Laser ultrasonics for civil engineering: some applications in development for concrete non-destructive testing

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Abstract. Non-destructive testing of civil engineering infrastructures is becoming of primary importance for their diagnosis, residual time life estimation and/or structural health monitoring. A particularity of civil engineering application is the large size of the survey zones and the expected low cost of inspection. In this context non contact ultrasonics may offer the possibility to built robots that can automatically scan large areas (or eventually be integrated in moving vehicles) to recover mechanical properties of material or to perform imagery for geometrical information recovery. In this paper we present two possible applications of "in situ" laser ultrasonics: one is the detection of voids in tendon duct with the impact echo method, the other is the use of surface waves to recover mechanical properties of the first centimetres of concrete structures (here after called cover concrete).

1. Introduction

The use of non contact ultrasonic measurements is becoming more and more popular in the field of civil engineering as the surfaces to be investigated are very large and speed is a key factor to come up with economically viable non destructive testing methods. Alongside with air coupled sensors some developments are underway at LCPC with laser interferometers. For on-site measurements a Polytecs PI (OFV-505 sensor and OFV-5000 controller) with a VD-02 demodulator is currently used at LCPC. Two applications are described below: one, called impact echo, in the frequency range 1kHz – 60 kHz for the detection of voids of decimeter size in concrete wall, the other, surface waves analysis, in the frequency range 50 kHz – 200 kHz for the mechanical characterization of cover concrete.

Impact echo is a resonance method that has been developed more than 20 years in concrete slabs to measure thickness and to detected interface between layers. Recent works have clearly established that the underlying physics is a resonance phenomenon associated to the Zero Group Velocity frequency of the first symmetric Lamb mode [2,3]. Here we investigate the modification of the resonance response (measure with laser interferometer mounted on a scanning robot) of concrete wall where pipes of various filling have been embedded.

For material characterization of cover concrete we have developed a robot that records seismograms with a laser interferometer. We focus here on surface waves that offers from measurements at the surface the possibility to reconstructed shear wave velocity profiles as a function of depth. The dispersion curves obtained on 8 concrete mixes of various porosity at water saturation ranging from 0 to 100% are commented.
2. Impact echo for the detection of voids in tendon ducts

The detection of voids in tendon ducts with the impact echo method is a real challenge as it could result in the diminution of gammagraphy need. Two major phenomena are indicative of the presence of a void in the impact echo method: a decrease of the thickness resonance frequency $f_{\text{c}}$ [1] and the apparition of a higher frequency in the literature named $f_{\text{void}}$. The first observable alone might be in a number of case misleading as a frequency shift has been sometime observed above tendon that are diagnosed as fully filled by gammagraphy. In this paper we follow the thickness frequency shift above various tendon filling showing that this single phenomenon is not sufficient to diagnose of void.

2.1. Experimental set-up

In order to carry out reproducible and reliable impact echo diagnosis imagery, using B-SCAN or C-SCAN, is recommended. This is why a robot we designed to conduct measurements over a surface of almost 4 m² with a precision of 5 mm in both vertical and horizontal direction (figure 1). The source system is a steel ball impacting the concrete surface driven by an electromagnet. The source is maintained at a fixed distance from the wall with a wheel so that the impact is reproducible. The sensitivity of the laser interferometer is set at 5 mm.s⁻¹.V⁻¹ with a corresponding bandwidth from 0 to 250 kHz. One originality of the robot is the possible movements of the source and the receiver independently one from another in the horizontal direction. Indeed, our objective in a near future is to take advantage of this degree of freedom to perform spatial stacking to improve signal to noise ratio and to remove the Lamb fundamental antisymmetric mode perturbation.

