ACCOUNTING FOR STRUCTURAL NOISE AND ATTENUATION IN THE MODELING OF THE ULTRASONIC TESTING OF POLYCRYSTALLINE MATERIALS

V. Dorval¹, F. Jenson¹, G. Corneloup², and J. Moysan²

¹CEA, LIST, F-91191 Gif-sur-Yvette, France
²Université de la Méditerranée, IUT Aix-en-Provence, Avenue Gaston Berger, 13625 Aix en Provence, France

ABSTRACT. Structural noise and attenuation can cause significant losses in detection performances in the ultrasonic non destructive testing of diffusive metals, such as some austenitic steels. Being able to predict these phenomena can help in designing better testing procedures. In this purpose, a computational method has been developed to take into account both structural noise and attenuation in the simulation of an ultrasonic testing. The method makes use of a single scattering model based on the Born approximation, accounting for anisotropic scattering and for mode conversions. It assumes that scattering is due to the variations in the orientations of anisotropic crystals. Attenuation effects are accounted for by convoluting a computed ultrasonic field with a filter issued from a scattering model. The backscattered noise is predicted by computing the response of a set of point-like scatterers randomly distributed in the inspected volume. The parameters of the statistical distribution of the scatterers are determined from the characteristics of the metallurgical structure, using the above scattering model. This ensures that it generates a fully developed speckle equivalent to the speckle caused by a polycrystalline medium. In this communication, the computational method is described and comparisons between its predictions and experimental results are shown.

Keywords: Ultrasonic, Polycrystalline Material, Grain Noise, Attenuation

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INTRODUCTION

The ultrasonic non-destructive testing of some metals can be made difficult by structural noise and attenuation. It is the case for some types of steels used in nuclear power plants and in the petrochemical industry. During the inspection of such materials, signal to noise ratios tend to be reduced due to attenuation and structural noise. Both of these phenomena may therefore have a significant impact on detection performances. Their modeling and prediction help the design of ultrasonic testing procedures.

A computational method has been developed to account for these phenomena in the simulation of ultrasonic testing. The general principles of this method are derived from previous works [1]. A pencil method [2] is used to compute non attenuated ultrasonic fields. The attenuation is taken into account afterward, by applying the Beer-Lambert law. A signal resembling structural noise is obtained by summing the echoes of a set of randomly generated scatterers. The method presented in [1] yields useful and precise results in a number of configurations, but its input parameters have to be set using...
reference ultrasonic measurements. In addition, it does not account properly for anisotropic
scattering and for mode conversions. A new method has been developed in order to
overcome these limitations.

This new method takes intrinsic properties of the metal, such as grain sizes and
elastic constants, as entry parameters. A scattering model, based on the Born
approximation, is used to compute scattering and attenuation coefficients as a function of
the material properties.

In this communication, this computational method and the associated scattering
model are described. Computation results are compared to experimental measurements.

SCATTERING MODEL

Both structural noise and attenuation are related to the scattering of ultrasonic
waves by the microstructure of metals. Structural noise is due to the scattering of energy
back to the receiver, and attenuation is due to the loss of energy by the wave due to the
scattering.

Metals are composed of distinct crystals, or grains. It is usually assumed that the
scattering in metals is due to the different orientation of neighboring grains. As the elastic
properties of these grains are anisotropic, the differences in orientations create an acoustic
contrast between crystals, even in monophasic metals. We are assuming that there is no
other cause of scattering. This assumption has been proven to allow for a satisfactory
agreement between model predictions and measurements in a number of cases [3-4].

The average scattered energy is calculated following the approach proposed by
Rose [5], which is based on the Born approximation and on a statistical description of the
microstructure. The microstructure is assumed to be monophasic and equiaxed. The
geometry of the microstructure is described using a spatial correlation function, which is
defined as the probability that two points separated by a vector \( r \) are in the same grain. The
correlation function is assumed to have an exponential form:

\[
W(\vec{r}) = \exp \left[ -\frac{2|\vec{r}|}{D} \right]
\]

(1)

where \( D \) is a parameter known as the effective grain size.

