GIMA ground penetrating radar system for monitoring concrete bridge decks

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Abstract

Ground Penetrating Radar (GPR) has been investigated as a non-destructive method for evaluating damage in concrete structures. However, the commercially available techniques are limited to detection of gross quantities of deterioration, due to the limited resolution of the system. The objective of this research is to evaluate a ground penetrating radar system with a novel Good Impedance Match Antenna (GIMA) for concrete structural assessment. This system has the capacity to detect concrete cracks as small as 1 mm thick, while being able to reflect from and detect features at depths of up to 360 mm. Laboratory results of testing of the GIMA antenna by using a step-frequency and a high-frequency impulse system are presented. The experimental results reveal that the GIMA antenna is capable for use in frequency ranges, at least as broad as 500 Mhz to 6 GHz for the step-frequency and 1 to 16 GHz for the high-frequency impulse system. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Concrete bridge decks must survive for decades under repeated loading and environmental stress. Inevitably, damage, such as cracking and delamination occurs. In areas with severe winter weather, the use of deicing salts promotes corrosion. However, the damage is often hidden inside the deck and is not manifested on the surface until it is at an advanced stage. In order to maintain and rehabilitate bridge decks effectively, a precise assessment of the condition of the bridge is critical.

GPR is a potentially powerful method of non-destructive evaluation because it is relatively insensitive to ambient conditions and is effective with and without asphalt overlays (Maser, 1990). GPR is capable of collecting data at highway speeds, and will work with materials that are a mixture of several constituents (Sansalone and Carino, 1989; Maser, 1990).
Cantor and Kneeter (1982) showed that GPR is a functional and reliable technique for determining the structure and condition of concrete pavements. They established a 90% correlation between radar evaluation predictions and pavement condition.

Even though GPR is potentially a promising technique, the low resolution of commercially available radar facilities, which operate with wavelengths in air on the order of 100 mm (1 GHz), limit their applicability. These GPR systems cannot directly detect the small air-filled delaminations (1 mm thick), which are common in bridge decks (Maser, 1989). In order to overcome this difficulty, higher frequency (0.5 to 6 GHz) electromagnetic (EM) waves with shorter wavelengths and potentially higher resolution are examined in this study.

While frequency range plays an important role, the performance of the GPR antenna is also critical to the overall system performance. Prior research has been conducted to design and fabricate antennas with high radiation power, high penetrating ability, and high resolution. Ondrejka et al. (1995) studied design issues of antennas used for time-domain signals. Smith (1995) compared the advantages and disadvantages of two most common element configurations, the horn antenna and the flat bow-tie antenna. Resistive loadings have been to improve the bandwidth of the antenna by attempting to match the impedance of the antenna to that of free space. The disadvantages of resistor loaded antennas are: low efficiency and directivity, the reactive input impedance of inconvenient magnitude, large dimensions, difficulty of mechanical construction, and lack of not pulse-optimization (Theodorou et al., 1981). Theodorou et al. (1981) suggested the design of tapered impedance traveling-wave antenna (TWIT antenna). The concept is to use a controlled variation of TEM wave impedance to minimize the internal reflections of the input signal over the frequency band interested. In this paper, a new antenna, Good Impedance Match Antenna (GIMA antenna) is introduced. By avoiding resistive loading, this design suggests a higher radiation efficiency and penetrating capability.

2. Experiment

2.1. Equipment

Two main instruments were used in the antenna performance tests. The first instrument provided a step-frequency testing capability. It was a HP 8753D Network Analyzer with a frequency range of 30 MHz to 6 GHz. The second instrument was used for high-frequency impulse testing. It was a TEK CSA803 Sampling Scope coupled to a custom impulse generator with a 27 ps pulse rise time.

2.2. GIMA Antenna

A number of antennas were used in the early stage of the research. These included: Vivaldi antennas built by Weedon (1994); a TEM Horn antenna based on a design by Ondrejka et al. (1995). These antennas did not perform well. There were high signal losses and large end reflections. A new TEM antenna was built based on a design by Aurand (1997). The antenna had a clean impulse, but had a large reflection at the aperture. Experimental data showed that it had a relative small penetrating depth, about 127 mm. A new antenna design was then developed — the GIMA antenna. The concept behind the design of GIMA is to provide a smooth impedance transition from the antenna to the air. This was accomplished with a combined taper and flare of the ends of the horn.

