Automation in Construction 58 (2015) 155–164

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Application of contactless ultrasound toward automated inspection of concrete structures

Suyun Ham, John S. Popovics *

Department of Civil and Environmental Engineering, The University of Illinois at Urbana-Champaign, 205 N. Mathews Ave, MC-250, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 8 November 2014
Received in revised form 11 June 2015
Accepted 20 July 2015
Available online 5 August 2015

Keywords:
Air-coupled
Infrastructure
MEMs
Microcracking
Non-destructive
Rail ties
Sensor
Surface waves

ABSTRACT

In this paper we demonstrate the potential of contactless ultrasonic sensing for rapid and automated characterization of concrete structures. Practical generation and detection of ultrasonic surface waves are made possible using air-coupled sensors, offering the potential to overcome limitations associated with infrastructure assessment measurements. The objective is to demonstrate enhanced performance when miniature, micro-machined sensors (MEMS) and high voltage solid-state capacitance transmitters are used in a scanning configuration, suitable for automation. The employed sensors, system and testing configuration, with respect to sensor height and incident angle, are described. An optimal test configuration is defined and incorporated into a controlled scanning system. Tests with the optimized configuration were carried out on reinforced concrete elements: a pre-stressed concrete rail tie that contains rail seat damage and concrete blocks with varying levels of simulated micro-cracking damage. In both cases, obtained surface wave velocity and attenuation signal characteristics show sensitivity to concrete material damage.

1. Introduction and motivation

Rapid in-place structural damage characterization of large or extensive concrete infrastructure elements has become an issue of great importance for those responsible for their management [1–3]. Automated inspection procedures are desirable, especially considering the massive and often inaccessible nature of concrete infrastructure elements, as illustrated in Fig. 1. For example, concrete is widely used in nuclear power generation structures, which under normal operating conditions may be exposed to aggressive environmental exposure (moisture and contaminating ions), high temperature hot spots at piping penetrations, turbine foundations and shield walls within the primary containment structure, and sustained radiation exposure [4]. Another example of important concrete infrastructure elements is rail ties for high-speed rail systems. High-speed rail systems demand increased track structure stability, so the physical condition of the rail track structure must be regularly monitored in order to ensure its safe and operating efficiently [5]. Though significant progress in health monitoring and non-destructive testing of large concrete infrastructure systems has been made over the years [6], reliable methods for rapid and effective material characterization of concrete in the particular systems described have not yet been realized.

Most conventional concrete non-destructive test (NDT) methods currently employed, such as visual inspection, sounding (e.g., chain drag), pulsed microwave/radar techniques (GPR) and infrared thermography, cannot reliably detect and characterize internal distributed damage in concrete [6]. Mechanical wave methods, such as ultrasonic wave pulse propagation, do show sensitivity to distributed damage, and can be applied to large structures in the field. However, conventional ultrasonic methods utilize sensors that require physical contact and proper coupling with the concrete structure. This sensor coupling process is both time and labor intensive, and thus prohibitively slow to carry out. When the concrete surface is rough, surface preparation (e.g., grinding) is needed prior to testing, and in extreme cases tests simply cannot be applied. Furthermore, the sensor coupling conditions may affect received signals and disrupt measurements. Thus, conventional ultrasonic tests on concrete show limitations owing to the need for physical coupling.

The deployment of contactless (air-coupled) ultrasonic sensors offers potential to overcome some of these limitations and to provide a pathway for automated rapid inspection of concrete infrastructure elements. Contactless ultrasonic tests have been successfully applied to inspect a wide range of materials, where ultrasonic wave speed or signal energy attenuation are normally measured and material properties inferred [7]. The first applications of contactless ultrasound to concrete

* Corresponding author. Tel.: +1 217 244 0843.
E-mail address: johnpop@illinois.edu (J.S. Popovics).