Based on these hypotheses, a scattering coefficient \( \eta \) can be calculated. It is defined
as the energy scattered per unit volume into a unit solid angle, per unit incident sound
intensity:

\[
\eta_{inc\rightarrow scat}(\omega, \theta) = \frac{\omega^4}{(v_{inc})^3(v_{scat})^3(4\pi\rho)^2} P_{ijkl}^{inc\rightarrow scat}(\theta) \langle \delta C_{ij} \delta C_{kl} \rangle_{Or} \pi D^3 \left[ 1 + \frac{\vec{k}_{inc} - \vec{k}_{scat}}{4} \vec{k}_{wave} \right]^2
\]

(2)

The following notations are used: \( inc \) and \( scat \) are indices of the incident and scattered
modes, \( \omega \) is the angular frequency, \( \theta \) is the scattering angle, \( v_{wave} \) is a wave velocity, \( \rho \) is
the density of the metal, \( \delta C \) is the deviation of the elastic constants from their average
value on the possible orientations of the grains and \( \vec{k}_{wave} \) is a wave vector. \( \langle \rangle_{Or} \) is an
average on the possible orientations of the grains. The function \( p \) yields weighing factors
on the different elements of \( \langle \rangle_{Or} \), and its values are dependant on the modes and on the
scattering angles. This expression is equivalent to those given in [6] and [7]. Values of \( p \)
for different modes, as well as values of the \( \langle \delta C_{ij} \delta C_{kl} \rangle_{Or} \) terms, can be found in both [6]
and [7].

The coefficients will be used to compute both noise and attenuation.
COMPUTATIONAL METHOD

Accounting for Attenuation

Non attenuated ultrasonic fields are obtained using the pencil method described in [2]. Attenuation is applied to these fields using filters dependant on the propagation distance, following the Beer-Lamber law. If $d$ is the propagation distance in the material before the wave hits a point, the attenuated field at this point is calculated using the non-attenuated field:

$$u_{att} = u_{non\_att} \exp\left[-\alpha(\omega)d\right]. \quad (3)$$

It is assumed that absorption phenomena are negligible, and that the attenuation is entirely due to the scattering. This assumption allows expressing attenuation coefficient as the integral of the coefficients $\eta$ given in equation (2):

$$\alpha_L = \pi \int_{\theta=0}^{\pi} \sin(\theta)\left[\eta_{L\rightarrow L}(\theta)+\eta_{L\rightarrow SH}(\theta)+\eta_{L\rightarrow SV}(\theta)\right]d\theta. \quad (4)$$

$$\alpha_S = \frac{\pi}{2} \int_{\theta=0}^{\pi} \left[\eta_{SH\rightarrow L}(\theta)+\eta_{SH\rightarrow SH}(\theta)+\eta_{SH\rightarrow SV}(\theta)+\eta_{SV\rightarrow L}(\theta)+\eta_{SV\rightarrow SH}(\theta)+\eta_{SV\rightarrow SV}(\theta)\right]\sin(\theta)d\theta. \quad (5)$$

The modes SV and SH are defined as in [6]: SV is the shear wave polarized in the scattering plane, and SH is the shear wave polarized in a direction orthogonal to the scattering plane. The equations (4) and (5) can be obtained by several ways. One way is to consider the balance between the energy of a plane wave entering a scattering volume, the energy of the plane wave exiting this volume, and the scattered energy. Identical results can also be derived from the Dyson equation, using a series of approximation [8].

The developed method uses the coefficients given by (4) and (5) in equations (3). Consequently, the attenuation is determined by the same scattering model as the noise. This constitutes an improvement from the method described in [1] which treats noise and attenuation as separated phenomena.

Noise Generation

Noise is generated using a single scattering approach: waves that are scattered several times before reaching the receiver are not taken into account. As in [1], the synthetic noise will be produced by a set of randomly positioned scatterers. The noise is obtained by summing the echoes of these scatterers. In the frequency domain, it can be written:

$$N(\omega) = S(\omega) \sum_{k_{scatterers}} U_{em}(\omega, \vec{x}_k) U_{re}(\omega, \vec{x}_k) A_k(\omega) \exp\left(-i\omega \tau_k\right). \quad (6)$$

$S$ being the emitted signal, $\vec{x}_k$ the positions of the scatterers, $A_k$ the scattering coefficients, and $\tau_k$ the times of flight. $U_{em}$ is the amplitude of the wave generated by the emitter at the position of the scatterer. $U_{re}$ is the amplitude of the signal measured at the receiver for a point source located at the position of the scatterer.

Expression (6) is specific to one emitted mode and one received mode. If there are several possible combinations of modes, one noise signal is calculated for each combination and the total noise is obtained by summation. The terms $U_{em}$ and $U_{re}$, as well as the time of flights $\tau_k$ and the scattering coefficients $A_k$, are dependant of the modes. The
scatterer positions $x_k$ are not dependant on the modes because the same set of scatterers is used for all modes.

This set of scatterers is generated using a scatterer density and distributions of scattering coefficients for each mode. A sufficient scatterer density is chosen based on the principle presented below. The distributions of the scattering coefficients are obtained as a function of the scatterer density and of the coefficient $\eta$ from equation (2).

