Characterization and modeling of ultrasonic structural noise in the multiple scattering regime

Thomas Bedetti, Vincent Dorval, Frédéric Jenson, Arnaud Derode

CHARACTERIZATION AND MODELING OF ULTRASONIC STRUCTURAL NOISE IN THE MULTIPLE SCATTERING REGIME

T. Bedetti[1], V. Dorval[1], F. Jenson[1], and A. Derode[2]

[1] CEA - LIST, centre de Saclay, Bât. 611 - PC120, 91191 Gif-sur-Yvette, France
[2] Institut Langevin, Université Paris Diderot – Paris 7, ESPCI ParisTech, CNRS UMR 7587, 1 rue Jussieu, 75005 Paris, France.

ABSTRACT. Multiple scattering can occur when performing ultrasonic measurements on highly scattering materials such as coarse grain steel or concrete. It constitutes in general a limiting factor for NDE techniques. In this communication, a method to simulate the structural noise due to multiple scattering is described. It requires three parameters: the diffusion constant, the elastic mean free path and the correlation distance. A method to obtain these parameters based on a single measurement procedure is presented. This approach has been applied to samples of coarse grain steel. The backscattered noise has been calculated for different probes and compared to experimental signals.

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INTRODUCTION

In the context of ultrasonic non destructive evaluation, the detection of flaws in highly scattering material represents a challenge. Such materials, from coarse grain steel to concrete, are widely used in the industry. The difficulty of inspection comes from the interaction between the ultrasonic wave and the microstructure: it causes the attenuation of the transmitted beam and the appearance of structural noise. Both these phenomena reduce the signal to noise ratio.

A distinction is usually made between single scattering and multiple scattering. There has been an important focus recently on the simulation on single scattering in non destructive testing (for example by [1] and [2]). One of the motivations of the work presented here was to add the simulation of multiple scattering to the simulation of single scattering of [2].

In cases where the scattering is most important, multiple scattering dominates. Being able to characterize and to model the structural noise due to multiple scattering can help design appropriate inspection procedures. In this communication, a method to simulate structural noise based on three parameters is proposed. A procedure to extract these parameters based on a single measurement is described. Outputs of simulations are compared to experimental results.

SIMULATION OF STRUCTURAL NOISE

This simulation method presented here can be decomposed in four steps: the emission by the probe, the diffusion of the average ultrasonic energy, the conversion from average energy to an ultrasonic field, and the reception by the probe.

This method differs significantly from methods that simulate structural noise based on a single scattering approximation. The method presented here relies on the diffusion approximation, which assumes that multiple scattering dominates and can be considered to be the opposite of the single scattering approximation.

Computation of the Field Emitted by the Probe

This step is the computation of the ultrasonic field before any diffusion occurs. It concerns the propagation from the probe to the metal sample, and also the propagation in the sample over a certain distance. We make the approximation that no diffusion occurs until the wave has traveled a distance l_e in the sample, and that the diffusion approximation can be used afterwards. l_e is the elastic mean free path and is defined as the characteristic distance of extinction of the coherent intensity.

In this step, we compute the ultrasonic field at a depth l_e in the sample assuming that no diffusion occurs. In the following step, the diffusive regime assumption will be used. This abrupt transition from an incident wave to a diffuse field is an approximation: an ideal simulation should be able to account for a smooth transition from a coherent wave to a diffuse field.

To compute the propagation of the incident wave from the probe to a depth l_e in the sample, we use the ultrasonic field computation module of the Civa platform. It relies on a paraxial beam method [3].

Computation of the Energy Diffusion

The scattering of the ultrasonic energy in the sample is modeled using the diffusion approximation, which assumes that the multiple scattering is largely dominant. In this approximation, the propagation of ultrasonic energy is analog to heat propagation and is governed by a diffusion or heat equation [4]:

$$\frac{\partial E}{\partial t} = D\nabla^2 E + \text{source} \tag{1}$$

where D is the diffusion constant.

Analytical solutions of this equation exist for some cases, notably for a cuboid with no outgoing ultrasonic flux [5]. We use that representation for samples of steel immersed in water.

Using that solution we can, knowing a source of ultrasonic energy in the medium, calculate the ensemble averaged ultrasonic energy after diffusion at any position in the sample and time. In our simulation, the source is the energy of the ultrasonic field at depth l_e, computed in the previous step. We use the solution of the diffusion equation to calculate the ensemble averaged energy $<E>$ as a function of time at the surface of the sample.

We use in the diffusion equation the value of D experimentally determined with the method described later in this communication.

Random Generation of a Diffused Ultrasonic Field

The previous step yields an ensemble averaged quantity. To obtain realizations of structural noise signals, realizations of the ultrasonic field need to be considered instead of averaged quantities. Therefore, in this step of the simulation, realizations of the ultrasonic field are randomly generated.

