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Nonlinear Acoustic Evaluation by Rayleigh Wave for Assessing Concrete Cover Layer Properties

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Abstract

The nonlinear acoustic applied to non-destructive evaluations is a new tool for assessing the properties of concrete with a high sensitivity. Today, the evaluation of concrete properties as a function of the depth is often difficult. In this paper we propose a new approach using Rayleigh waves for the evaluation of nonlinear properties of the concrete cover. It was developed in the lab and requires an experimental approach based on the contribution of numerical modelling. Two methods based on Dynamic Acousto-Elasticity Testing (DAET) which has pump-probe principle are proposed. The application to the case of the evaluation of the carbonation depth in concrete is presented. The first configuration shows high sensitivity in comparison with velocity measurement. The second approach is proposed for on-site measurements and shows high potential to be implemented to the field.

Keywords: nonlinear acoustic, concrete cover, Rayleigh waves, Dynamic Acousto-Elasticity Testing (DAET), carbonation, on-site measurements

1. Introduction

In the context of concrete structures, the cover layer has an essential role for the protection of reinforcement bars against corrosion and for the long-term serviceability of the structures durability. Today, the Non Destructive Evaluation of the cover layer properties as function of depth is often difficult, particularly in the case of in situ measurement. The cover layer measuring 3 to 5 cm in depth is the highly affected by various harmful environmental agents. Rayleigh waves can be used for assessing the condition of the cover layer. In fact, Rayleigh waves have a several applications in NDE of concrete [1] [2]. The propagation depth of Rayleigh waves is in the order of one wave length. The latter could be chosen to adapt the inspection scope. Moreover, the single-sided generation-reception setup allows us to apply the measurements in the field. For these reasons, Rayleigh waves show high potential for in situ evaluation of the first centimetres of concrete.

It is well known that the elastic behaviour of concrete is nonlinear and hysteretic. Particularly, in the case of dynamic solicitation (strains of 10^{-6} and above), the modulus of elasticity exhibits the so-called non classical phenomena, such as conditioning and slow dynamic effect [3]. Up to date, the most recent model describing the nonlinear mechanical behaviours of materials like concrete, is a phenomenological 1D equation (Eq.1a and 1b), in which both classical nonlinear parameters [4] explained by atomic scale and non-classical nonlinear phenomena explained by mesoscopic scale are introduced [5].

$$\sigma = \int M(\varepsilon, \dot{\varepsilon}) d\varepsilon \quad (1a)$$

With $M(\varepsilon, \dot{\varepsilon})$ is the nonlinear and hysteretic modulus given by:

$$M(\varepsilon, \dot{\varepsilon}) = M_0[1 - \beta\varepsilon - \delta\varepsilon^2 - \alpha(\Delta\varepsilon, \varepsilon(t) * \text{sign}(\dot{\varepsilon})) + \dots] \quad (1b)$$

Where M_0 is the linear modulus, $\Delta\varepsilon$ is the local strain amplitude over the previous period, $\Delta\varepsilon = (\varepsilon_{max} - \varepsilon_{min})/2$ for a simple continuous sine excitation, $\dot{\varepsilon} = \varepsilon / t$ is the strain rate, $sign(\dot{\varepsilon}) = 1$ if $\dot{\varepsilon} > 0$ and $sign(\dot{\varepsilon}) = -1$ if $\dot{\varepsilon} < 0$. The parameters β and δ are the classical nonlinear coefficients, and α is a measure of the material hysteresis. This latter could relate to the conditioning. Note that this approach does not include slow dynamic, which is described by a time dependence recovery of elastic properties occurring after a disturbance. This phenomena is also observed experimentally but is not analyzed in this study.

In addition, NDE literature [6] [7] [8] [9] reported that the sensibility of the parameters of nonlinear acoustics measurements are increased tenfold than ones evaluated by linear measurements, particularly with damage presence [7] [9]. These results showed a high potential of nonlinear acoustic for precocious quantification of damage.

Another important point of this study is the choice of the evaluation method. Among the nonlinear acoustic methods, Dynamic Acousto-Elasticity Testing (DAET) allows analysing simultaneously classical and non-classical parameters. This method was applied to assess the nonlinear properties in of various types of rock [10] [11]. Generally, DAET is based on pump-probe principle. The pump wave at low frequency (LF) imposes an important deformation into the sample in order to activate the nonlinearities. In the same time high frequency (HF) waves play the role of probe waves in order to inspect the material changes. The nonlinearities are analyzed by measuring the variations of probe wave velocity and amplitude. Thus, the variation of elastic properties of the investigated volume can be determined.