http://dx.doi.org/10.1016/j.autcon.2015.07.018

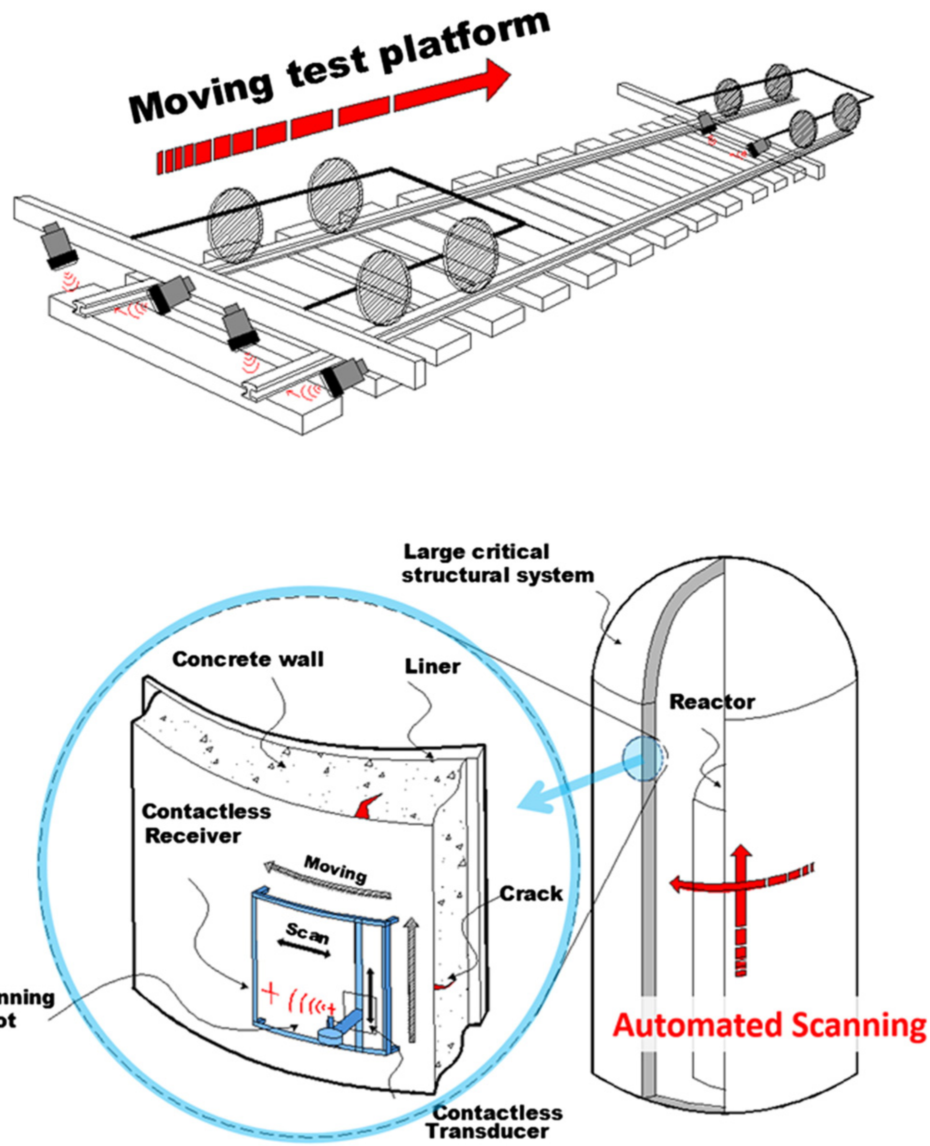

Fig. 1. Deployment concepts for fast and accurate air-coupled ultrasound inspection of (top) concrete rail ties from a moving platform and (bottom) large structural systems such as a nuclear power plant containment dome using a scanning robot.

and other cement-based materials involved the use of compressional waves (p-waves). Air-coupled sensors were positioned on opposing sides of a sample in a through-thickness configuration, and the airborne ultrasound p-wave pulses were projected normal to the surface of the samples [8–11]. Although generally good results were obtained by these investigators, the method is limited by the fact that access to opposing sides is required and, further, only relatively thin samples (less than or equal to 10 cm) can be tested because of the low signal amplitudes that were received. Furthermore, the signal-to-noise ratio (SNR) of the data is low, so additional signal processing (e.g. signal averaging and wavelet analysis) is usually required. The signals also suffer from internal wave scattering in concrete when higher frequencies (>200 kHz) are employed.

The application of ultrasonic surface waves to concrete followed, allowing tests on samples with only one-sided access. In these tests, the air-coupled transducers are located on the same side of the sample, where the airborne ultrasonic energy is usually projected at the surface at some non-normal "critical" angle to promote surface wave generation. Air-coupled, contactless surface wave tests have been used in laboratory test studies to monitor porosity or cracking in small cement paste [12], mortar [13], and concrete [14–16] samples, and to characterize aggregate distribution in asphalt concrete [17]. In some cases, sophisticated signal analyses schemes were employed, such as dispersion analysis with slant-stack transforms [14] and non-linear analysis [16], which suggest that high quality signal data can be obtained. Preliminary but limited application of air-coupled ultrasonic tests to a concrete structure in situ has been reported [15]. However, field application of air-coupled ultrasonic tests remains uncommon. Abraham et al. [14], Piwakowski et al. [15] and Garnier et al. [16] used the same commercial air-coupled ultrasonic testing hardware system, where low SNR signals and high sensitivity to the surface condition are reported for some cases.

This paper presents work conducted to overcome key technical barriers to automated contactless ultrasonic testing implementation in concrete infrastructure elements. In particular, we evaluate the utility surface-guided waves for this purpose. First, we introduce and optimize a contactless ultrasonic testing configuration that uses low cost and practical sensors so that multi-sensor arrays may be more readily deployed. The testing system produces high quality (high signal-to-noise ratio) signal data and enables reasonably large inspection lengths, e.g. greater than 0.5 m, in conventional concrete without necessitating surface preparation. We deploy the