![Figure 1. Left: plan of the wall Right: frequency of the maximum of the FFT (C-SCAN)](image)

2.2. Results

A wall 0.25 m thick including 8 tendon ducts with various filling has been built at LCPC (figure 1 left). The source used here has a diameter of 19 mm. No wall preparation is required for the measurement as the energy level is sufficient to record signal with a good signal to noise ratio. Figure 1 (right) shows a C-SCAN of the frequency of the maximum of the FFT of each signal. As expected above empty tendon duct we see a decrease of the thickness resonance frequency. In the case of a filled pipe with epoxy having a rigidity lower than normal cement grout the shift is also visible. Finally this shift is not present in the case of a empty thick steel pipe. The resonance frequency is linked to the global local stiffness of the slab.
3. Surface waves for concrete characterization

Within the scope of the French National Agency project SENSO several non-destructive methods have been studied with the aim of characterizing concrete mixes of various compositions including variation of aggregate type and size, porosity, water content, chloride content and carbonation depth.

Surface Waves (SW) are a good candidate to evaluate non-destructively the mechanical properties of cover concrete and thus to tackle the problem of assessing in situ, non-destructively, some durability indicators. SW can be easily generated and represent the more energetic wave train recorded at the surface. Surface wave investigation depth is approximately equal to half their wavelength, so that, their velocity varies with frequency as soon as the material presents some mechanical characteristics varying with depth. The phase velocity dispersion curve, namely the phase velocity as a function of frequency, becomes the input to an inverse problem which aim is to recover as a function of depth the shear wave velocity \( V_s \).

In the SENSO project, 9 concrete mixes have been studied. For each concrete mix 8 slabs, of 0.5 m x 0.25 m x 0.12 m size, are available to perform the parametric study. For dry and fully saturated concrete the 8 slabs are available. For subsequent water content (20 %, 40 %, 80 %), carbonation depth and chloride content, this number is reduced. In order to perform the requested large number of measurements a robot that uses a non-contact receiver has been designed.

3.1. Experimental set-up

SW are generated with a sensor in contact. This source has been designed especially for this purpose by the French society IMASONIC. It is made of a matrix of piezoelectric components. Its is a large band transducer with a central frequency at 110 kHz [50 kHz – 300 kHz at -3 dB]. A wedge adapted for a Rayleigh wave speed around 2100 m/s is used to favor the generation of SW. The source is amplified by a Ritec RAM 500 amplifier. The receiver is a laser interferometer from Polythec PI (OFV-505 sensor and OFV-5000 controller) with a VD-02 demodulator that has a sensitivity of 25 mm.s\(^{-1}\).V\(^{-1}\) and a bandwidth from 0 to 1.5 MHz. The measurements points are aligned with the source. An aluminum tape is glued onto the line to improve the reflectivity of the surface. The laser interferometer is moved automatically every 0.005 m, from 0.01 m to the source up to 0.43 m, the largest offset.

3.2. Results

Figure 2 shows one recorded seismogram and a zoom on one signal situated at 0.2 m from the source. All signals are windowed automatically based on an automatic procedure that picks the maximum amplitude of each trace to center the window.

We have decided to follow within the SENSO project the phase wave velocity \( V_\phi \) at given wavelengths. Our aim was to always investigate the slabs at given depths range: six values \( V_\phi \) called observables, corresponding to wavelengths from 0.01 m to 0.06 m, were extracted from the dispersion curves. The observable that has proven to be the more relevant, on the basis of statistical studies carried out by other partners of the project [6] was \( V_\phi \) having a wavelength equal to 0.03 m. Obviously smaller wavelengths are more sensitive to the heterogeneity of concrete, while larger wavelengths could be perturbed by the thickness of the slab here equal to 0.12 m. Finally this wavelength was in the frequency region where our source was the more energetic so that signal to noise ratio was optimal.

The phase velocity dispersion curves are computed with the slant stack method in the frequency domain [4].
Figure 2. Left: one seismogram. Right: one signal at 0.2 m from the source.

Figure 3 shows examples of phase velocity dispersion curves obtained for the more (G8) and less (G1) porous concrete in the fully saturated (100%) and dry (0%) cases. The water to cement ratio respectively equals to 0.9 for G8 and 0.3 for G1. The inversion of the surface wave dispersion curves inform on the homogeneity of the water content with depth.

Figure 3. Left: robot Right: Phase velocity dispersion curves for G8 (W/C=0.9) and G1 (W/C=0.3) for the [saturated case – 100%] and [dry case – 0%]

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