In this paper, two approaches of DAET are presented.

The first one uses a shaker for pump wave generation, would impose into the material a vibration with constant amplitude (steady state). This configuration is considered as the standard DAET [12] [13]. Recently, we [13] developed this configuration and validated the method for the assessment of thermal damage. We evaluated the classical nonlinear coefficients β , δ and the non-classical ones α [13].

The second configuration relies on the same principle of DAET but uses hammer impact to generate the pump wave. It is proposed for in situ measurements.

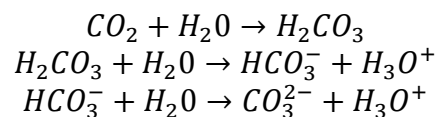
This paper deals with carbonation penetration as a function of the depth from the free surface, and allows addressing a gradient problem. To date, the characterization of carbonation depth in concrete has been a challenge of non-destructive testing (NDT).

2. Material

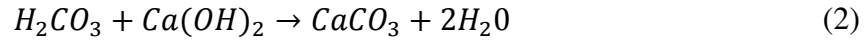
This work focuses on the carbonation that is difficult to evaluate. The Non Linear Acoustic evaluation is one of the rare technics able to distinguished carbonated or not carbonated specimens [8].

Carbonation

The carbonation corresponds to the progressive formation of calcium carbonate into concrete due to the penetration of the carbon dioxide CO_2 of the air (also a small quantity existed in porosity) that reacts with the calcium hydroxide $Ca(OH)_2$ found in the cement. The chemical reactions can be described as [8]:



The reaction between carbonic acid and carbon dioxide in cement paste after the dissolution is:



The direct consequence of these reactions is the decrease of PH in the affected zone. Consequently, the reinforcing steels loose then their passive film protection and the risk of corrosion increases dramatically. The carbon dioxide penetrates from outside so the concrete is most exposed in cover layer.

In this paper, carbonation series consists of three concrete samples of 12x25x50cm in size exhibiting a carbonated layer of 5 mm, 10 mm and 20 mm, respectively. Carbonation treatment was done by an accelerated lab process within the framework of the French project EVADEOS (*EVALuation non destructive pour la prédiction de la DEgradation des structures et l'Optimisation de leur Suivi*). One face of each sample is protected, so carbon dioxide could attack only one face of the samples. The affected depth is verified on companion specimens that follow identical treatment. The physical properties of the carbonated samples are listed in Table 1.

Results show that the carbonation layer exhibits small degradations of the modulus of elasticity. It is primarily generated by the formation of calcium carbonate that leads to a decrease of the porosity, the molar volume of carbonates being larger than that of hydrates. It explains the increase of wave velocities.

Table 1: Properties of carbonated samples

Designation	C1	C2	C3
Carbonation depth (mm)	5	10	20
Density (kg/m ³)	2267	2277	2283
V _{pressure} (m/s)	4191	4001	4173
V _{shear} (m/s)	2393	2356	2423
V _{Rayleigh} (m/s)	1987	2064	2153

3. Nonlinear acoustic evaluation methods

This study consists to apply the two approaches based on DAET principles. All tests were carried out in the laboratory. The first approach has the standard configuration of DAET, so all the conditions between LF pump wave and HF probe wave are respected [13]. In this configuration, a shaker is used to generate the vibration corresponding to LF solicitation. The second configuration keeps the pump-probe principle and uses impact of hammer to generate the LF solicitation. The generation mode of Rayleigh waves (probe wave) in each configuration was set differently. This study only focuses on the nonlinear parameter α because in situ measurements need simple and robust evaluation.

The first configuration is called “DAET by shaker” and the second one “DAET by hammer”. The nonlinear parameter α_s (shaker configuration) and α_h (hammer configuration) are analysed and presented. These parameters correspond to the conditioning effect in concrete behaviour resulting from the LF or the hammer solicitations. These α_s and α_h are thus supposed to be comparable.

