AN INTELLIGENT ELECTRICAL TIME DOMAIN REFLECTOMETRY SYSTEM FOR THE DETECTION AND CHARACTERISATION OF FAULT CONDITIONS IN POST-TENSIONING DUCTS OF SMART CONCRETE STRUCTURES

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INTRODUCTION

In civil engineering structures involving prestressed concrete, the use of post-tensioned systems is very common. Post-tensioning is achieved by passing steel cables into ducts previously cast into the concrete. When the concrete has set, the cables are tensioned with hydraulic jacks and then sealed into the duct by pumping in a slurry of cement and water, called grout. The grouting mixture, being alkaline in composition, protects the steel cable from corrosion.

It is clear that if there are voids in the grouted section, such areas of voids may, with time, become filled with water which will lead to corrosion in the steel tendon. If this occurs in an area where de-icing salts are used on the roads in the winter, this corrosion is likely to be more rapid in its action. Corrosion leads to a reduction in the tensile strength of the tensioned cable and, in extreme cases, may lead to catastrophic failure of the structure[1]. From the foregoing, it is apparent that the detection and characterisation of voids in ducts carrying prestressing cables in post-tensioned concrete structures is very important for safety monitoring.

Many approaches for effecting this monitoring are currently in use, based on x-ray[2], ultrasound[3] and electromagnetic[4] scanning. All these methods have one common

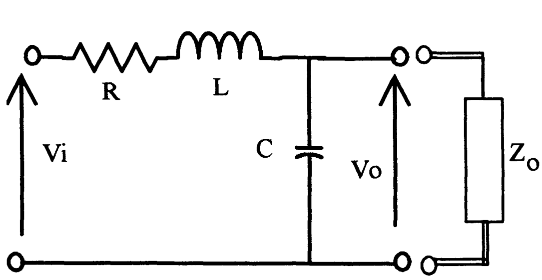

Figure 1. Lumped parameter equivalent circuit of a transmission line.

drawback: they depend on scanning incremental sections of the structure under test. This, inherently, is a slow process and whole sections of highways must necessarily be shut down in order to carry out such inspections. The Electrical Time Domain Reflectometry (ETDR) system presented in this paper holds the possibility of facilitating fast inspection of duct/cable systems in post-tensioned concrete structures.

THEORY

In ETDR, an electrical pulse is fired along a cable. Reflections of this pulse due to impedance mismatches along the cable are then captured and analyzed to obtain more information about the nature of these impedance variations. A lumped parameter equivalent circuit of such a line is shown in Figure (1), with Z_o being the equivalent impedance of the line to ground. This circuit is applicable to a 'well-behaved' line, i.e. a line with homogeneous constitution, and which is parallel to the ground conductor[5].

It can be shown that, for the circuit,

$$Z_o = \sqrt{\frac{R+j\omega L}{j\omega C}}. \tag{1}$$

For small series losses, $Z_o = \sqrt{(L/C)}$, and V_p, the propagation velocity of the wave, is given by

$$V_p = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\epsilon\mu}}. \tag{2}$$

Here, ε is the dielectric constant, while μ is the permeability of the material between the line and ground[6]. In vacuum, ε is equal to 8.854×10^{-12}F/m, and μ has a value of $4\pi \times 10^{-7}$ H/m. This makes V_p equal to c, the speed of light. The two quantities Z_o and V_p form the centre of focus in most work involving electrical time-domain reflectometry.

Reflection

For the transmission line shown in Figure(2),

$$\frac{v_i}{i_i} = z_i, \quad \frac{v_t}{i_t} = z_t, \quad \frac{v_r}{i_r} = -z_i. \tag{3}$$

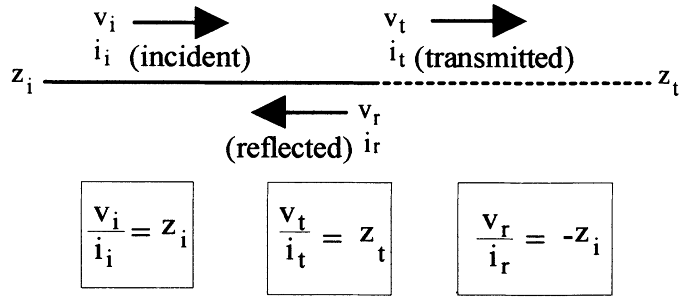

Figure 2. Wave reflection in a transmission line.

The negative sign on the reflected wave is indicative of the fact that the reflected wave has a 'negative' velocity.

The reflection coefficient (ρ) is given by

$$\rho = \frac{v_r}{v_i} = \frac{z_t - z_i}{z_t + z_i}. \tag{4}$$

For example, if
(1) $z_t = 0$, $\rho = -1$
(2) $z_t = z_i$, $\rho = 0$, and
(3) $z_t = \infty$, $\rho = 1$.

