01 Jul 2014

Comparison of Synthetic Aperture Radar and Impact-Echo Imaging for Detecting Delamination in Concrete

John S. Popovics

Suyun Ham

Mohammad Tayeb Ahmad Ghasr
Missouri University of Science and Technology, mtg7w6@mst.edu

R. Zoughi
Missouri University of Science and Technology, zoughi@mst.edu

Recommended Citation

J. S. Popovics et al., "Comparison of Synthetic Aperture Radar and Impact-Echo Imaging for Detecting Delamination in Concrete," *Proceedings of the 40th Annual Review of Progress in Quantitative Nondestructive Evaluation, Incorporating the 10th International Conference on Barkhausen and Micro-Magnetics (2013, Baltimore, MD)*, vol. 1581 33, pp. 866-871, American Institute of Physics (AIP), Jul 2014.
The definitive version is available at https://doi.org/10.1063/1.4864912

Comparison of Synthetic Aperture Radar and Impact-Echo Imaging for Detecting Delamination in Concrete

Article · January 2014

DOI: 10.1063/1.4864912

4 authors, including:

John S Popovics
University of Illinois, Urbana-Champaign

Mohammad Tayeb Ghasr
Missouri University of Science and Technology

Comparison of synthetic aperture radar and impact-echo imaging for detecting delamination in concrete

J. S. Popovics, S. Ham, M. T. Ghasr, and R. Zoughi

Citation: AIP Conference Proceedings **1581**, 866 (2014); doi: 10.1063/1.4864912
View online: http://dx.doi.org/10.1063/1.4864912
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1581?ver=pdfcov
Published by the AIP Publishing

Comparison of Synthetic Aperture Radar and Impact-Echo Imaging for Detecting Delamination in Concrete

J. S. Popovics[a], S. Ham[a], M. T. Ghasr[b], and R. Zoughi[b]

[a]*Department of Civil and Environmental Engineering, The University of Illinois at Urbana-Champaign, Urbana, IL 61801*
[b]*Department of Electrical and Computer Engineering, Missouri University of Science and Technology (S&T), Rolla, MO 65409*

Abstract. In this paper we evaluate the utility of microwave and mechanical wave nondestructive testing techniques to detect delamination in reinforced concrete bridge deck mock-up samples. The mechanical wave tests comprise air-coupled impact-echo measurements, while the microwave measurements comprise three-dimensional synthetic aperture radar imaging using wideband reflectometery in the frequency range of 1-4 GHz. The results of these investigations are presented in terms of images that are generated from these data. Based on a comparison of the results, we show that the two methods are complementary, in that provide distinct capabilities for defect detection. More specifically, the former approach is unable to detect depth of a delaminated region, while the latter may provide this information. Therefore, the two methods may be used in a complementary fashion (i.e., data fusion) to give more comprehensive information about the 3D location of delamination.

Keywords: Concrete Bridge Decks, Impact-Echo, Flexural Mode, Microwave Imaging, Synthetic Aperture Radar, Near-Surface Delaminations
PACS: 43.20+g; 43.40+s; 43.60+d, 84.40.Xb, 84.40.-x, 42.40.Kw

INTRODUCTION

Reinforced concrete bridge deck structures are susceptible to early deterioration. A serious problem affecting the service life of the reinforced concrete bridge decks is the formation of a delamination, which is a thin cracked area that lies directly above the steel reinforcement mat within the deck [1,2]. The inspection of near-surface defects can be time-consuming and subjective and often requires multiple instruments and advanced techniques to draw robust conclusions [3,4]. Thus, effective nondestructive testing (NDT) methods, or some combination of NDT methods, capable of detecting such delaminations are needed. Test that can be deployed from a continuously moving platform are desired, as that enables rapid data collection and could eliminate the need for bridge deck lane closure during testing. Furthermore, the large amount of data should be presented in an effective and unambiguous manner. We propose that images that represent the spatial extent of the inspected structure are the best format to display the data particularly when presented in 3-D format. Air-coupled impact echo [5] and synthetic aperture radar (SAR)-based microwave imaging methods show promise in this regard, so the fusion of these methods may lead to more robust detection and localization of delamination.

