Modeling Ultrasonic Structural Noise Based on the Microstructural Properties of Metals in the Context of Non Destructive Evaluation

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Abstract
Structural noise tends to reduce signal to noise ratio during the non destructive evaluation of metallic parts. The simulation of this phenomenon can help design adequate testing procedures or interpreting experimental results. The simulation method described in this communication uses metallurgical data as input and is valid in the single scattering regime. A theoretical model is used to relate properties of the microstructure to a scattering coefficient. A computation is then performed to obtain structural noise based on this scattering coefficient, using a set of scatterers randomly arranged in the sample.
Some metals (some titanium alloys for example) have two phases whose crystallographic orientations are related: this is taken into account by the model and has an effect on the scattering coefficients obtained. Grain elongation can also be taken into account. Simulation results are compared to experimental data.

Keywords: Ultrasound, structural noise, scattering model

1. Introduction

Structural noise can occur during the non destructive evaluation of metallic parts, due to interactions between ultrasonic waves and the microstructure of the metal. This phenomenon can limit the detectability of flaws as it tends to reduce signal to noise ratio. The simulation of structural noise can help design adequate testing procedures or interpreting experimental results.

In the first part of this communication, a method to simulate structural noise is described. It relies on a random set of scatterers whose scattering amplitude can be determined using a direct model, whose entries are the properties of the microstructure. In the second part, results of simulation of structural noise are compared to measurements performed on samples of steel and titanium alloy.

2. Simulation method

2.1 Expression of the noise

The method discussed here simulates structural noise by summing the echoes of a large number of random discrete scatterers. The simulated structural noise \( SN \) can be expressed in the frequency domain as a sum over scatterers \( k \):

\[
SN(\omega) = S(\omega) \sum_{k=1}^{N} U_{em}(\omega, x_k) U_{re}(\omega, x_k) A_{\omega, p_{em}, k_{em}, p_{re}, k_{re}} \exp(-i\omega \tau_k).
\]  

(1)

Ultrasonic fields are locally approximated as plane waves at the position of each scatterer. \( S \) is the emitted pulse, \( \omega \) is the angular frequency. The index \( em \) indicates the wave emitted by the emitting probe and \( re \) the wave that would be emitted by the receiving probe if it acted as an emitter. \( U, p \) and \( k \) are respectively the amplitudes, polarizations and wave vector of these wave.
waves. $x_k$, $\tau_k$ and $A_k$ are the position, time-of-flight and scattering amplitude corresponding to scatterer $k$. $N$ is the total number of scatterers.

Emitted and received ultrasonic fields are obtained using a paraxial beam method [1]. The attenuation due to the microstructure is included in these fields.

Expression (1) is similar to the expression of noise [2], except that here the scattering amplitudes depend on the properties of the material and of the emitted and received waves.

For a large enough $N$, the simulated structural noise is a fully developed speckle similar to the one described by [3]. This implies that it is distributed according to a zero-centered normal law, as often assumed for structural noise. Additionally, the simulated structural noise has correlations in time (stemming from the correlation in time of $S$) and correlations for neighboring probe positions (because the same set of scatterers is used for every position). Similar correlations are observed in experimental structural noise.

### 2.2 Number of scatterers

The number of scatterers per unit volume needs to be high enough compared to the resolution capabilities of the probe to ensure that the scatterers cannot be resolved and that fully developed speckle is obtained. Computation times increase with this number, so a compromise has to be found.

It is important to note that the number of scatterers is chosen independently of the number of scatterers in the actual microstructure that is being modeled. In the case of a metallic microstructure, there can be thousands of grains per cubic millimeter. Simulating the noise due to this microstructure by matching the number of scatterers to the number of grains would lead to unnecessarily long computations: satisfying results have been obtained in such configurations using less than one scatterer per cubic millimeter.

### 2.3 Distribution of amplitude

With a high enough $N$, the noise given by expression (1) is a zero-centered distribution and is entirely determined by its standard deviation, regardless of the form of distribution of $A_k$. Only the mean square of $A_k$ is relevant. We choose to draw $A_k$ from a zero-centered normal distribution in order to ensure that, even for a lower value of $N$, the simulated noise still follows a zero-centered normal distribution. Its amplitude is determined by the standard deviation of the distribution of $A_k$.

This standard deviation can be set empirically by fitting the simulated noise to measured noise [4]. A scattering model can also be used to set it. $A_k$ can be obtained based on the coefficient $\eta$ [5]:

$$A_k(\omega, \tilde{p}_s, \tilde{k}_s, \tilde{p}_r, \tilde{k}_r) = \frac{w_k}{|\tilde{k}_s|} \eta(\omega, \tilde{p}_s, \tilde{k}_s, \tilde{p}_r, \tilde{k}_r).$$

(2)

$w_k$ is a random variable drawn from a zero-centered normal distribution with a standard deviation of one. $\eta$ is defined as the average scattered energy by a unit volume in a unit solid
angle for a unit incident energy. This expression allows simulating noise based on $\eta$, an intrinsic property of a material that can be obtained using a model.

