Analysis of the backscattered waves in an heteregeneous material: Application on concretes

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In heterogeneous materials, ultrasonic waves can be scattered forward or backward. The set of the backscattered contribution generates a wave that is attenuated over time. We make the measurement of this attenuation with the envelope of the backscattered signal. This information evolves with the nature, shape and size of the scatterers hence with the material state. First, we propose the simulation of the signal in which we introduce the attenuation dependence on the frequency. Second, we develop this application on concretes in which many scatterers contribute to the signal's generation. We apply the technique with different tools to generate and exploit the backscattered waves. The attenuation evolutions with the material's nature, porosity, damage and saturation rate of the concrete are analysed.

Introduction

Estimating the state of a concrete structure is an important challenge. It implies implementing control over the material at different ages. This material's pathologies are generally well identified [1] and many techniques [2, 3] can be considered in order to bring them forward and estimate their importance.

Acoustic wave propagation testing is resorted to under the form of echo impact, acoustic emission and ultrasonic waves. The latter can be used with transmitted, reflected or surface waves. The major part of applications allows determining the velocity and/or the attenuation of the waves. Accessing these measurements implies to know the length covered by the wave in the structure. It is often difficult to measure this distance on site or its precision is weak. Some techniques allow working without this data and the measurement needs only one side access. The backscattered wave analysis is one of them and is particularly simple to implement.

The principle is to generate an ultrasonic wave from the surface of the structure. The wave that propagates through the material is in interaction with all scatterers on its path and each of them diffuses this wave in space. The forward part contributes to build the coherent or incoherent part of the transmitted wave [4, 5, 6]. They apply homogenization modelling to obtain an equivalent velocity or attenuation for the material or they analyse the coda to extract the diffusion coefficient of the wave. Some authors extract the noise out of the signal to emphasize the searched information [7].

We propose to work in the opposite way. We assume that the noise is depending on the nature, the size and the density of the scatterers. The backward part of the scattered wave goes back to the surface and is recorded by the transducer. The received signal is the sum of all the contributions backscattered by the different scatterers and generally the signal decreases with time.

Some authors have proposed an analysis of the backscattered signal. Sanïe [8] extracts the wave attenuation of the signal in a metallic material. Fuentes [9] analyses the divergence cone to extract the porosity rate of mortar. Chaix [10] tests the possibility to control concretes by this type of waves by applying the solution advanced by Sanïe. He proposes exploitable depth and frequency ranges.

The concrete is particularly adapted to this analysis because it is a very heterogeneous material with a very large range of sizes and shapes of scatterers.

The objective of our work is to explain and to model the evolutions of the backscattered waves with the concrete and its damage or its pathologies. The interest is to propose a solution very simple to implement in the measurement on real structure.

In this way, we study in a first part the influence of the attenuation dependence of the ultrasonic wave in the concrete on the backscattered wave analysis. In a second part, we show results of concretes characterization by laboratory tests.

Backscattered waves

The generation principle of the backscattered wave is proposed in figure 1

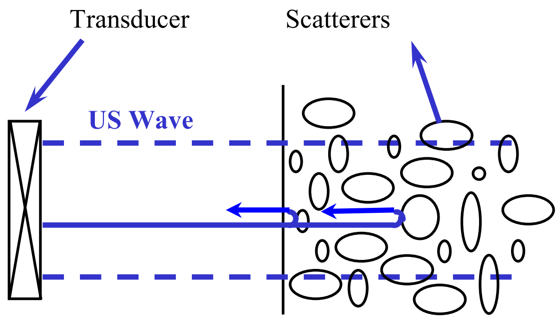

Figure 1: Generation of the backscattered waves

The sum of all the contribution of the backscattered part of the wave gives a signal presented in figure 2.

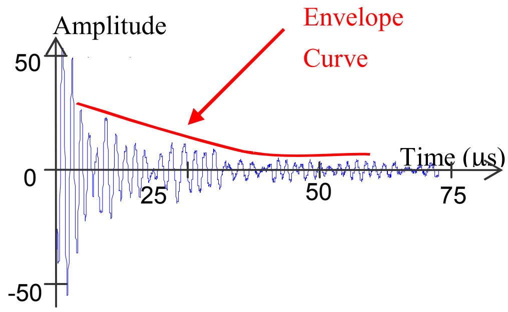

Figure 2: Backscattered signal

The ultrasonic backscattered waves can be generated with a simple transducer and an ultrasound generator. A former study [11] has explored the different possibilities and signal processing to improve the measurement process.