AIR-COUPLED IMPACT ECHO

The equipment needed to carry out the impact-echo test are a contact sensor, an impactor, a data acquisition and a computer, as shown in Fig. 1. In the conventional configuration, the obtained response signals are obtained by physically touching the surface of the deck with a sensor. More recently, air-coupled sensing has been implemented. In air-coupled IE testing the conventional contact sensor is replaced with a contactless (air-coupled) sensor. The basis of air-coupled sensing is that leaky waves propagate into the air that bounds the concrete deck, caused by the generated wave motion of the surface [6]. Although the amplitudes of these leaky waves are very small, air-coupled sensors can detect these leaky wave components with excellent fidelity and high signal to noise ratio. In fact properly configured air-coupled sensors provide equivalent IE data as that collected using conventional contact sensors [7].

The received response time signals are transformed into the frequency domain, for example using a fast Fourier transform (FFT) protocol, and dominant vibrational responses are identified in the frequency spectrum (amplitude) as

40th Annual Review of Progress in Quantitative Nondestructive Evaluation
AIP Conf. Proc. 1581, 866-871 (2014); doi: 10.1063/1.4864912

spectral peaks. Two different families of vibration are expected: the flexural modes, which occur over delaminated regions and thickness modes, which occur over solid deck regions. In usual practice, the obtained spectrum for each test point is evaluated. Generally the modal frequencies associated with the flexural modes are significantly lower than those with the thickness modes, so occurrences of dominant low frequency modes are associated with the presence of delamination underneath and nearby the region of the test point.

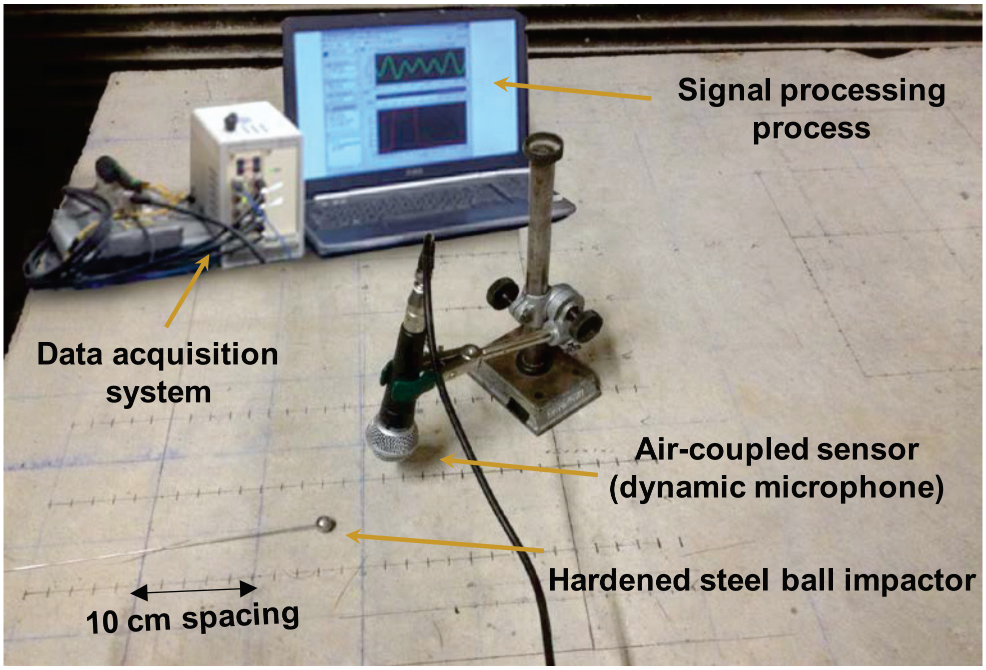


FIGURE 1. Air-coupled impact-echo imaging test set-up on concrete test slab containing simulated delamination defects.

