Available online at www.sciencedirect.com
ScienceDirect
NDT&E International 40 (2007) 208–214
NDT&E international
www.elsevier.com/locate/ndteint

Static and dynamic testing of bridges through microwave interferometry

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Received 20 July 2006; received in revised form 23 September 2006; accepted 9 October 2006
Available online 21 November 2006

Abstract

A novel microwave sensor capable of remote detection of structural displacements is experimented as geotechnical instrument for static and dynamic testing of bridges. The sensor is based on an interferometric radar providing range imaging capability and sub-millimetric accuracy range displacement measurement. Dynamic monitoring calls for sampling rate high enough for transient analysis, while static monitoring requires long-term stability. The instrument has been designed in order to provide both these features. The results of a validation campaign on a railway bridge during the final test before going into service are reported.

Keywords: Radar; Remote sensing; Interferometry; Dynamic monitoring; Structural test

1. Introduction

Static and dynamic tests of bridges are routinely carried out before going into service in order to validate structural specifications, or during their operation life, in order to provide diagnostic surveys for planning rehabilitation, maintenance and repair.

Currently, static and dynamic tests are implemented by using different equipments [1]. Static tests are performed using a dumpy level, which optically detects the vertical displacement of targets positioned on the bridge. Dynamic tests are usually implemented by networks of accelerometers installed on the structure. In both cases, the placement of targets, or accelerometers, is the most time consuming and expensive operation, as monitoring of large structures can require the use of costly scaffolding. Moreover, the installation of sensors can require to keep the bridge out of service for a considerable time. That can be a serious drawback if the structure supports a public utility. Non-contact sensors have already been proposed in literature. In 1999, Farrar [2] described a microwave sensor without imaging capability for non-contact measurements of vibration frequency in dynamic testing of structures. Static deformation of a variety of structures, such as concrete girders in anechoic chamber [3], dams [4], bridges [5], and buildings [6] have been detected using ground-based synthetic aperture radar. While this technique offered both imaging capability and displacement measurement, it was too slow to detect dynamic behavior.

Recently, the authors designed and realized an interferometric radar able to provide images with sampling rate high enough to track the movements of architectural structures [7,8]. In this paper, the application of this novel instrument to perform both static and dynamic testing of bridges is described. The working principle, potential and issues are discussed with particular attention to the operating conditions. Experimental results of a number of validation tests on a just built railway bridge are reported.

2. The equipment

The equipment is based on a continuous-wave step-frequency radar [5–8], that transmits, step-by-step, continuous waves at discrete frequency values, sampling a

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doi:10.1016/j.ndteint.2006.10.007

bandwidth B at a constant interval Δf. Proper processing of the CW echo signals provides images with resolution ΔR given by

$$\Delta R = \frac{c}{2B} \tag{1}$$

with c speed of light.

Because of frequency sampling, however, unambiguous range measurement is obtained only provided that the range of targets does not exceed the maximum interval [9]

$$R_{\max} = \frac{c}{2\Delta f}. \tag{2}$$

Because of transceiver coherence, the images keep the phase information. Thus, two images acquired at different times exhibit phase differences depending on the motion of the scatterers along the radar line-of-sight. The phase shift $\Delta\varphi$ of the pixel relative to a specific target in the scenario is related to its range displacement Δr, occurred in the time elapsed between the two images, through the following basic relationship:

$$\Delta r = \frac{c}{4\pi f_c}\Delta\varphi \tag{3}$$

with f_c the band center frequency.

The interferometric sensor has been implemented as a portable equipment powered by a battery pack and held by a tripod, as shown in Fig. 1. It radiates at 16.75 GHz center frequency with 350 MHz bandwidth, and is controlled via the USB port of a common portable PC.

As the instrument has been designed for both static and dynamic testing, the electronics design must meet two types of stringent requirements.

In dynamic testing the key feature is the speed of acquisition. Large structures like buildings, bridges, towers can have movements with typical vibration period not higher than 100 ms (10 Hz) can be conservatively sampled at 30 Hz. In order to keep a cautious value of about 1000 m for the unambiguous range (2), a sampling interval Δf lower than 150 KHz is required, i.e. the number of frequencies sampling the above bandwidth should be as large as about 2500. Thus, to acquire images at 30 Hz rate the radar must be able to perform each CW acquisition in about 13 μs. This is a challenging requirement that calls for specific design solutions [7].

On the other hand, static measurement requires long-term phase stability. The duration of a test can extend from tens of minutes to many hours, depending on the engineering issues. During this interval of time the instrument has to maintain the signal coherence and must not exhibit phase shift comparable to that corresponding to the expected accuracy (tenths of millimeter). This result has been obtained by a high stability reference oscillator and an internal calibration procedure [10]. It is to be noted that, as the instrument operates in field using a battery pack, it is not possible to provide long warm-up cycles, thus making the stability requirements harder to be achieved.

Fig. 1. Radar equipment.

3. Geometry of bridge measurement

The typical measurement arrangement for both static and dynamic testing of a bridge using the interferometric radar is sketched in Fig. 2. The instrument must be positioned in an observation position allowing the lower part of the deck to be illuminated. This position is dictated by the need of avoiding the radar echoes due to vehicles passing on the upper deck. As the radar possesses only range resolution, in order to image the bridge, every point of the deck must be seen at different range. These conditions are usually fulfilled by placing the instrument at the base of a pillar, as shown in Fig. 2. If the lower surface of the deck presents discontinuities such as corners, crossbars, solders, bolts, these discontinuities act as scattering centers, producing peak echo responses. Measurement of bridge displacement is possible just in correspondence of these scattering points, so they can be viewed as a sort of ''virtual sensors'' distributed along the structure. As the expected displacement is along the vertical direction (z), the effective displacement (Δz) is related to the detected displacement (Δr) along the radar line-of-sight by the following relationship:

$$\Delta z = \frac{R}{h}\Delta r \tag{4}$$

with R the distance between the radar and the scattering point, and h the deck height.

It is to be outlined that this measurement technique cannot work if the bridge has a complex shape, producing

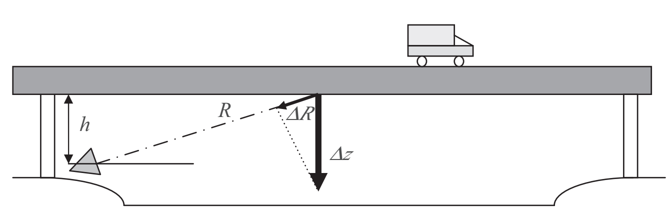

Fig. 2. Measurement geometry.