Under condition (1) above, the line is shorted to the ground conductor, and an inverted pulse of the same magnitude is reflected to the source. Condition (2) defines a condition in which a perfect match exists. Therefore, no reflection occurs and the line appears to have an infinite length, seen from the source. The open-circuit (infinite impedance) condition indicated by condition (3) results, as with case (1), in total reflection back to the source, but with no phase inversion. Resistive impedance mismatches of intermediate magnitudes between open- and short-circuit conditions merely result in scaled-down versions of the reflections described above.

In post-tensioned ducted systems, such distributed changes in impedance may be due to the presence of severe corrosion in the steel tendons[7], or the existence of dry or wet voids in the ducts themselves[8]. These conditions can therefore be readily detected with ETDR.

SYSTEM DESCRIPTION

The system presented here, shown in Figure(3), consists of two basic units: a Tektronix 1503C, classified by the manufacturer as a cable tester, and a PC which contains the classification software. Waveforms captured by the equipment are displayed on an LCD screen with a 128-step resolution. The 1503C is linked, via a serial interface, to the computer system which performs the necessary analysis of the echo waveforms and classifies any detected faults in the cable/duct systems. The automatic classification scheme employed is described later in this paper.

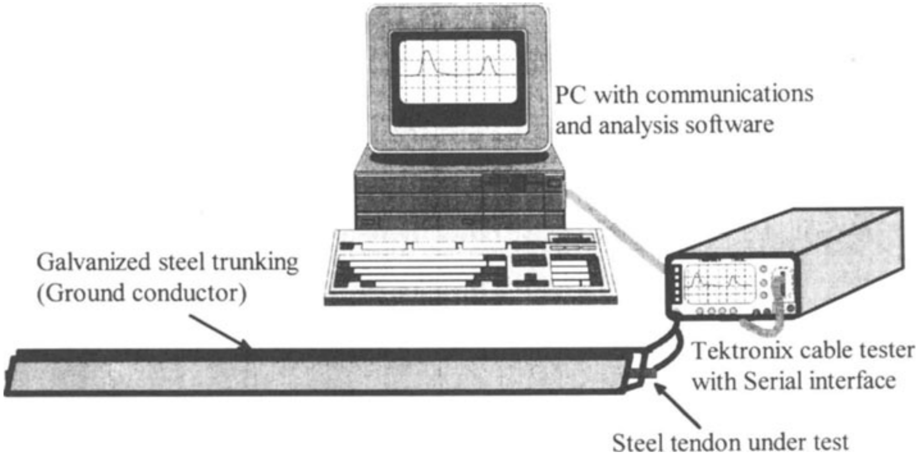

Figure 3. Equipment configuration for ETDR measurements and echo waveform classification.

EXPERIMENTAL WORK

The experiments under discussion were designed to focus on the detection of dry and wet voids in duct/cable units, and were carried out under laboratory conditions. Figure(4) shows a screen dump of some of the results of creating a wet area of different degrees of wetness at a location which is 1.75m along a 5mm diameter, 2.4m cable. It can be seen that the reflection due to this anomaly increases in amplitude with increasing void length.

A similar effect to that in Figure(4) is present in Figure(5). Here, the anomaly is due to a dry void of different lengths, at a location of 1.50m. The positive-going reflections indicate that this is a region of higher impedance, hence a region of an air-filled void, in this context. In all the experiments, sand was used as a substitute for cement grout.

RMS plots of the echo amplitudes for the dry and wet voids above are shown in Figures(6(a,b)), respectively. Both show a high degree of correlation with the measured quantities, making it possible for reasonably accurate predictions to be made about one, given the other.

In Figures(7(a,b)), The Fourier Magnitude plots of the same echo waveforms are shown. Here, any obvious correlation exists only at zero frequency, i.e. at d.c. This information, however, is already implicit in the RMS plots of the time-domain signals, since the RMS value of a waveform is an indication of the equivalent d.c. content of hat waveform. For this reason, there is no obvious advantage in using the more computation-intensive Fourier domain descriptors in carrying out classification of these waveforms.

CLASSIFICATION SOFTWARE

The flowchart of the software for the ETDR echo waveforms classification is shown in Figure(8). The user is required to indicate the signal window containing the echo signal of interest. Thereafter, this signal is saved to a buffer for subsequent processing. As indicated above, only the time-domain waveform statistical indicators are used in the analysis and classification procedures.