MICROWAVE SYNTHETIC APERTURE RADAR (SAR) IMAGING

Microwave SAR imaging is finding increasing utility in NDT of concrete structures [8]. The benefits of SAR imaging are multifold. Wideband SAR imaging is capable of producing three-dimensional (3-D) images of indications. SAR imaging techniques are provide for a relatively constant image resolution (in three dimensions) irrespective of size of the sample being imaged or the location of the target [9]. Furthermore, SAR imaging can be readily field deployed, with commercial scanners and using low-cost, small, and light weight wideband reflectometers [10]. Moreover, utilizing an array of reflectometers, the imaging process can be accomplished in (near) real-time [11].

SAR imaging at microwave frequencies in the range of 4–18 GHz has been previously used for 3-D imaging and detection of corrosion in steel reinforcing bars embedded in mortar and concrete blocks [8]. For an electromagnetic wave at microwave frequencies, concrete is an inhomogeneous and lossy medium. The presence of large aggregates causes significant scattering of the electromagnetic wave and severely limits penetration depth. Additionally, concrete is made of a lossy material in the form of cement binder, attenuating the electromagnetic wave and further reducing penetration depth. Internal moisture in concrete, either in the internal pores, or permeated as a result of rain, etc. also attenuates microwave signal penetration into concrete. To this end, it is advantageous to operate at low microwave frequencies when imaging concrete structures. The disadvantage of operating at lower frequencies is the resulting degradation in image resolution and more significantly in the range (depth) direction due to the reduced available bandwidth [9]. On the other hand, utilizing wideband antennas such as ridged horns helps maintaining acceptable range resolution (which is dependent on the transmitted signal bandwidth) and increases signal-to-noise ratio (SNR) of the image due to coherent nature of SAR imaging over wideband measurements.

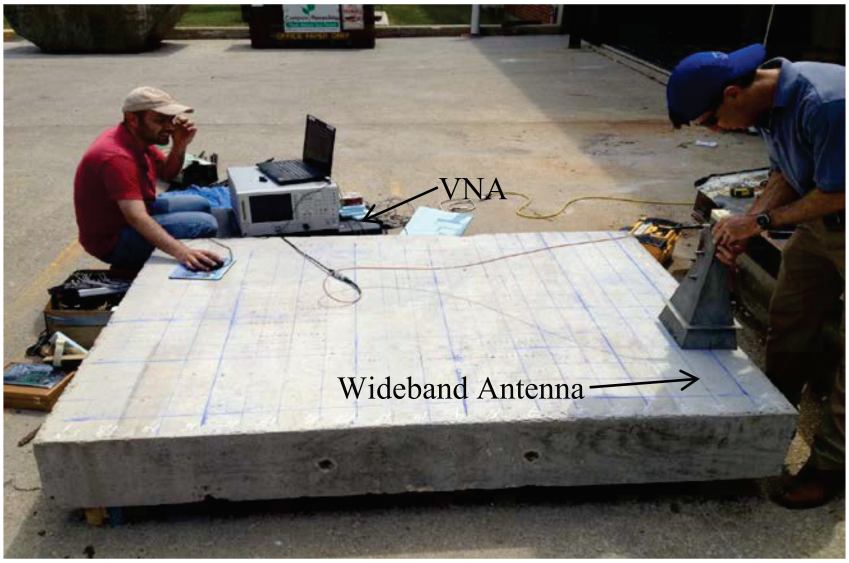


FIGURE 2. Synthetic aperture radar test set-up on concrete test slab containing simulated delamination defects, using a wideband ridged horn antenna.