### 2.4 Scattering coefficients

A model [6] was developed to calculate the scattering by a polycrystalline microstructure based on the Born approximation. In this model, the scattering is due to the differences of orientations of different anisotropic grains which create variations of elastic properties at grain boundaries. This model has been extended to obtain scattering coefficients for any mode and any direction for single phase equiaxed microstructures [5]. In a generic case, assuming no fluctuation of density in the material, $\eta$ can be expressed:

$$\eta = \frac{1}{v \cdot v' 4\pi \rho} p_i'' k_{i''} p_r'' k_{r''} p_{r''} k_{r''} p_i'' k_{i''} \int \left[ \delta C_{ijkl} (\delta C_{ijmn}(\delta C_{pqrs}(\delta C_{i''j''} + \delta C_{i'r'r'}))) \exp\left\{\delta C_{i''j''} + \delta C_{i'r'r'}\right\}\right] d\bar{s}. \quad (3)$$

$v$ is the ultrasonic velocity, $\rho$ the density and $\delta C$ the variation of elastic constants compared to their ensemble average.

This model has been applied [7] to obtain longitudinal backscattering coefficients for equiaxed duplex microstructures, i.e. microstructure composed of two phases whose crystallographic orientations are related. We adapted it to obtain scattering coefficients for any mode and any direction for duplex microstructures with elongated grains [9].

### 3. Comparison to experiment

Outputs of this simulation method have been compared to structural noise measurements performed on steel with different grain sizes [8] and on titanium alloys [9]. For each measurement, the envelopes of the noise as a function of time were calculated and then averaged over probe positions. This yields an average of the noise level as a function of time. These noise levels are expressed in dBs relative to the maximum amplitude of the echo of a reference defect. Simulated noise was obtained with an implementation of the method in the CIVA software, and the simulated reference echo was obtained using existing CIVA models.

The inputs of the simulation are the characteristics of the measurement system and the geometry of the part, as well as properties of the microstructure. Grain sizes were obtained through metallurgical studies and elastic constants were obtained through parametric studies within a realistic range of values.

Results obtained for a steel sample with grains of approximately 120 $\mu$m diameter with a contact probe are presented Figure 1. Two different wedges were used in order to emit shear waves at 45° in one case and longitudinal waves at 45° in the other. At this frequency, the wavelengths of shear and longitudinal waves are approximately 1.4 mm and 2.6 mm, respectively.
In the shear wave configuration, the evolution of the noise as a function of time is correctly predicted. This indicates an accurate simulation of the incident and received fields and of the attenuation coefficients. The simulation seems to underestimate noise by approximately 5 dBs on most of the time interval. We attribute this discrepancy to the fact that this steel is highly anisotropic, therefore a high contrast exists between different grains which can cause errors in the Born approximation.

In the longitudinal wave configuration, there is again a correct prediction of the evolution of noise as a function of time and an underestimation of its level. Interestingly, it is necessary to simulate the noise due to all modes to obtain the correct evolution of noise: the noise due to shear wave is higher than the noise due to longitudinal waves, even though the incident amplitude of longitudinal waves is higher.

In both configurations, peaks of noise are correctly simulated (around 27 µs for the first configuration and around 22 µs or the second one). They are due to constructive interferences related to reflections at the bottom of the block.

Results obtained in the shear wave configuration on a sample with grains of approximately 500 µm diameter are presented Figure 2. This time the simulated noise decreases faster than the measured one. Our interpretation of this result is that the scattering is higher due to the larger grains and that multiple scattering, which is not taken into account by our method, is significant.

Figure 2. Measured and computed mean noise envelope as a function of time. 500 µm grains steel sample.
Results obtained in an immersion configuration on a duplex titanium alloy sample with elongated grains are presented Figure 3. Even though the microstructure is more complex than for the steel samples, the simulated noise is close to the measured one. This might be due to the fact that titanium grains are less anisotropic than steel grains, which is more favorable for the Born approximation. The curves of Figure 3 are more irregular than the previous ones, but it is simply due to the fact that the number of probe positions considered in this case was not sufficient to obtain a smooth average.

![Figure 3. Measured and computed mean noise envelope as a function of time. Duplex elongated titanium sample.](image)

4. Conclusion

The simulation method presented here permits realistic computation of ultrasonic structural noise in the single scattering approximation. In the results presented here, it relies on a Born approximation model to obtain the scattering coefficients of a polycrystalline microstructure. Nevertheless, it could be associated to a different scattering model and be applied to other types of microstructures.

Comparisons with experiment in the case of a duplex elongated titanium alloy indicate that the complexity of the microstructure does not limit the applicability of the model. However, comparisons for a single phase equiaxed steel sample seem to indicate that the single scattering and Born approximation can lead to errors in the noise levels.

Despite its underestimation, simulated noise for small grain steel samples shows interesting features: it is able to predict peaks of noise at certain times that are due to reflections and constructive interferences, even when several modes are involved.

Results could potentially be improved by using a more accurate model for scattering coefficients but the limitation to single scattering would remain and would have to be handled another way.

5. Acknowledgments
Part of the work leading to this publication has received funding from the European Commission Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 234117: PICASSO project.

The conditions of experimental setup and the metallurgical study concerning the titanium alloy have been provided by Snecma (Safran group) NDT department of Villaroche and Metallurgical department of Genevilliers and Corbeil.

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