The signal measured by the receiving probe is proportional to displacements and stresses in specific directions. In the current version of the method, these fields are not determined precisely. We only consider a generic quantity noted Φ, defined as the weighted sum of displacements and stress that is measured by the probe. We assume the following proportionality relation with $<E>$ (the output of the previous step of the method):

$$\langle |\Phi(\vec{x},t)|^2 \rangle \propto \langle E(\vec{x},t) \rangle. \tag{2}$$

The proportionality factor is not determined in the current version of the method. As a consequence, the outputs of the simulation will not be properly calibrated.

We assume that the statistical distribution of Φ at a given position and time is normal with a zero average. This is based on the fact that the statistical distribution of structural noise if often described as a normal distribution with a zero average, and we expect Φ to have similar characteristics.

An important property of Φ is the fact that there is a correlation between $\Phi(\vec{x}_1, t_1)$ and $\Phi(\vec{x}_2, t_2)$ for close positions $\vec{x}_1$ and $\vec{x}_2$ and for close times t_1 and t_2. The correlation in time is related to the form of the incident pulse. The correlation in position is related to a correlation distance d_c, which is an input parameter of the simulation. We reproduce the correlations in the simulation by first generating a white noise and then convolving it in time and space by functions that ensure correlations.

We multiply this correlated noise by $\sqrt{\langle E(\vec{x},t) \rangle}$ in order to make sure that equation (2) is verified. We then obtain a realization of the field $\Phi(\vec{x},t)$. It is possible to randomly generate several realizations of $\Phi(\vec{x},t)$.

Computation of the Reception by the Probe

The signal measured by the probe is computed using a reciprocity theorem similar to the one of [6]. As a consequence, the simulated signal is proportional to the integration over the surface of the sample of the product of $\Phi(\vec{x},t)$ by the field of the receiving probe. The field of the receiving probe is obtained using a Civa computation.

CHARACTERIZATION OF THE SCATTERING BY A MATERIAL

The simulation method described above requires three input parameters: the elastic mean free path l_e, the diffusion constant D and the correlation distance d_c. A method to determine these three parameters based on a single experiment is described in this section.

Experimental Setup

In the experiment, an ultrasonic array is placed parallel to a steel plate in a water tank (figure 1). The array is moved and for each position the response matrix K is recorded. This matrix contains the N*N signals measured for each of the N elements used

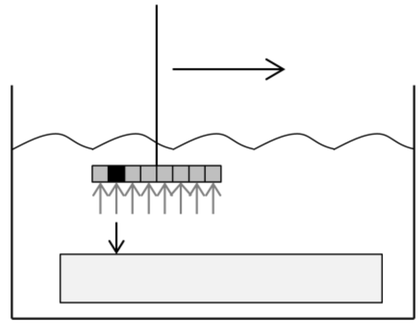

FIGURE 1. Experimental setup.

as an emitter and as a receiver. The recorded signals contain the structural noise and several geometry echoes.

Several post-processing techniques are applied to the measured data in order to obtain values that characterize the scattering. We distinguish techniques that are based on the analysis of the coherent and of the incoherent field. The coherent field is the part of field that resists to averaging over positions. It contains the incident wave and geometry echoes. The incoherent field, that disappears when averaged over positions, contains the structural noise.

Determination of the Attenuation Coefficient and of the Elastic Mean Free Path

The elastic mean free path l_e is a significant indication of the scattering properties of a material. It is related to the attenuation coefficient α by:

$$l_e = \frac{1}{2\alpha}. \tag{3}$$

We use the measured response matrix to obtain the value of l_e. To this aim, we consider the successive echoes of the coherent wave in the plate. For a given probe position, we sum the N*N signals of the response matrix in order to obtain the signal corresponding to the emission and reception by all the elements of the array. We average this signal over all the positions of the probe to reduce the part related to the incoherent field and obtain an estimation of the part related to the coherent field. We observe in this signal the successive echoes of the wave at the bottom of the block, as in the example in figure 2.

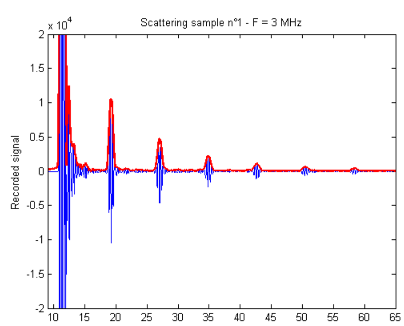

FIGURE 2. Example of successive echoes measured in a steel sample.

If we approximate the coherent wave as a plane wave, we relate l_e and α to the amplitudes of two successive echoes:

$$l_e(\omega) = \frac{1}{2\alpha(\omega)} = d\left[log(R^2) + log\left(\frac{|A_{echo\ 1}(\omega)|}{|A_{echo\ 2}(\omega)|}\right)\right]^{-1}, \tag{4}$$

where ω is the angular frequency, d is the height of the sample and R the reflection coefficient at the surface and backwall of the sample.