EXPERIMENTS WITH CONTROLLED DELAMINATIONS

Test Specimen

To verify the effectiveness of the NDE methods to identify near-surface delamination in concrete, air-coupled IE and SAR tests were carried out on a concrete test slab. This test specimen contains a variety of embedded artificial delaminations and voids; a description of that sample can be found elsewhere [7]. The concrete has a 28-day compressive strength of 30 to 40 MPa, with ultrasonic pulse velocity in the mature concrete (measured following ASTM C597) ranging from 4,000 to 4,200 m/s. The size of the concrete test slab is 1.5 × 2.0 m with a nominal thickness of 0.25m. Since the loading capacity of the slab is significantly reduced by the presence of artificial defects, the slab is reinforced with steel bars in two dimensions and at two layers, 60 and 200 mm depths. The slab contains artificial delaminations and voids of varying size and depth. Double-layered plastic sheets and soft foam blocks simulate artificial rectangular and circular delaminations, respectively. A 100 × 100 mm test point grid was defined on the surface and test data collected at the grid locations.

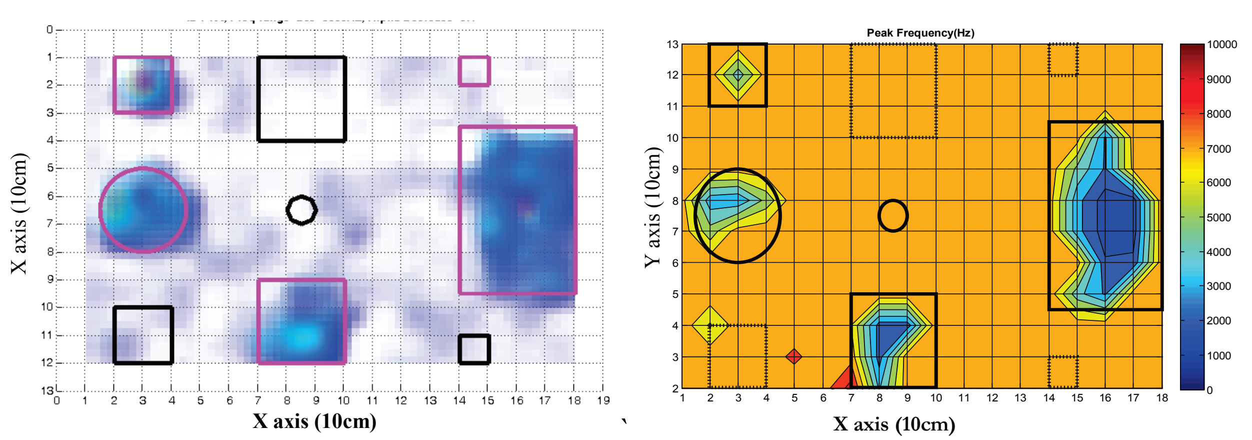
Test Procedures

An IE testing configuration was consistently applied to the test specimen. A steel ball with an 18 mm diameter was used as an impact source. The forcing function associated with an impact event of this type exhibits consistent and broad spectral content, ranging from zero frequency (DC) to 15 kHz [5].The generated surface vibrations set up by the ball impact event are detected by air pressure sensors. The air pressure sensor is a dynamic vocal microphone, which has 1.85 mV/Pa sensitivity at 1 kHz and a 50 Hz to 15 kHz working frequency range. The sensor is connected to the data acquisition system where the analog signals are converted to digital data using 16-bit analog-to-digital resolution at a sampling frequency of 1 MHz. The testing hardware set-up is shown in Fig. 1; in this photo the air-coupled sensor is placed as closely as possible to the surface, where the hand-controlled impact event is applied nearby each sensor. For each test, time signals with 10 ms duration are obtained. The normalized time domain data are stored on a connected data acquisition computer for subsequent processing. The time data are later converted to the frequency-domain (amplitude spectrum) by Fast Fourier Transformation (FFT) in preparation for spectral image processing.

