when using through-thickness ultrasonic transmission measurements. The hardware used to measure one-sided wave signal transmission consists of a controlled impact based stress wave source, two receiving accelerometers, a digital oscilloscope, and a personal computer. The two receivers are located on the surface of the test specimen along a line with the source, away from the impact site. Two stress wave sources and two receivers (accelerometers) are placed on the surface of the specimen along a line that straddles the crack, as shown in Fig. 2. Transient stress waves, which are generated by the source propagate along the surface of the specimen, first passing Receiver 1 and then Receiver 2.

Only the direct surface-bounded wave components and the first L-wave reflection from the opposing side of the specimen are captured within the time window. Next, the impact source is applied at location D and the entire data collection procedure is repeated. As a result of the data collection, a total of four signals are obtained. In the frequency domain, we can represent a stress wave signal sent by the source at location A and received by the nearest accelerometer at location B as a simple product of terms

$$V_{AB} = S_A d_{AB} R_B \tag{2}$$

where V_{AB} is the FFT of the captured time domain signal, S_A the generating response term, R_B the receiving response term, and d_{AB} the signal transmission function between locations A and B [4]. We are interested in determining d_{BC} by eliminating the R_i, S_i and extraneous d_{ij} terms. This can be accomplished by collecting an appropriate set of wave signals sent along the receiving accelerometer pair along the same line. Simple manipulation of the V_{ij} terms results in an expression for the transmission between locations B and C

$$d_{BC}(f) = (V_{AC}V_{DB}/V_{AB}V_{DC})^{0.5} \tag{3}$$

d_{BC} is a function of frequency and can be visualized as the ratio of the amplitude of the signal from the far accelerometer to that of the near accelerometer. Thus, a transmission value of 1 indicates no amplitude loss (complete transmission) as the wave propagates between points B and C, whereas a value of 0 indicates complete signal amplitude loss (no transmission). Standard wave transmission or attenuation measurements are inappropriate for concrete because of the difficulties associated with the sensor and coupling variations. However, d_{BC} does provide an accurate estimate of wave transmission in a practical manner because of the self-compensating scheme. The sensitivity of d_{BC} measurements to the depth of surface-breaking cracks in concrete is demonstrated.

Transmission measurements were performed on a free $10cm$ thick concrete slab under three different path conditions between the accelerometers at B and C: across an undamaged path, across a 1 cm deep notch cut into the surface, and across the same notch after the slab was subjected to flexure until a crack emanating from the notch propagated several cm into the slab. Fig. 3 shows the obtained signal transmission curves within a frequency range of 0 to 200 KHz for the three cases. Clearly, d_{BC} suffers a severe reduction in value for nearly all frequencies when the surface waves pass across the notch. A further reduction in all frequencies is noted when cracking is introduced additionally to the surface wave path. Thus, d_{BC} is sensitive to the presence of near-surface damage in concrete. Further, this technique has been successfully applied to monitor the depth and propagation of a surface breaking crack [5].

4. SHEAR WAVE REFLECTION FACTOR MEASUREMENT

An approach by which the setting process (stiffness change) in concrete is nondestructively monitored is described. The reflection factor of shear wave pulses at a steel-concrete interface is measured, from which the stiffness change (setting) of the concrete is inferred. Freshly mixed concrete is placed in a mold. A transducer excites and receives ultrasonic wave pulses from the steel form or a steel plate embedded in the concrete. The reflections at the steel-concrete interface are recorded. When concrete is placed in the mold, it is in a plastic state that resembles a fluid. According to wave mechanics, a shear wave traveling through metal that is incident upon a steel-water interface is entirely reflected. Thus, at early ages most of the wave energy is reflected and the amplitude of the received wave is large. As the concrete stiffens, more of the wave energy is transmitted through the concrete and less is reflected at the interface. The process of wave reflection can be quantified using a wave reflection factor (WRF) that defines the ratio of the amount of incident wave energy that is reflected from an interface between the two materials [6]. A plot of the typical variation of the wave reflection factor as a function of time is shown in Fig. 4. The WRF is measured continuously after casting up to 48 hours. The temperature is also monitored throughout the hydration process using a disposable thermocouple inserted in the concrete. The temperature profile for the same concrete mixture is also shown in Fig. 4.