The link between the amplitude and attenuation of the backscattered noise with the size, nature and density of the scatterers is depending on the material.

Sanïe proposed a model [8]. The signal received by the transducer corresponds to the function r(t) that is the convolution of two time-dependent functions

$$r(t) = u(t) * g(t) \quad (1)$$

where u(t) is the generated signal and g(t) the transfer function of the propagation medium.

$$r(t) = u_0.e^{-\alpha.C.t}.\sum_{k=1}^{M} \sigma_k.e^{i.\phi_k} \quad (2)$$

where u_0 is the initial amplitude of the wave, α is the backscattered attenuation wave, C is the velocity of the ultrasonic wave in the material, t is the time.

M defines the number of scatterers and σ_k corresponds to the scattering section. This section is depending on the scatterers characteristics.

Eventually $\phi_k = \omega.(t - \tau_k)$ is the temporal position of the scatterers τ_k.

On the hypothesis that the signal is in the farfield and that the scatterers are randomly distributed in terms of size and thus scattering section, we can approximate the exponential signal decrease $-\alpha.C.t$ of the curve by an envelop like in figure 2.

If we know the velocity of the ultrasonic waves we can deduce the attenuation coefficient of the backscattered wave. It is defined without frequency dependence.

For the experimental measurement, we propose this parameter to follow or determine the characteristics of the concrete.

For some different types of scatterers, we can introduce this parameter in the equation by the scattering section defined for each of them.

For example, in the case of damage, we propose

$$r(t) = u_0.e^{-\alpha.C.t}.(\sum_{k=1}^{M} \sigma_{sk}.e^{i.\phi_k} + \sum_{j=1}^{M'} \sigma_{sj}.e^{i.\phi_j})$$

(3)

where the first term corresponds to the scattering from the aggregate with a scattering section σ_{sk} and the second from the cracks with a section σ_{sj}.

The domain defined by Chaix [10] on which it is possible to prospect is in frequency from 500 to 2500 kHz and in depth from 40 to 140 mm. These ranges are proposed for the case of the concrete characterisation.

This means it is possible to control some centimetres of the cover concrete. This latter is very important for the protection of the reinforcement steel bars.

This first study on the concrete damage has showed the high sensitiveness of the backscattered wave attenuation coefficient that increases strongly between sound specimens or those damaged by thermal stresses (200 °C). The attenuation of the backscattered waves is threefold.

Attenuation of the wave

This paragraph presents the expectations of the backscattered signal and more precisely the attenuation importance in the model to take into account or not the attenuation dependence on the wave frequency. We show the difference of the results that we obtain in the two cases and the consequences on the extraction of the α coefficient.

Modelling

The attenuation generates a decrease of the wave bandwidth with time and affects the response of each scatterer when it propagates on its path. That induces that the first contributions move with high frequency and the latter are mainly composed by low frequencies. We introduce the attenuation as a function of the frequency in the calculation of the contribution of each scatterer.

We can represent it by the following algorithm:

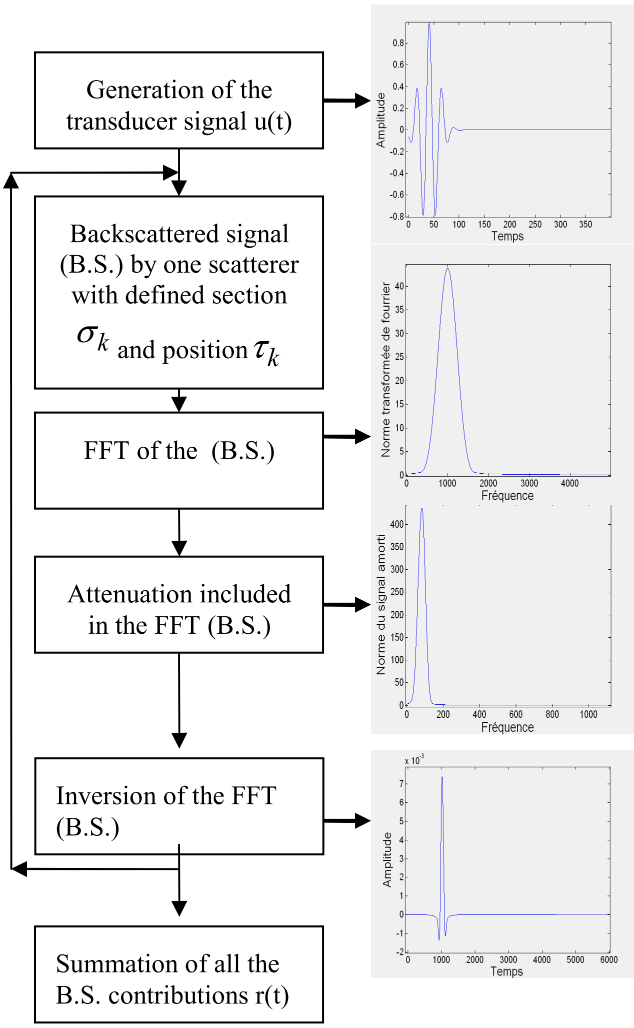

Figure 3 : Principle of attenuation implementation

On the basis of this protocol, we have to define each step of the calculation.

The first step is the transducers with a diameter D and the spectrum of frequency. The function generated is typically

$$u(t) = u_0.e^{-\gamma.t^2}.e^{i.\omega.t} \quad (4)$$

The second step is the definition of the medium. It is a specimen composed of a cement matrix and scatterers. We have chosen polystyrene balls in order to get the most important impedance difference between the matrix and these scatterers. The balls are very similar to the air and can simulate the presence of defects or of porosity. Its radius is a=2.84 mm. This value is chosen to work in the stochastic domain in order to be sure to get an important scattering effect. The value of $k_l.a$ goes from 0.3 to 3. k_l is the wave number of the longitudinal waves. The scattering section [12] is important and the amplitude of the scattered contributions is high. It is given in figure 4.

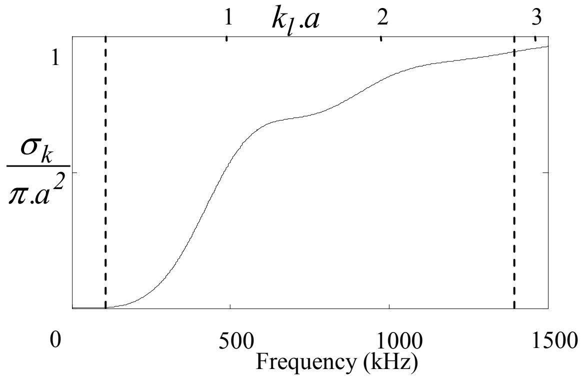

Figure 4: Scattering function normalised on the scatterer area

Data concerning the material are deduced from experiments on a real specimen realized with 30 % of polystyrene balls in a cement matrix. The specimen is 250 mm in diameter and 80 mm thick. The velocity and attenuation of the medium are obtained by the transmission wave's measurement. The velocity is 4 300 m/s. We have verified that the frequency does not have a lot of influence on its value. The field attenuation is given by figure 5.

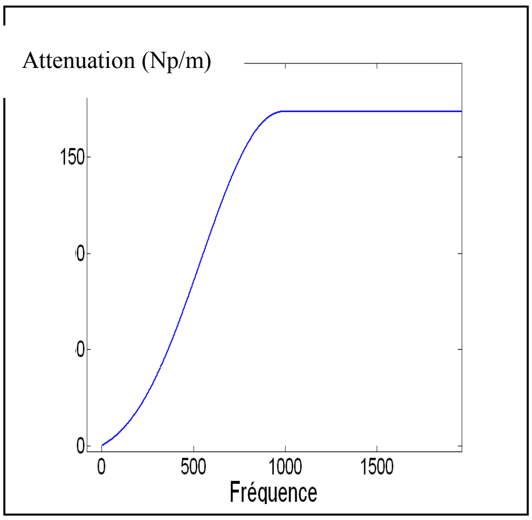

Figure 5: Attenuation as a function of the frequency

The curve is obtained by fitting experimental results.

We generate 32 signals for one medium. The scatterers are introduced randomly on the wave path. The number of them depends on the volume of the specimen run through by the wave. This volume is a function of the beam diameter (D/4) and the specimen thickness. We introduce 400 scatterers for a composition in volume of 30 % of balls.

Results and discussion

We do two simulations.

In the first one, we do nott take into account the attenuation evolution with the frequency. In this case, the attenuation introduced in the model is constant at 170 Np/m. This value is measured for the central frequency of the transducer (1 MHz). The attenuation coefficient of the backscattered wave extracted from the simulation is 470 Np/m. This value is more important than the one introduced in the calculation.

The second simulation takes into account the attenuation evolution described by figure 4. The attenuation coefficient of the backscattered wave is 267 Np/m. This result is more in accordance with the initial value.