3.1 DAET by shaker

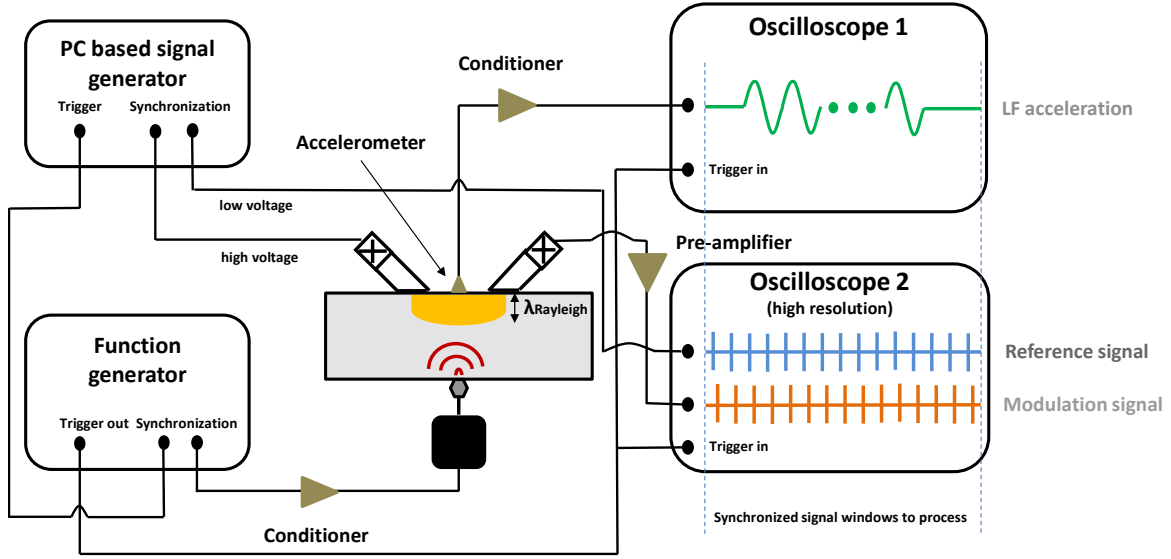


Figure 1: “DAET by shaker” experiment description; green signal: low frequency excitation, blue signal: reference pulses, orange signal: modulation pulses

Figure 1 shows “DAET by shaker” experimental setup. The shaker generates the “pump wave”, and the sample resonates in a flexural mode. The resonant frequency range of each sample is ascertained by an Eigen-frequency analysis using COMSOL and the effective value is found experimentally. The LF acceleration signal is recorded by an accelerometer attached at the centre of the specimen. Two HF signals are sent simultaneously from the function generator. It contained pulses (one 100–kHz cycle) regularly spaced in time that are sent in synchronization with LF signal and also between themselves. The first HF signal, termed “reference” goes directly to the oscilloscope. The second signal termed “Modulation” is sent with a high voltage. It generates Rayleigh waves into concrete samples through the transducers-wedges system. The wedges are made out in Teflon. The LF signal and two HF signals are recorded to be processed. The reference signal determines the reference time for the windows used to analyse each pulse of the HF signals (without LF or with LF). The investigated depth of Rayleigh waves at 100 kHz is about 2 cm that is in the same order with the biggest carbonation depth of the samples.

In fact, the flexural mode causes geometric changes in the propagation direction of the wave path changes, which result in a linear time shift. This time shift is computed from the displacement in wave direction and Rayleigh wave velocity [13]. As a consequence, the time of flight modulation (TOFM) (in order of ns) after correction is assumed to characterizing solely the nonlinear modulation information. Finally, the variation of the material modulus is estimated as being proportional with relative nonlinear time shift (Eq.3).

$$\frac{M(\epsilon_{LF}) - M_0}{M_0} \cong -\frac{2}{TOF_0} TOFM \quad (3)$$

Where TOF_0 is the average of the time of flight of Rayleigh wave for the pulses recorded before LF activation.

Based on (Eq.1b), the modulus evolutions can be evaluated as a function of strain amplitude (Eq.4) [10]. A second-order polynomial is applied to extract the nonlinear elastic parameters β , δ and C_s . β and δ are assumed to be proportional with anharmonicities content according

to the classical nonlinear theory. C_S corresponds to the conditioning effect linked to the hysteretic behaviour of the concrete. It evolves with the excitation level.

$$\frac{\Delta M_\varepsilon}{M_0} \approx \delta \varepsilon^2 + \beta \varepsilon + C_S \quad (4)$$

Thus, the slope of C_S evolution with the applied strains amplitudes allows calculating the parameter α_S as:

$$\alpha_S = \frac{C_S}{\Delta \varepsilon} \quad (5)$$

The strain appeared in (Eq.4) is considered in this configuration as the average value of the volume strain found in the propagation zone and along the wave direction. It is noted that both geometric displacement and the strains amplitude in (Eq.5) are estimated from the measured acceleration with the vibration model [14].