The tests indicated that the performance of the various antennas was highly sensitive to geometric variations. Geometric fidelity was ensured by using Teflon spacers at the apex and by using expandable sealing foams to hold the plates into the desired positions. Both sides of each metal plate were tapered in by 30 mm. Fig. 1 shows the shape and the critical dimensions of the GIMA antenna used in this study. The GIMA
is about one-half the size of an equivalent untapered horn antenna. The penetrating capability and the resolution of a GPR system that used the GIMA antenna with a step-frequency network analyzer was tested by using the experimental settings shown in Fig. 2.

2.3. Test 1: return loss test

It is very important to understand the ability of the antenna to transmit each individual frequency. It is desired to have an antenna that is frequency independent. Frequency domain monostatic reflection tests in the air give information on the antenna and cabling reflection, independent of other objects. The return loss of the GIMA antenna was studied through frequency domain monostatic tests in air. The tests were conducted on a step-frequency system, i.e., an HP 8753D Network analyzer with a frequency range from 29.85 MHz to 6 GHz.

2.4. Test 2: test of attenuation in the air

The experimental procedures are described below. First, the baseline data (air-shot data) were collected. The antenna was faced away from nearby objects. The baseline data provides information about the antenna that can be subtracted from subsequent data to minimize systematic antenna errors. In the following results, unless indicated otherwise, the air-shot response was subtracted from the overall response.

Next, the attenuation of the radar signal in the air was studied by using a metal plate with a dimension of $305 \times 610 \text{ mm}^2$ as a reflection plate. Initially, the reflection plate was placed right at the aperture to provide the information. This provided a strong reflection that could be correlated in time, and hence space, with the location of the antenna aperture. The same reflection plate was then placed at sequential intervals of 76.2, 152.4, and 228.6 mm apart from the aperture. The experimental data showed that as the plate was moved farther away from the antenna, the magnitude of the return signal decreased. This is most likely due to near-field geometric effects.

2.5. Test 3: penetrating capability test

A concrete slab with a thickness of 89 mm was placed 76 mm away from the aperture. A metal plate was placed at the bottom surface of the slab so as to provide a strong signal corresponding to the bottom surface of the slab. Next, three more concrete slabs were stacked together with the first slab, one at a time, to produce a variety of the concrete stack thicknesses (Fig. 2). The first three slabs had the same thickness, 89 mm. The fourth slab had a thickness of 76.2 mm. The arrangement of these slabs was to produce an artificial crack with a
width of about 1 to 2 mm thick between the slabs.

2.6. Test 4: resolution test with high-frequency impulse system

In order to measure the ability of the GPR systems combined with a GIMA antenna to distinguish air-filled cracks, two large concrete slabs (914 × 914 × 36.0 mm³) were placed flat next to one another. An air-filled gap ranging from 0.0 to 3.0 mm was formed between the slabs. The variation in the air-filled gap width is due to the slabs not being perfectly flat. Both the step-frequency and the high-frequency impulse systems were used to test the specimen. The step-frequency system was operated in a 0.5 to 6 GHz range. The high-frequency impulse system was operated in the 1 to 16 GHz range. All data were collected in monostatic mode.

3. Experimental results

The frequency domain data of monostatic air-shot is given in linear magnitude (Fig. 3), which gives information on the return loss of GIMA antenna. It is shown that the GIMA antenna is relatively independent of frequency in the higher frequency ranges. The arrow marker indicates the location of 500 MHz.

In Fig. 4, the air-shot data (solid line) of the GIMA were compared with the data when a metal plate was placed near the aperture about 6.4 mm away from the aperture (dashed line). Peak 1 is identified as the location of the antenna apex location. Peaks 2 and 3 correspond to aperture locations. The GIMA has a very small energy loss at the aperture (Peak 2). The ringing after Peaks 2 and 3 was caused by the reflection between the antenna flares and the metal surface. This ringing was also observed in subsequent experiments. A series of steps were taken to minimize the ringing. These included using two antennas in an angled bistatic mode, placing a window of radar absorbing foam over the aperture, and fine-tuning the relative angles of the flared part of the antenna. Ultimately, the fine-tuning procedure worked the best. However, it is an empirical procedure that is not well-understood.