To comment on the simulation part, we can note

* the value of the attenuation coefficient of the backscattered wave is in coherence with the initial data when we take into account the attenuation dependence on the frequency. We reduce the value extracted by 1.8.

* the fact that the extracted value from the coefficient αC is different from the one introduced in the model shows the importance of the determination of the scattering section. To improve these results, we can introduce the multiple scattering in the model by the calculation with the forward and backward scattering functions that give the amplitude of the scattered wave in space with an angular distribution.

* the attenuation coefficient of the backscattered waves calculated on the basis of the Sanïe's modelling is not the same as the attenuation coefficient measured with longitudinal waves. The future works will tell us if it will be possible to obtain a realistic value. That will be the first step for the inversion process.

It is also important to know the sensitiveness of the information deduced from this technique simple to implement on the structure or the piece to be controlled. So in the next part, we analyse some results obtained in laboratory tests.

Experimental data

In the second part, we present experimental data performed in a French project that explores and quantifies the sensitiveness of several non destructive testing techniques regarding pathologies of concrete specimens.

The attenuation coefficient of the backscattered waves is one of the 70 measurable quantities estimated in this project. The specimen dimensions are 50*25*12 cm^3. This experimental plan proposes to calibrate all the techniques in order to work on their complementarity by using data fusion.

The results presented concern the sensitiveness of the backscattered waves as a function of the water saturation rate and concrete's porosity.

The specimen set is composed of 6 batches with 6 specimens. The concretes are made with the same components. Only the ratio water/cement (W/C) evolves for each batch in common values.

So the porosity and the Compressive Strength changes as shown in table 1. The porosity presence induces additional scattering effects on the wave propagation. The size of the aggregates ranges from 4 to 14 mm.

Batch	G1	G2	G3	G4	G5
Water/Cement	0.30	0.45	0.55	0.6	0.9
CS (MPa)	68.6	55.2	53.0	43.3	30.8
Porosity (%)	12.5	14.3	15.5	15.9	18.1

Table 1: Water/Cement ratio, Compressive Strength, porosity of the six batches.

The water ratio is modulated for each concrete for five levels (0 – 40 – 60 – 80 – 100 %). The water fills up the entire vacuum available in the concrete. They are cracks or porosities. The presence of water modifies the nature of the porosity and cracks, which means that the scattering section evolves with the water ratio. The controlled water ratio implies supplementary difficulties in coupling. We have to preserve the specimens with an adhesive and protective band. So the measurement uncertainties increase.

The tests are done on three marked points at same positions on each specimen. The transducer (emitter-receiver) used has a 1 MHz. central frequency with a bandwidth ranging from 630 to 1270 MHz at -6 dB. Its diameter is 25.4 mm.

To extract the attenuation coefficient of the backscattered waves with the envelop analysis, we need randomly distributed scatterers. If we look at the size of the beam in the farfield (6 mm) compared to the aggregates size, we see that they are approximately the same. So at one of the points and with a single shoot, first we are not able to exploit the signal theoretically, and second we get local values that depend on the presence or not of one big aggregate. To avoid this configuration, we have to work out the average of 100 signals moving the transducer in a circular zone. This zone is defined by a guide with a size double that of the transducers. This spatial average allows validating the random position and distribution of the scatterers.

The value deduced for one batch is the average of the mean values obtained on the three points of each specimen. We define the standard deviation similarly.

The standard deviation varies from 2,1 to 3,1 NP/m.

The results obtained for different water saturation rates as a function of the five batches are plotted on figure 6 and those obtained for different batches as a function of the water saturation rate are on figure 7.

We can make comments on the curves evolutions:

* the amplitude of the variations for the different curves evolves from 24 % to 93 % as shown on figure 6 and from 13 % to 64 % on figure 7. They are significant intrinsically but we have to discuss on the standard deviation.

They are two times as important as the evolutions of the ultrasonic velocity of the longitudinal waves measured on the same specimens (4% to 23 %) presented in figure 8.

* the evolutions are not linear neither for the backscattered waves nor the transmitted waves. To explain them, we can make the hypothesis that the different comportments of the water in the cement matrix can modify the evolutions.

The first effect of the water is the easier sliding of the lips of the cracks or the porosity. These cracks are naturally numerous in concrete. The second effect is the increased internal pressure in the concrete when more and more cracks or porosity are filled up with water. These two effects can act or and be prominent for different levels of water saturation rates.