3.2 DAET by hammer

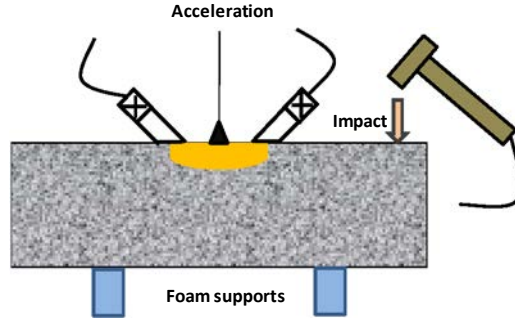


Figure 2: “DAET by hammer” experimental setup

This configuration has been designed for in situ measurements. The single-side device of measurement (Figure.2) is suitable for applications on service structures. The hammer impact plays the role of pump wave. The impact point is set at the end of samples to promote the flexural vibration mode by placing the sample on the foam supports at the positions 0.224 times the sample length (Figure 2). LF signal is recorded by the accelerometer. The HF transducer positions are kept unchanged from “DAET by shaker” configuration. Two continuous waves are sent (reference and modulated) with a sinus of 100 kHz. Because the hammer impact is done manually, it is impossible to repeat exactly the same impact. Therefore, the continuous HF waves allow having all the nonlinearity information due to an impact during all the recorded time. The continuous reference signal synchronized with Modulation signal is also recorded. Both HF signals are triggered by the LF acceleration signal generated by hammer impact.

A sliding window protocol is applied for the signal processing, in parallel in Modulation and Reference signals. The phase shift $\Delta\varphi_i$ of high frequency 100 kHz between two signals (Eq.6) is calculated for each window i . Then, the time shift Δt_i is derived according to (Eq.7).

In order to determine the time of flight modulation for each window $TOFM_i$, we subtract the time of flight of the signal before impact Δt_{01} after displace the time shift curve to zero (Eq.8).

$$\Delta\varphi_i = \varphi_{iModulation} - \varphi_{iReference} \quad (6)$$

$$\Delta t_i = \frac{\Delta\varphi_i}{\omega} \quad (7)$$

$$TOFM_i = \Delta t_i - \Delta t_0 \quad (8)$$

Index i designates i^{th} signal window

Thus, the modulus variation curve is obtained through (Eq.3).

The description of the nonlinear elastic response associated with the hammer impact was presented elsewhere [16]. A typical curve (bleu curve) of the nonlinear modulus variation is shown in figure 3. The decrease of the modulus is related to the perturbation of the material associated with the impact. The red curve corresponding to the mean value of modulus in function of time is obtained by applying a low filter (500 Hz) to this curve. This curve is assumed to represent the conditioning of elastic behaviour associated with the impact. The parameter C_h is defined then being the maximum value of red curve for a given excitation level. This value is supposed to correspond to conditioning offset C_S by representing the nonlinear non classical effect.

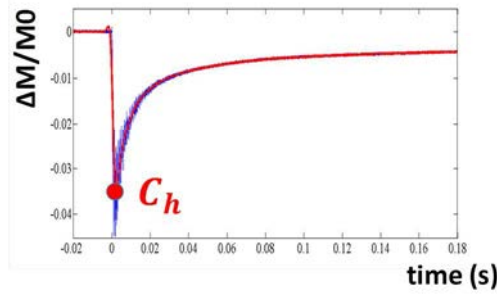


Figure 3: Typical curve of nonlinear modulus variation (bleu curve). C_h is the maximum value of conditioning (red curve) in “DAET by hammer” measurement

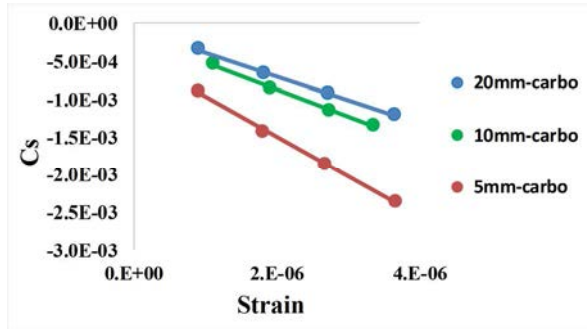
The value of strain amplitude is determined by the normalized spectral amplitude of the first flexural mode frequency extracted from the accelerometer signal. The dominant peak of LF spectrum is verified that corresponds to flexural mode frequency. We assumed in this study that almost energy of impact transmitted to the sample is included in this vibration mode. Consequently, the strain amplitude imposed to the sample with an impact can be estimated from the spectral acceleration amplitude with COMSOL vibration model. The nonlinear parameter α_h derived from the hammer configuration is introduced with (Eq.9). It represents the evolution of C_h as a function of strain amplitudes $\Delta\varepsilon$ corresponding to different hammer impact levels.