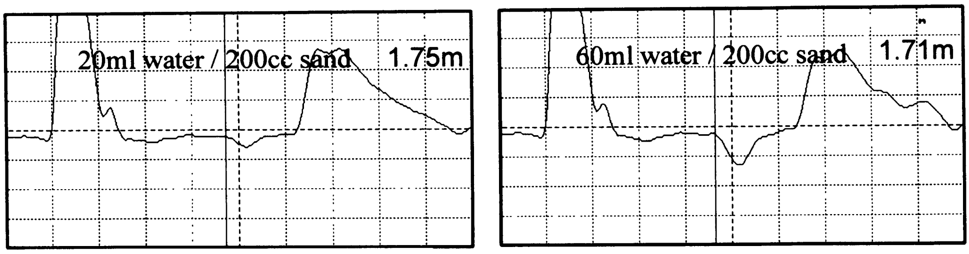

Figure 4. Annotated 1503C screen waveforms for different degrees of wetness at 1.75m.

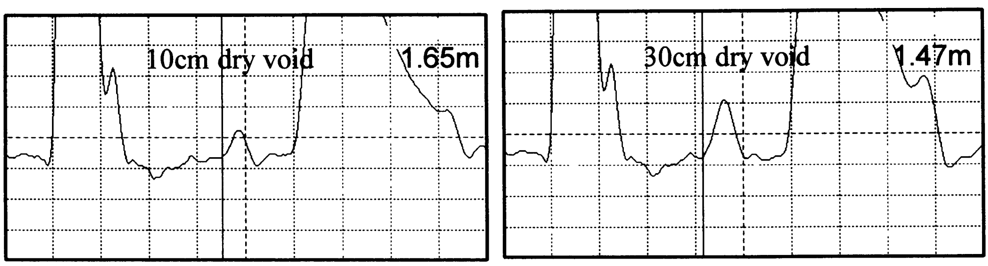

Figure 5. Annotated 1503C screen waveforms for different dry void lengths.

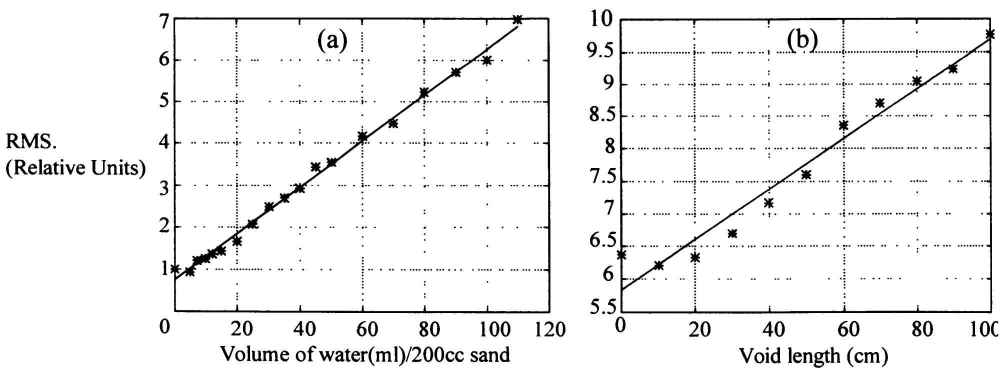

Figure 6. Echo RMS plots for the detection of (a) wet sections and (b) dry voids.

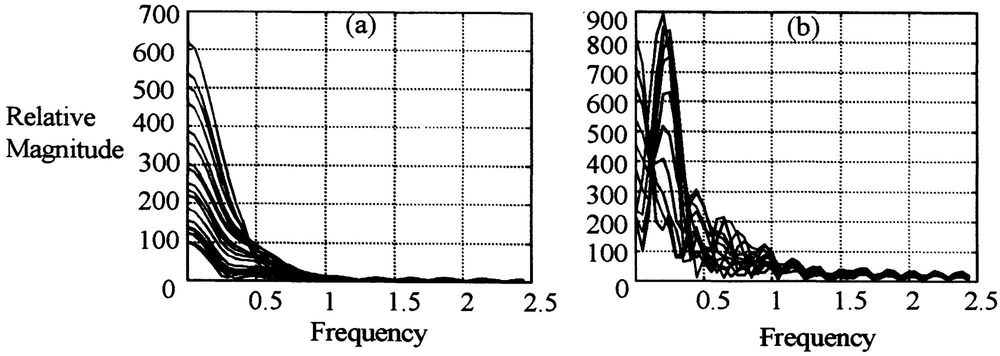

Figure 7. Fourier magnitude plots for the detection of (a) wet sections and (b) dry voids.