Figure 2 shows SAR imaging being performed on concrete slab of concrete. A vector network analyzer (which may be replaced by a coherent reflectometer) incorporating a wideband antenna operating in the frequency range of 1-4 GHz is used to measure wideband reflection coefficient data on a two-dimensional 2-D grid with a predetermined spacing of 100 mm that is optimized for this particular application based on frequency of operation and the required resolution [9]. The wideband ridged horn antenna was placed directly on the top surface of the concrete slab. However, the antenna can be also held at a fixed distance away from the test panel (i.e., non-contact measurement) and be moved using a raster-scanning platform. A vector network analyzer (VNA) is used to measure the reflection coefficient calibrated in the frequency range of 1-4 GHz to the aperture of the antenna. The SAR imaging algorithm compensates for the wave propagation from each measurement location to every single point in the volume of the sample and coherently combines the measurements from all antenna locations. This process is performed in the spectral domain with proper compensation for the wave phase velocity above the sample (i.e., in air) and within the dielectric sample [9]. The result is a 3-D image that can be plotted in 2-D slices in any direction indicating the size and location of any possible indication.

RESULTS AND DISCUSSION

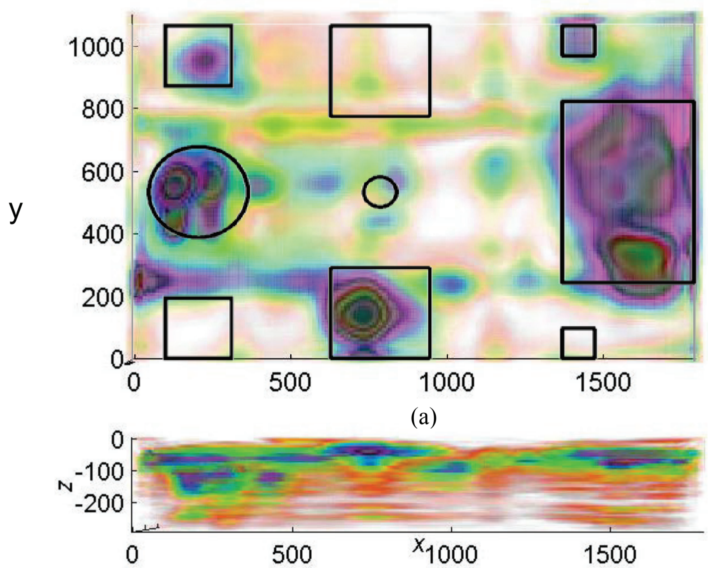
The 4-D plot format is used to present the air-coupled IE data. A 4-D plot comprises a data volume with a series of individual spectral signals up to a defined frequency limit located over the test area space. A horizontal X-Y plane defined by a specific frequency is called a "C-scan" plane. The size of the data volume is 36 × 12 × 10000, representing the number of data in x, y and z directions, respectively. The space between any two data points can be interpolated by linear or quadratic regression. The 4-D plot includes all IE data over the test area, over both solid and defected regions, but the internal character cannot be identified due to the surface opacity of the data volume. However, spectral features in the interior of the data volume can be revealed only by selecting the interested ranges. Within some frequency range, usually between zero frequency (DC) and some upper cut-off frequency value, unwanted portions of the data volume are screened out beyond of the range of interest such that the dynamic behavior of the delaminations, only, is monitored. This is achieved by setting the cut-off frequency value at a frequency above which flexural resonances from delamination are not expected, typically 6 kHz. Figure 3(a) shows a top-perspective view of the 4-D data volume built up from IE data collected across the face of the test slab. The top perspective (X-Y view) of the 4-D plot displays the dominant amplitudes in an effective manner for accurate identification of the area of the defect [12]. The 4-D plot defines the extent of near-surface delaminated area well, but does not detect the deeper delaminations. Also, small near-surface delamination defects may be missed. If the test point spacing is relatively large, defects with that areal size or smaller will likely be missed, regardless of other performance parameters. On the other hand, if the cut-off frequency value is too low, natural vibrations from smaller or deeper defects will be missed, since their frequencies lie above the defined frequency cut-off value. If defects with smaller areal extent or larger depth are expected and need to be detected, the cut-off frequency must be increased accordingly. Figure 3b shows the more conventional peak frequency plot representation of the IE data. This plot does indicate all of the larger near-surface delaminations, but the deeper defects are missed. Furthermore, the areal extent of the detected near-surface delaminations are under-estimated.