$$\alpha_h = \frac{C_h}{\Delta\varepsilon} \quad (9)$$

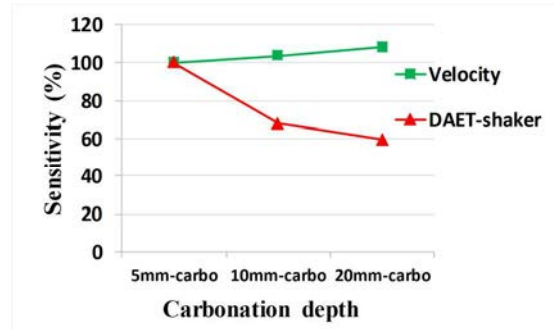
4. Results and discussions

4.1 DAET by shaker

An increase of absolute values of conditioning offset C_S in function of strain amplitude (Figure 4-a), while the nonlinear parameter α_s evolves inversely with the carbonation depth (Figure 4-b). The values of α_s are provided in table.2.



a/ Evolution of C_s as a function of strain amplitude



b/ Normalized evolution (%) of α_s and V_R

Figure 4: Results of “DAET by shaker” for carbonation analysis

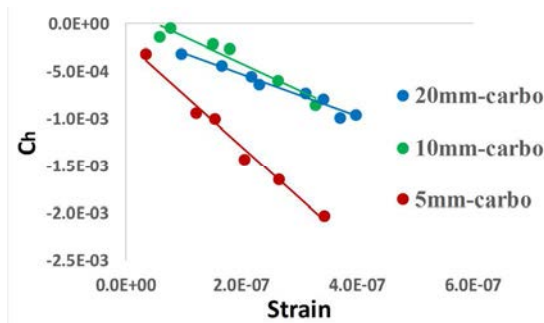
Table 2: Nonlinear parameters in carbonation analysis

Carbonation depth	5mm	10mm	20mm
α_s	-528	-359	-314

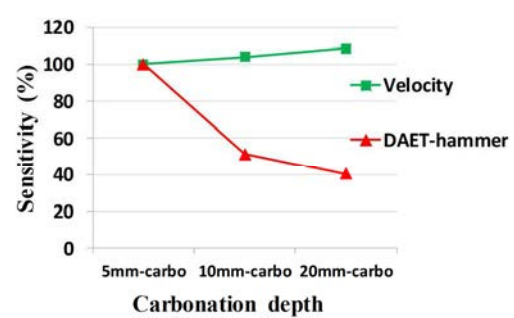
The material exhibits nonlinear behavior when increasing imposed strain amplitude. It is confirmed by the evolution of the absolute value of C_s . We can also observe that α_s decreases with carbonation depth. This confirms that the nonlinearity depends on the density of the contact-loss in micro cracks and the porosity. It is also consistent with Bouchaala et al. [8] and Gun Kim et al. [17].

4.2 DAET by hammer

The results of “DAET by hammer” configuration aim at comparing with DAET by shaker on the same carbonation samples. The HF transducers positioning is kept unchanged. The linear evolution of parameter C_s is plotted as a function of strain amplitude (Figure 5-a). The different points correspond to the different hammer impacts. The coefficients of determination of linear regression are good (from 0.92 to 0.999). The evolution of α_h (Figure 5-b and table.3) is consistent with the result of α_s . The absolute values of α_h are found being about ten times of α_s values. This point is explained by the different strain amplitude scale.



a/ Evolution of C_h as a function of strain amplitude



b/ Normalized evolution (%) of α_h and V_R

Figure 5: Results of “DAET by hammer”

Table 3: Nonlinear parameters in carbonation analysis

Carbonation depth	5mm	10mm	20mm
α_h	-5505	-2836	-2213

5. Conclusion

This research combines nonlinear acoustics DAET and surface Rayleigh wave to assess a typical distress in concrete. Both proposed methods yield a new tool for the evaluation of the carbonation depth. The first configuration uses a shaker as excitation source. It was conducted for laboratory measurements. The results showed a good sensitivity of the nonlinear parameter α_s to the carbonation depth of concrete cover. The second method used a hammer as excitation source. It is a single-sided configuration adapted for in situ measurement. The results of nonlinear parameter α_h showed good agreement in terms of sensitivity with the first configuration. This second configuration could be developed for in situ assessments. Implementing this NDE method on site requires to monitor the strains applied on the structures and to quantify them. Similarly it is useful to understand the nonlinearities generation mechanisms. These concerns are the aims of a new research project “Dynamic and Non Destructive Testing (DCND)”, accepted in a first step by the National Radioactive Waste Management Agency (ANDRA) and the French Agency of Research (ANR).

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