As a test of the ability of the system to reflect off objects at preset distances, a metal plate was placed at different distances from the aperture, after subtracting the air-shot response. Fig. 5 is a comparison among the cases when the metal plate was placed 76.2, 152, and 229 mm away from the aperture. Peaks 2, 3, and 4 indicate the metal plate location at 76.2, 152, and 229 mm away from the antenna, respectively. Each major peak has several rings after it. These rings repeat at the same time interval and attenuate in a repeatable manner for each observed reflection.

Fig. 6 is the experimental result of four stacked concrete slabs. When the metal plate was not used, the data are plotted with a solid line. The dashed line shows the data with metal plate positioned at the bottom surface of the four concrete slabs. The peaks indicating each
surface are shown in Fig. 6. Peak 1 is the location of the top surface of the concrete stack, while Peak 2 is the interface between the Slab 1 and the Slab 2. Peak 3 represents the artificial crack between Slabs 2 and 3. The gap between slab 3 and 4 is indicated by Peak 4. Peak 5
Fig. 6. Experimental result of four stacked concrete slabs penetration test. The peaks indicating each surface are shown. The correlation between peak and surface was found by placing a metal plate at the indicated positions and observing the change in response.

shows the location of the bottom surface of the four-slab concrete stack. Peak 5 increased significantly when a metal plate was placed at the bottom of the four-slab concrete stack, thereby indicating the bottom surface location of the stack. Thus, it can be concluded that the radar signal has reached the thickness of 360 mm deep in concrete.

Fig. 7 shows the resolution test (see Section 2.6, test 4 for the experimental set-up) results from using a step-frequency system, which collects data in the frequency domain and synthesizes an equivalent impulse response in the time domain using a discrete Fourier transform. The spacing between two concrete slabs was about 1 to 3 mm and the thickness of each slab is 90 mm. Fig. 7 plots the data using a real format, which is the real part of the synthesized impulse response. The reason for using the real format is that it indicates the sign of the reflections, which are indicative of whether the reflection is due to waves traveling from a higher to lower dielectric medium, lower to higher dielectric medium, or metallic reflection. The disadvantage of using the real format is that some of the information from the imaginary part of the data is not presented. If the frequency range of the step-frequency system is infinite, rather than band-
limited, then the entire synthesized time domain signal would be real. When the radar wave travels from a material with low dielectric constant to a material with high dielectric constant, the sign of the signal changes. When the radar wave travels from a material with high dielectric constant to a material with low dielectric constant, the sign of the signal does not change. It is found that the step-frequency system indicates the presence of a crack that is about 1 mm thick. In Fig. 7, the front surface of the first slab, the gap between the slabs and the back surface of the second slab are all distinguishable by examining the reflections. The reflection from the front surface of the first slab and the back surface of the second slab changes sign, as expected. The reflection in the gap is comprised of reflections off the back of the first slab and off the front of the second slab. The system is not able to distinguish the two surfaces. This is because the width of the reflected pulses is too wide for the 0.5 to 6 GHz frequency test range.

Experimental results with a high-frequency impulse system show that when the upper bound of the frequency range is high enough, the GIMA antenna can resolve the front and back surface of the crack as two distinct envelops in time domain trace. (Fig. 8 shows results from a test with two slabs with thicknesses that range from 36 to 40 mm and have a gap of 1 to 3 mm between them. For this specific impulse system, the signature of the reflection appears to be one single peak. The sign change due to the nature of each reflection stays true for this system. A smaller gap size could not be produced because the slabs were not perfectly flat. In Fig. 8, Peak 1 is the front surface of the concrete stack. Valley 2 indicates the front surface of the artificial crack (back surface of the first concrete slab). Peak 3 represents the back surface of the artificial crack (the front surface of the second concrete slab). Peak 4 is the back surface of the second concrete slab. Even though the two envelopes representing the rear surface of the first slab and the front surface of the second slab are starting to overlap, the two independent signals appears clearly with a change in sign. These results indicate that the GIMA antenna coupled to a high enough frequency system has the capacity to identify concrete cracks with separations of 1 to 3 mm.

4. Conclusion

A GPR antenna, (GIMA), has been developed mostly from an empirical approach. The antenna seems to be able to discern 1 to 3 mm cracks using a 0.5–6 GHz bandwidth step-frequency system. However, the signals from the delamination do not stand out from ring-down signals. When a 0.5 to 16 GHz impulse system is used with the GIMA antenna, the 1 to 3 mm delamination is easily identified. The system is able to detect signals that penetrate and return through 360 mm of concrete.
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