**Scatterer Density of the Synthetic Structure**

A typical measured structural noise is produced by scatterers (the grains) that have a very high density compared to the resolution capabilities of the ultrasonic probe. Such a noise is called fully developed speckle. It occurs in many different fields of physics [8]. A fully developed speckle is obtained in any configuration where a signal is generated by a large number of non resolvable scatterers. The statistical properties of such a signal are independent of the density of scatterers, as long as this density is higher than a critical density. The typical density of grains in metals is usually significantly higher than the critical density.

This critical density is related to the characteristics of the ultrasonic probe. It is possible to determine it by running a series of computations with different scatterer densities and by analyzing the statistical properties of the obtained noises. This analysis can be done by comparing the distributions of their noise envelopes to Nakagami distributions [10]. The Nakagami parameter of a grain noise indicates how close it is to a fully developed speckle. The critical scatterer density is chosen as the lower density that yields a noise close to a fully developed speckle.

This critical density was evaluated for several cases, and it is usually significantly lower than the density of grains in a metal. For example, for a case of shear waves generated at a 45° angle with a 6.35 millimeter diameter probe, the sufficient density is 0.2 scatterers per cubic millimeter. In most situations this is significantly lower than the grain density: a metal with a 100 micrometers effective grain size will have a grain density of approximately 1000 grains per cubic millimeter. In this example, the sufficient scatterer density is 5000 times smaller than the grain density.

This example demonstrates that, in typical ultrasonic NDT configurations, it is theoretically possible to mimic the fully developed speckle generated by grains using a number of scatterer significantly lower than the number of grains. This principle can be used to generate noise significantly faster than by calculating the individual echoes of a realistic set of grains.

**Distribution of the Scattering Coefficients**

Using the notion of critical density, a number of scatterers lower than the number of grains is used. Scatterers are randomly positioned and randomly generated scattering coefficients are affected to them. The distribution of the scattering coefficients has to be chosen in a way that ensures that the noise generated by those scatterers is similar to the noise generated by the grains, despite their lower number.

The noise generated by grains is supposed to be a fully developed speckle. According to [8], it implies that the distribution of the noise is normal with a zero mean. To ensure that the noise generated by the set of scatterers has the same properties, their coefficients will be issued from a normal distribution with zero mean.

The only adjustable parameter of such a distribution is its standard deviation. It is chosen in a way that ensures that the set of scatterers has the same coefficient $\eta$ as the
metal. Therefore, both media scatter the same amount of energy. The coefficient $\eta$ of the metal is given by equation (2). For any mode, frequency, and direction, the coefficient $\eta$ of a set of discrete scatterers can be obtained using the following equation, given by [6]:

$$\eta_{\text{Scatterers}} = n\sigma^2 \frac{v_{\text{scat}}}{v_{\text{inc}}},$$  \quad (7)

$n$ is the scatterer density. $\sigma$ is the standard deviation of the scattering amplitudes. The velocity ratio is related to the fact that $\sigma$ is an amplitude coefficient and $\eta$ an intensity coefficient. According to equation (7), $\eta_{\text{Scatterers}}$ will be equal to $\eta_{\text{Metal}}$ if the standard deviation of the scattering amplitudes is set using this expression:

$$\sigma = \left( \frac{v_{\text{inc}}}{v_{\text{scat}}} \right)^{\frac{1}{n}} \eta_{\text{Metal}},$$  \quad (8)

$\eta_{\text{Metal}}$ being the scattering coefficient of a metal, given in equation (2).

Using a sufficient density of scatterers and a normal distribution with zero mean ensures that the generated noise is a fully developed speckle, similar to the one generated by the metal. Setting the standard deviation of the coefficient using equation (8) ensures that the synthetic noise carries as much energy as the noise from a metal.

The principle used to set the standard deviation of the scattering coefficient has been tested: the outputs of this method were compared to the outputs of a reference method that calculates noise by summing the echoes of individual grains. Both methods gave the same results.

**VALIDATION MEASUREMENTS**

Validation measurements were performed in order to evaluate the computation method and the relevance of the scattering model. Examples of measurements performed using a 2.25MHz central frequency at several angles are presented in this communication.

One block composed of small grain austenic steel and one block composed of coarse grain austenitic steel were used. Their microstructures were characterized using micrographic images. It was shown that they both could be correctly described using exponential correlation functions. Their effective grain sizes were determined to be respectively 120 micrometers and 500 micrometers. These values were used as entry parameters in the computations. The other entry parameters of the computation were the same for both blocks and are summarized in Table 1. Ultrasonic velocities were measured. The values of the elastic constants and density of a single crystallite that are given in [3] were used.