(a) (b)

FIGURE 3. Experimentally obtained air-coupled impact-echo data collected over concrete test slab containing shallow (pink lines) and deep (black lines) delamination defects: (a) top view of 4-D image over all test points (up to 6 kHz), and (b) peak frequency plot representation of same data set.

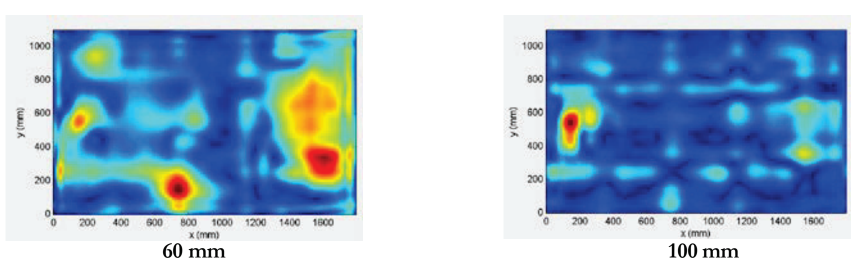
The results of the wideband SAR imaging are presented as a 3-D intensity image. The intensity of the reflected wave, as reconstructed by the SAR imaging algorithm, is typically depicted as a grey scale or false color image. Figure 4, shows the top (X-Y) and side (X-Z) views of this 3-D image where darker colors indicate stronger reflections and thus stronger discontinuities in the specimen. The top view image in Fig. 4a, shows that all four square delamination on the top level are detected. The large circular foam insert is also detected. This figure also shows variations within the large delamination of the right side of the image. This figure also shows indications of two horizontal rebars located approximately at y = 250 mm and y = 750 mm. The vertical rebars were not detected due to the linear polarization of the antenna, which is oriented orthogonally to those rebars. The three bottom level delaminations were not successfully imaged due to the dielectric losses and scattering due to aggregates associated with the concrete material limiting the signal penetration. More significantly, the presence of a tight metallic wire mesh in-between the rebars (used to hold the artificial delaminations) acts a reflector of electromagnetic energy and thus limits signal penetration. Figure 4b shows the side view of the 3-D image correctly showing delamination indications on top of the rebars at a depth of z = 60 mm. It also shows the indications of the large foam insert extending deeper within the concrete block. Figure 5 shows 2D XY-slice images of the 3D SAR image of Fig. 4 at depth of 60 mm on top of the rebars and depth of 100 mm below the rebars. Figure 5a shows that all the delaminations that were placed at this level. This figure also shows the large circular foam insert starting at this depth and extending into the depth of 100 mm as shown in Fig. 5b.



(a)

(b)

FIGURE 4. Experimentally obtained SAR 3D image collected over concrete test slab containing shallow and deep delamination defects. (a) top view, and (b) side view.



(a) (b)

FIGURE 5. 2-D slice images of 3-D SAR data at depth of: (a) 60 mm, and (b) 100 mm.