By taking the Fourier transform of the echoes, we can obtain the value of α and l_e for a range of frequencies. In cases where the diffusion is very strong, the noise level is high and the incident wave decreases quickly. Therefore the second echo of the coherent wave might not be visible. In these cases we will consider that l_e is very low compared to the depth of the sample.

It should be noted that the values obtained by that method express not only the intrinsic attenuation of the material but also some amplitude variations due to the divergence of the beam. In the scope of this study, we consider that this divergence is negligible compared to the attenuation and we ignore it by assuming that the wave emitted by the array is perfectly plane. The measurement could be refined by correcting for this divergence. It could be done either using an apodisation on the response matrix to obtain a beam closer to a plane wave, or by taking into account the divergence of the beam in the expression of the attenuation coefficient.

Determination of the Noise Correlation Distance

Even though the measured structural noise is not the same at different positions, there is a correlation for positions close to each others. Knowing this correlation will give information about the spatial behavior of the phase term of the backscattered field, and can be used to simulate structural noise.

Contrary to the mean free path, this distance is a characteristic of the incoherent field, not the coherent one. The coherent field mainly contains the front surface and back surface echoes that are not relevant in structural noise statistics. To get rid of the coherent part of the signal, we substract from signals the average of signals over transducer position: what remains corresponds to the incoherent field.

For each transducer position, we sum the signals of the response matrix only over emission. It yields the signal measured by each element when the entire array emits. Then, we calculate the correlation between measurements as a function of the distance between the measuring elements. To obtain the correlation at a distance δ, we consider every pair of elements separated by a distance δ and we calculate the correlation. We consider the signals s for the entire range of time available from 0 to T and the N_p transducer positions:

$$Cor(\delta) = \frac{1}{N_p}\sum_{p=1}^{N_p}\frac{1}{N_\delta}\sum_{i,j}\frac{1}{T}\int_0^T s_i^p(t)s_j^p(t)\,dt \tag{5}$$

where the sum over the index i,j is over all the N_δ pairs of elements i,j separated by a distance δ.

The function Cor that we obtain decreases as a function of δ, because the correlation is less important for elements that are far from each others. We fit that function with a decreasing exponential function of the form $exp(-\delta/d_c)$. It yields the characteristic correlation distance d_c.

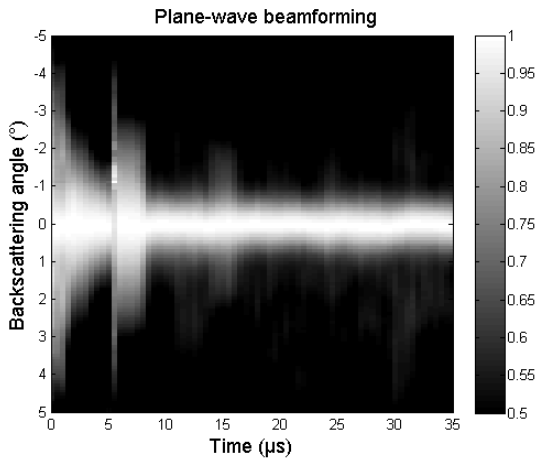

FIGURE 3. Example of backscattering cone obtained by beamforming (the peak around 8µs is a remnant of backwall echo and not part of the cone).

Determination of the Diffusion Constant

The diffusion equation (1) is entirely determined by the diffusion constant *D*.

A way to obtain *D* experimentally is to use the coherent backscattering effect [7]. This effect is related to the persistence of coherent interferences even in a disordered medium. It can be observed by emitting an ultrasonic wave in a multiple scattering sample and measure the average scattered intensity around the backscattering direction. In such an experiment, the coherent backscattering effect creates a peak in the measured intensity around the incident direction. The width of this peak decreases as a function of time. Figure 3 is an example of such a measurement. The pattern formed by the peak in this figure is known as the coherent backscattering cone.

To obtain the scattered intensity at different angles we use beamforming in a manner similar to [7]. By applying delay laws to the response matrix, we can obtain the signal corresponding to emission and reception at given angles. We can then look at the measured intensity as a function of the difference between the emission and the reception angles.

It is known that the evolution of this width is related to the diffusion constant *D*. This relation can be expressed [7]:

$$\Delta\theta^{-2} = \frac{k^2 D}{log2} T \qquad (6)$$

where $\Delta\theta$ is the half-width at half-maximum of the coherent peak, *k* the wave number of the emitted wave and *T* is the time. There is a limit to the validity of that relation, as the resolution in $\Delta\theta$ in far field is limited by the size of the array [7]. It is the reason why after 10 µs the width of the cone seems to remain stable. That part of the figure should not be used for the determination of *D*.