The first operation to be performed on a *copy* of this echo waveform is a modified form of bipolar thresholding, to remove some of the baseline noise. Each value of the waveform is compared against a reference value; any waveform values below the reference are set to zero, while all other values are left unmodified. This thresholded waveform is then integrated and the absolute value of this result is used to decide whether or not the waveform contained a detectible void.

Because dry voids result in positive polarity echoes and wet voids generate inverted echoes, this fact is used in classifying a detected echo as originating from a dry or wet void. This is achieved simply by testing the actual integration result, rather than its absolute value, against the original reference value: this preserves the sign of the waveform, hence its polarity. Additional information about the void concerning its length and the degree of wetness (if a wet void) is finally computed by employing the appropriate regression, based on the RMS plots of Figures(6(a,b)). The location of the void itself is determined from the position of the first defining value for the echo, after the initial thresholding operation.

DISCUSSION

As indicated above, the system is still under development; however, in its present state, it already serves to provide a proof of concept, upon which future attempts at refinement can be based. Such may include, but may not necessarily be limited to, the refinement of the classification algorithm to be able to recognise regions of corrosion in steel tendons, multiple voids, combinations of dry/wet voids, and voids which are located in the 'dead zone' of the incident pulse. Also of importance is the ability to accommodate ducts and tendons of different sizes, a requirement which will involve the development of suitable theoretical models for various cable/duct systems.

In practice, it should be possible to employ the fully developed system in interrogating prestressing tendons in existing and future structures, at regular intervals, as part of a preventive maintenance scheme. This could be performed with self-contained units, or with distributed units which are accessed remotely by telemetry from a central control point.

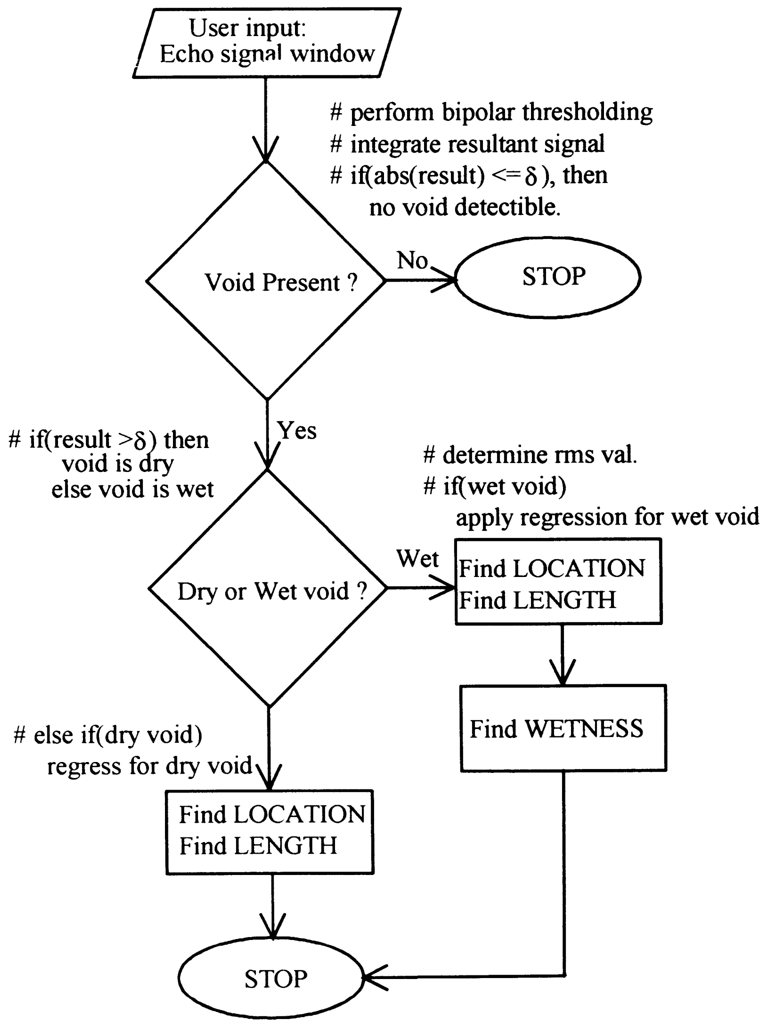

Figure 8. Flowchart for echo waveform classification.

CONCLUSION

The ETDR system described in the foregoing, when fully developed, has the potential of performing automatic characterisation and classification of fault conditions in ducts carrying prestressing cables in post-tensioned concrete structures. It has the capability of analysing and classifying reflections due to single voids in ETDR waveforms, identifying the location of the voids, and, in the case of wet voids, providing an indication of the degree of wetness. Further work is going on involving tests on samples with cement grout rather than sand, development of theoretical models to embrace a wider range of cable/duct combinations, and refinement of the void classification algorithm.

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