**Comparisons Between Computation and Measurement on the Small Grain Block**

Measured and computed B-Scans for a shear wave inspection at a 45° angle is compared in Figure 1. The B-Scan representations of both noises appear reasonably similar.

To allow for a quantitative comparison, the levels of the noise are calibrated using the amplitude of the echo of a side-drilled hole in a reference block. The mean envelopes

<table>
<thead>
<tr>
<th>$v_L$</th>
<th>$v_T$</th>
<th>$C_{11}$</th>
<th>$C_{12}$</th>
<th>$C_{44}$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 650 m.s(^{-1})</td>
<td>3 100 m.s(^{-1})</td>
<td>169 Gpa</td>
<td>145 Gpa</td>
<td>123 Gpa</td>
<td>8.12 g.cm(^{-3})</td>
</tr>
</tbody>
</table>
of the measured and computed calibrated signals are plotted in Figure 2 as a function of time for 45° angle shear wave and longitudinal wave inspection setups.

For the inspection using longitudinal waves, shear waves are also generated. Several computations were performed in order to evaluate the contributions of the different modes to the global noise level. It appears that the noise level due to longitudinal waves only is insufficient. The shear waves contribution is actually more important, even though shear waves have a lower amplitude than longitudinal waves in this configuration. When both modes and mode conversions are taken into account, the evolution of the noise is correctly predicted.

The peak that occurs at approximately 28 microseconds in the shear wave case is due to constructive interferences related to corner echoes at the bottom of the block. The computational method correctly mimics this phenomenon. In the longitudinal case, several peaks appear at different times. Those occurring around 17 and 23 microseconds can be identified respectively to longitudinal wave corner echoes and shear wave corner echoes. The one occurring around 20 microseconds is due to corner echoes involving mode conversions between longitudinal and shear waves. Those peaks are all correctly predicted by the computation.

In both cases, the decreasing of the noise with time is correctly computed: this is related to a correct estimation of the attenuation coefficient. However, the noise is underestimated by 5 decibels in the shear wave case and 4 decibels in the longitudinal wave case. This result seems to indicate an underestimation of the scattering coefficient. Similar discrepancies between the experimental and modeled noise levels are noted in [3],
It is rather surprising that the attenuation coefficient seems to be correctly predicted when the scattering coefficient seems to be underestimated: both coefficients are based on the same scattering model. It would be expected that, if the scattering coefficient are underestimated, the attenuation coefficient would be underestimated too. A possible explanation to this could be that the directivity of the scattering coefficient given by the model is not realistic: this would allow the backscattering, and therefore the noise, to be underestimated, while the total scattered energy, and therefore the attenuation, is correctly predicted.

**Comparison Between Computation and Measurement on the Coarse Grain Block**

The mean envelope as a function of time is plotted in Figure 3 for the case of a shear wave control at 45° on the coarse grain block. As opposed to the small grain case, the computation is unable to correctly predict the evolution of the noise. This is not a surprising result: as the scattering is very strong in this structure, multiple scattering quickly becomes more important than single scattering. The computation method only accounts for single scattering and is therefore unable to predict the level or the evolution of the noise in this case.

The fact that multiple scattering is dominant can be established by considerations on the attenuation and on the propagation distances. But it is also directly apparent on Figure 3: the measured noise does not exhibit the noise peak due to interferences at the bottom of the block. It proves that the inspection field has lost its coherence and directivity by the time it was supposed to reach the bottom of the block, which implies that multiple scattering dominates.

**CONCLUSION**

A method has been developed in order to model the noise and attenuation based on a scattering model. The model is based on the Born approximation and on the assumption that scattering stems from grain orientation differences. It is used to compute both scattering coefficients and attenuation coefficients. The computation of the noise is based on an original approach, which consists in using a smaller number of stronger scatterer to mimic the noise generated by a large number of grains. The validity of this approach can be verified by using the notion of fully developed speckle.

Computation results were compared to validation measurements. An excellent agreement was obtained concerning the variations of noise as a function of time. It
indicates that the attenuation coefficients are correctly predicted. The method also appears to be able to correctly predict the variations of noise for cases in which the noise is produced by several modes and by mode conversion. This is a significant improvement from the method presented in [1]. The noise appears to be underestimated by the computation: this could be related to a misrepresentation of the directivity of the scattering.

This approach is limited to single scattering and is therefore unable to mimic the noise occurring in coarse grain blocks. The modeling of multiple scattering is the focus of ongoing works.

REFERENCES