CONCLUSIONS

Two NDT methods are studied for the detection of delaminations in a concrete slab, namely air-coupled impact-echo and wideband (3-D) SAR-based microwave imaging. Both air-coupled impact-echo and SAR imaging offer a practical approach for testing concrete bridge deck structures. Both these methods have the potential for collecting data from a continuously moving platform. Air-coupled impact echo allows effective detection of near-surface delamination, but cannot detect deep defects nor embedded steel bars and does not provide depth information. Wideband SAR imaging method provides a 3-D image indicating the relative location, size and depth of some near-surface and deep defects and embedded steel bars. These methods have complimentary attributes, and work to fuse the test methods to improve detection of delamination is on-going.

ACKNOWLEDGMENTS

A portion of this study was carried out through support from the National Cooperative Highway Research Program IDEA program (NCHRP-IDEA), project #134, Dr. Inam Jawed program manager.

REFERENCES

1. R.E. Weyers, B.D. Prowell, M.M. Sprinkel and M.Vorster, Concrete bridge protection, repair, and rehabilitation relative to reinforcement corrosion: A methods application manual, Strategic Highway Research Program Report No. SHRP-S-360, National Research Council, Washington, D.C., 1993
2. W. Perry et al., Grand Challenges for Engineering Technical Report, National Academy of Engineering, Washington D.C, USA. Available at www.engineeringchallenges.org, 2008
3. M. Moore, B. Phares, B. Graybeal, D. Rolander, and G. Washer, Reliability of visual inspection for highway bridges volume I: Final report, Technical Report FHWA-RD-01-020, US Department of Transportation Federal Highway Administration, 2001.
4. D. Huston , N. Gucunski , A. Maher A, J. Cui J, D. Burns D and F. Jalinoos , "Bridge deck condition assessment with electromagnetic, acoustic and automated methods," In: Sixth international workshop on structural health monitoring, Stanford, CA, USA, 2007.
5. M.J. Sansalone and W.B. Streett, Impact-echo—Nondestructive evaluation for concrete and masonry, Bullbirer Press, Ithaca, N.Y., 1997.
6. J. Zhu and J.S. Popovics, "Non-contact detection of surface waves in concrete using an air-coupled sensor," in Review of Progress in Quantitative Nondestructive Evaluation, 20B, edited by D.O. Thomson and D.E. Chimenti, AIP Conference Proceedings Volume 615, American Institute of Physics, Melville,N.Y., 2001, pp. 1261–1268.
7. J. Zhu and J.S. Popovics, "Imaging Concrete Structures Using Air-Coupled Impact-Echo," J of Eng..Mech., 133, pp. 628-640 (2007).
8. S. Kharkovsky, J.T. Case, M.T. Ghasr, R. Zoughi, S.W. Bae, and A. Belarbi "*Application of Microwave 3D Imaging Techniques for Evaluation of Corrosion in Steel Rebars Embedded in Cement-Based Structures*," in Review of Progress in Quantitative Nondestructive Evaluation Vol. 31B, Burlington, VT, July 17-22, vol. 1430, AIP Conference Proceedings, edited by D.O. Thompson and D.E. Chimenti, American Institute of Physics, pp. 1516-1523, Melville, NY, 2011.
9. J.T. Case, M.T. Ghasr, and R. Zoughi, "Optimum 2D Uniform Spatial Sampling for Microwave SAR-Based NDE Imaging Systems," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 12, pp. 3806-3815, December 2011.
10. M.T. Ghasr, P. Puleo, and R. Zoughi. *Novel Reflectometer for Millimeter Wave 3D Holographic Imaging*. in *2013 IEEE International Instrumentation and Measurement Technology Conference*. 2013. Minneapolis, MN.
11. M.T. Ghasr, Kharkovsky, S.; Bohnert, R.; Hirst, B.; Zoughi, R., "30 GHz Linear High-Resolution and Rapid Millimeter Wave Imaging System for NDE," *IEEE Trans. Antennas Prop.,* vol.61, no.9, pp.4733-4740, Sept. 2013.
12. T.Oh and J.S. Popovics, "Effective visualization of local vibration data collected over large infrastructure elements," Comput-Aided. Civ. Inf. (in review).