It can be seen that significant changes in the early response of the WRF coincide with distinctive stage of hydration indicated by the temperature change. After five hours, the concrete begins to stiffen noticeably. This corresponds to the end of the induction period. The exothermic reaction starts and a stable cement matrix begins to coalesce. There is a noticeable kink in the WRF response at this time and the temperature begins to increase. This point in time correlates well with the set time for concrete containing various admixtures, determined using the pin penetration tests. Afterwards, there is a steady, almost linear decrease in the WRF. This indicates that the observed trends in the WRF are owing to the change in the mechanical properties of concrete.

5. SUMMARY

The presented results demonstrate the utility of signal processing techniques for NDE data obtained from concrete. The methods are shown to be robust and may be used to monitor the condition of concrete structures. Specifically, we conclude the following. SSP has been successfully utilized to inspect concrete using ultrasound in the MHz range and promises to be a practical approach for improving the present capabilities for NDT of concrete. However, for optimal utilization of SSP it is desirable to develop methods that can automatically select the processing parameters, which is the current focus of our work. One-sided elastic wave signal transmission measurements may be applied reliably to an unprepared surface of concrete and are sensitive to the depth of cracks in concrete. The WRF technique can monitor the setting and hardening of concrete since the trends in WRF are sensitive to physical phase changes in the concrete.

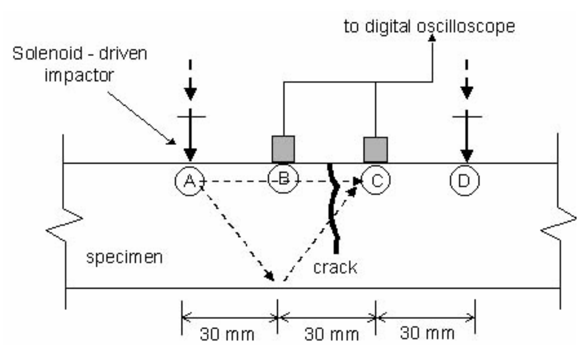


Fig. 2. Experimental setup for wave transmission measurement.

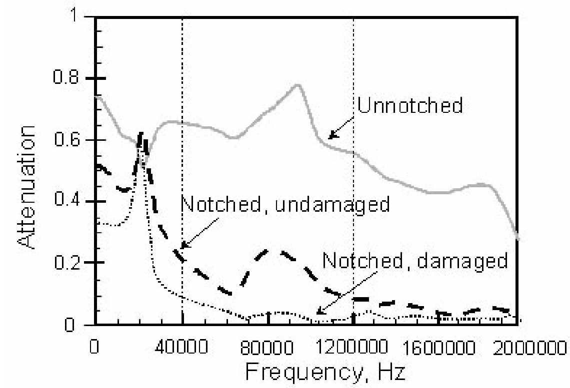


Fig. 3. Experimentally obtained surface wave transmission from a 102mm thick concrete slab with varying damage conditions.

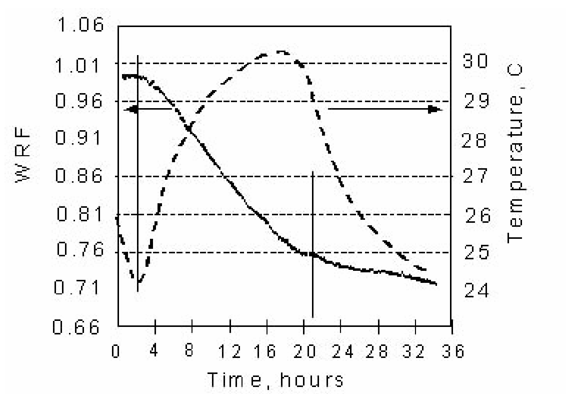


Fig. 4. Typical WRF response and temperature change measured during the first 36 hours after casting.

6. REFERENCES

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