Non-Contact Ultrasonic Non-Destructive Techniques: State of the Art and Their Use in Civil Engineering

Mariusz KACZMAREK¹, Bogdan PIWAKOWSKI², Radosław DRELICH¹

¹ Institute of Mechanics and Applied Computer Science, Kazimierz Wielki University, Bydgoszcz, Poland
² Ecole Centrale de Lille (IEMN, UMR 8520 CNRS) , Villeneuve d'Ascq Cedex, France

Abstract

Ultrasonic methods of testing of civil engineering materials in air where both transmission of waves into materials and reception of signals are contactless are reviewed. Short history, technical details and examples of applications of currently available methods are discussed.

Keywords: ultrasound, NDT, non-contact, air-coupled, cement based materials, degradation, flaws

1. Introduction

For effective and reliable non-destructive testing (NDT) of materials and structures in civil engineering (CE) new possibilities based on non-contact ultrasonic methodology are developed. The non-contact (NC) methods in air, where both transmission of waves into tested materials and reception of signals are contactless are interesting because they may be used for fast scanning of large surface objects avoiding problems with wet or dry coupling between contact ultrasonic transducers and tested materials. Important obstacles must be solved however related to acoustic impedance differences of solid CE materials compared to air leading to low signal to noise (S/N) ratio. This work aims at review of available solutions, opportunities and limitations of NC used in CE.

2. Features of experimental systems for NC methods

2.1. From contact to non-contact NDTs

NC techniques were initially developed for studies other than CE materials, like papers, composites or foods, see [1]. Few first examples of application of the technique for cement based materials (CBM) are 1) studies of attenuation of Rayleigh waves in CBMs using laser technique, [2]; 2) internal defects detection in concretes with echo mode, [3]; and 3) studies of role of humidity and aggregate composition for speed of sound in concrete by through transmission method, [4]. More recent applications of the methodology are discussed in the present paper. The review does not cover combinations of contact and non-contact methods which have been developed independently and use for example impact of hammer or ball [5] or contact piezoceramic transducers [6] as source and NC receivers.

2.2. Peculiarities of NC wave generation, reception and transmission

The generation and reception of ultrasound propagating in CE materials based on NC methods is possible by optical or mechanical devices. The former are usually problematic in field applications while the later need special solutions to overcome extremely large acoustic impedance mismatch with respect to air. The lost of energy between air and CE materials can be measured by the energy transmission coefficient

\[ T = \frac{4Z_1Z_2}{(Z_1Z_2 + Z_2Z_1)} \]

which is approximately equal to \(10^{-4}\) which induces very low S/N. Recent applications of NC methods mostly use piezoelectric or membrane transducers. The improvement of energy transfer is accomplished by matching layers or the effect of large surface and low mass of membranes, see e.g. [1].
2.3. Enhancement of ultrasonic energy with coded signals

A way to improve the S/N ratio is to use coded signals. The common feature of such signals is that their autocorrelation function is very short compared to length of emitted signals $T$. Usually in NC studies two types of coded signals are used: chirp and Golay’s sequence, [7]. Chirp signal is the frequency modulated sinusoidal signal for which the instantaneous frequency increases proportionally with time. Golay sequence (GS) is a signal composed of two $n$-bit length complementary sequences such that their autocorrelation functions have the secondary side lobes of opposite sign. The chirp or GS signals activate an emitter, the wave passes through studied materials and are received by sensor from which the signal is correlated with emitted form (in the case of GS the procedure is performed twice for both complementary sequences). This operation (known as matched filtering) compresses signals to a short pulse. The equivalent signal power increases is proportionally to coded signal length and spectrums obtained for chirp and GS excitations are practically the same as for spike type excitation but the signal to noise S/N improvement is significant.

3. Applications of NC methods in CE

3.1. Estimation of bulk properties of materials (through transmission method)

Velocities of bulk elastic waves in materials can be estimated using the NC approach, similarly to ultrasonic immersion method except that the coupling medium becomes air, see Figure 1. In order to improve the accuracy being low for direct application of immersion method because of random changes of the absorption loss and propagation velocity in air the measurements of intervals between multiple reflections within the sample can be used, [8].

Applying the method for mortar [8], the error of estimation of longitudinal wave velocity from multiple reflections was less than 1% while for direct transmission was close to 16%; the corresponding values for shear wave velocity amounted approx. 4% and 8%.

3.2. Evaluation of cover of concrete structures (surface wave methods)

NC surface wave (SW) technique is suitable to characterize concrete cover because the depth of penetration is proportional to the wavelength. The non-contact scanner enabling automatic emission and reception of SW is illustrated in Fig. 2, [6, 9]. The scanner uses chirp signals. The adequately inclined emitter and receiver act as velocity filters. The distance of receiver from examined sample is controlled and compensated throughout signal processing. The interference between SW signals and direct waves in air is limited by an absorbing screen. The scanner is connected to the control bloc via 20 m length cables enabling measurements over relatively large area.
The SW signals from scanner are exploited to obtain velocity dispersion, absorption characteristics, gradient of SW velocity and other parameters useful to characterize concrete cover, [10, 11]. The scanner has been used in number of French research projects giving results consistent with other methods [12; 13]. Taking into account the fact that the dispersion characteristic of SW depends on properties of concrete cover the results were used as the input for solving inverse problem in order to obtain the dependence of transversal velocity on depth, [14, 15].

3.3. Flaw detection (surface and plate waves methods)
Studies of surface or plate waves with help of NC scanners can be used for crack detection in cement based structural elements. The analysis can be then concentrated on amplitude decay of received signals or its spatial derivative and may serve as monitoring tool for cracks detection or finding other imperfections (e.g. for quality control). Fig. 3 shows examples of such results for concrete beam [16] and fiber cement boards [17].

3.4. Evaluation of porosity, tortuosity and permeability (reflectometry).
The measurements of reflection of ultrasonic waves in air can be used to determine structural parameters of dry porous materials [18]. Figure 4 presents experimental system and example of results for cellular concrete. Since for low permeability materials the reflection coefficient is close to one the methodology is applicable for materials with moderate and high permeability.

4. Conclusions
The main benefits of NC ultrasonic methods are: they can be easily automated and adapted to rapid inspection of great structures, no coupling agent is needed which eliminates the effects of its interaction with materials. They methods were already successfully used for
characterization of bulk and surface properties as well as for flaw detection and estimation of structural parameters. Further applications of the methods are limited by lack of commercially available low frequency emitters.

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References