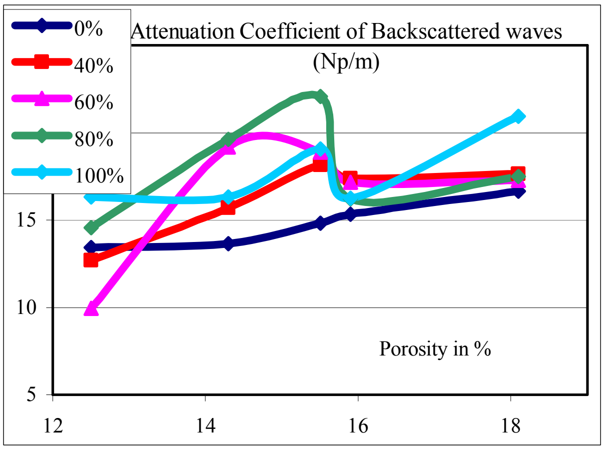

Figure 6: Attenuation coefficient of the backscattered waves as a function of the porosity for different water saturation rates.

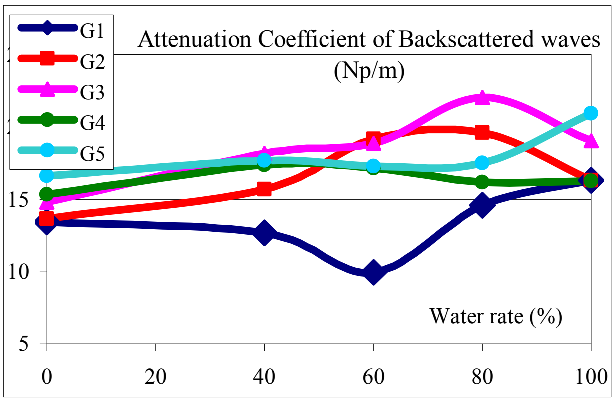

Figure 7: Attenuation coefficient of the backscattered waves as a function of the water saturation rate for different porosity rates.

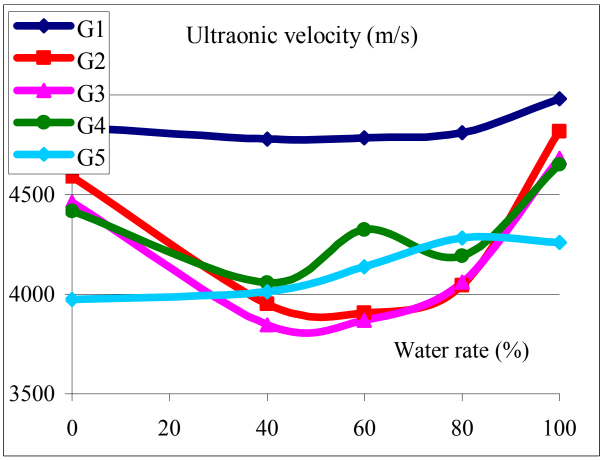

Figure 8: Ultrasonic velocity of longitudinal waves as a function of water saturation rates for different porosity rates

standard deviation of the tests performed on the ens varies from 2.1 to 3.1 Np/m. The value is not negligible regarding the results of the measured attenuation coefficient. One study [13] has shown that it is possible to reduce this standard deviation by 3 with a specific transducer (1 MHz) with separated emission and reception. In this case, the waves recorded are not perturbed by the emission and it is possible to amplify the signal very much. The same study has also shown that it is one more time possible to reduce the standard deviation by 3 with a different process of measurement. The idea is not to work out the average of 100 signals, but to work with the envelope of the maximum for these 100 signals. The information is not exactly the same, but it will be tested in laboratory tests and in structures evaluation.

5 Conclusion

To control the concrete and the structure integrity, we propose to exploit the backscattered waves because of theirs implementation simplicity. We have described a model to calculate the backscattered waves and to extract theirs attenuation coefficients. This simulation gives some divergences from the experimental values. Taking into account the real distribution of the material attenuation with the frequency, allows correcting the results. This model can be improved by a better implementation of the backward scattering function.

The tests carried out in a big experimental plan give the evolution of the attenuation coefficient of the backscattered wave as a function of the water saturation rate and the porosity of the concrete. The results analysis plots a sensitiveness of the coefficient with the different concretes state, but the amplitude of the variations are two times as important as the longitudinal wave velocity. The standard deviation of the results is due to the difficult tests conditions and some solutions to reduce it are proposed.

The backscattered waves are a new solution to non destructive testing of concrete. The results and the model proposed are a way to exploit and understand these waves. Some improvements are proposed or already tested.

Acknowledgement

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