By applying equation (6) to the time where the decrease of the cone is observable, *D* can be obtained.

EXAMPLES OF RESULTS

Structural noise was measured on a sample of stainless steel at two frequencies using a longitudinal wave at a normal incidence. The setup to measure structural noise was

TABLE 1. Characterization of the sample at two frequencies.

	l_e	d_c	D
1 MHz	27 mm	1.4 mm	20 mm²/µs
5 MHz	5 mm	0.5 mm	4.4 mm²/µs

similar to the one of Figure 1, with all the elements of the arrays acting as emitters and receivers with no delay laws. The sample was characterized at each frequency using the methods presented in the first section, and the results are given in table 1. These characterizations were used as input to simulate structural noise using the method described above.

Several realizations of the experimental noise were obtained by performing measurements at several positions. Several realizations of the simulated noise were obtained by randomly generating ultrasonic fields several times in the third step of the simulation. In the measurement, the noise was separated from geometry echoes by using the same method as the one described in the second section to obtain the incoherent signal (ensemble averaged signals were subtracted from each realization of the signal).

The envelopes of the noise as a function of time were computed for each realization of the noise and averaged to obtain figure 4.

As we noted before, the results of the simulation are not calibrated. In this figure, the amplitudes are adjusted so that the simulated and measured noises are at the same level at the end of the plot. We chose to visualize the results that way because, as the simulation is based on the diffusion approximation, we expect it to be more reliable after the diffusive regime had time to establish. But, due to the absence of calibration, only the evolution of noise as a function of time is meaningful.

At 1 MHz, there are two main differences between simulated and measured noise. The first one is a difference in the slope of the curve: we attribute it to the fact that, contrary to the assumption of the simulation, the diffusive regime is not established in the experiment. The second one is the presence of a peak around 23 µs in the measurement. They can be either the contribution of forward scattered noise that is measured after a reflection, or geometry echoes that remain due to an imperfection of the method we used to separate these echoes from noise. Neither of these two possible contributions is simulated by our method.

At 5 MHz, there is a good agreement in the variation of the measured and simulated noise. It indicates that the approximation of diffusive regime is appropriate at

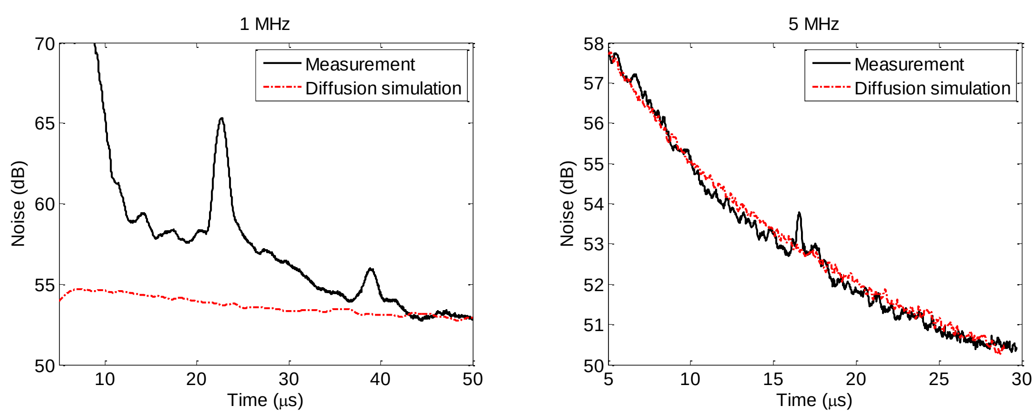

FIGURE 4. Averaged noise as a function of time. The front face echo corresponds to 0µs (the signal from 0 to 5 µs is masked by this echo and is not shown here). The backwall echo occurs at approximately 23 µs.

this frequency. The fact that the agreement is better at 5 MHz than at 1 MHz was expected: as the frequency increases, scattering is more important and the diffusion approximation becomes more appropriate.

CONCLUSION

A simulation method to obtain structural noise has been presented. This method is based on the diffusion approximation and should only be used in cases where multiple scattering is dominant. It utilizes three parameters characteristic of the scattering as input. These parameters are the elastic mean free path, the noise correlation distance and the diffusion constant.

An experimental method to obtain these parameters based on a single measurement procedure has also been presented. This method uses a phased array. The three parameters are obtained by post processing the measurement. This procedure allows reducing the time spent performing measurements, compared to a procedure where the three parameters would be determined using three different measurement setups.

Outputs of this method have been compared to measurement: this comparison confirms that better results are obtained when multiple scattering is stronger. Results could be improved by combining the method with another method that uses the single scattering approximation. Another direction for future works would be to obtain the proportionality factors that are needed to calibrate the outputs of the simulation.

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