ABSTRACT. Sensitivity of UT methods in materials such as coarse-grained steels depends on attenuation and noise, due to scattering by microstructural heterogeneities. Here, existing UT simulation tools developed at CEA are modified to account for experimental observations of noise and attenuation. A model-based inversion tool is developed to estimate from experiments the parameters to input into the forward models. Example of application is given, showing the quantitative importance of these phenomena in terms of performance demonstration.

INTRODUCTION

Alloys used in the nuclear industry are generally obtained by solidification of a liquid phase. At a macroscopic scale, their polycrystalline structure (made of many anisotropic monocrystals) can be considered as an isotropic medium. However, this approximation cannot be used anymore to study the propagation of ultrasonic waves in a coarse-grained metal. Point-like defects (precipitates, solid solutions, lacuna ...) and surface defects (grain bounds that can represent 4 to 5 atomic diameters, interfaces between two phases, ...) are present inside the structure. These defects can behave as diffracting elements or reflecting surfaces relatively to the propagation of ultrasonic waves. Echoes due to scattering by the microstructure give rise to backscattered noise and wave attenuation. To quantify the sensitivity of ultrasonic methods in such a coarse-grained steels or carbon epoxy composites, these phenomena must be accounted for. To this aim, models of attenuation and backscattered noise have been implemented in existing forward models for UT simulation, the Champ-Sons and Mephisto models.

Modeling tools for UT simulation are developed at CEA (French Atomic Energy Commission) for several years (Champ-Sons for predicting the field radiated by a transducer, and Mephisto for simulating a whole testing experiment). They are more and more used for demonstrating performances of UT methods. Until now, UT simulation tools were developed assuming perfect elastic media. However, in the case of noisy materials such as coarse-grained steel, performances are affected by noise and attenuation phenomena. It is therefore important to take them into account for predicting accurate sensitivity values of a given method.
The present paper addresses this problem and shows how existing simulation tools have been modified by introducing simplified models of noise and attenuation. These models require specific parameters to input. Variability of noise and attenuation in practice is very high. Therefore, a model-based inversion method has been developed together with the model modifications to measure these parameters from experimental ultrasonic images.

EXISTING ULTRASONIC SIMULATION TOOLS IN THE CIVA SYSTEM

Champ-Sons, Model for Field Computation

Champ-Sons predicts the transient field radiated by a transducer in a component. The transducer can be monolithic or a phased-array, either wedge-coupled or immersed. Components may be of complex geometry (CAD defined) and made of materials either homogeneous or heterogeneous, isotropic or anisotropic.

The integration of elementary fields radiated by point-like sources is performed over the radiating surface. Elementary fields are evaluated by means of the pencil method [1]. A pencil is a collection of rays emanating from a point source. The center ray is called axial ray and lays along a geometrical path between the source and the point of field calculation. It follows the energy direction. Reflection, mode-conversions can be taken into account at each interface. The path is associated to a time of flight \( T \). The contribution of the point source to the global impulse response is generally a \( \delta \)-function, delayed by \( T \). Its amplitude is given by the divergence of the pencil (inversely proportional to the radii of curvature of the wavefront). This model has been experimentally validated for several configurations and compared to other approximate or exact models [1].

Méphisto, Model for Simulating an Inspection

Méphisto simulates a whole ultrasonic examination from the input of the examination parameters (transducer, component, scanning and defects) and the 3D ultrasonic field computed with Champ-Sons. Méphisto predicts Cscan or Bscan ultrasonic images directly comparable to experimentally measured ones. It deals with homogeneous and isotropic media, immersed or wedge-coupled transducer and planar, volumic or complex defects.

The computation is based on a semi-analytical approach and directly carried out in the time domain, using Kirchhoff’s diffraction theory and the principle of reciprocity between radiation and reception. At each scanning position, the echoes are computed separately (mode by mode and defect by defect) then summed-up [2]. One echo from one defect is associated to one mode between the emitter and the receiver via the defect with possible mode-conversion onto the defect or component boundaries.

SIMULATION OF THE BACKSCATTERED NOISE

Simulated ultrasonic images are in general noiseless (numerical noise apart, resulting from too poor discretization at some stages of the computation, which is not desirable). At first glance, it seems strange to wish to pollute nice images with noise. However, actual noise seen in measured images is such that, depending on the material of the part under inspection, indications predicted to be measurable by simulation cannot be detected in practice. An accurate model to predict noise level must therefore be added to the simulations to predict signal-to-noise levels which are of importance as far as performance demonstration is concerned.
The backscattered noise and the ultrasonic attenuation have been widely studied [3-8]. The simplified approach used in most of the recent models consider the noise, in the time domain, as the superimposition of echoes arising from ideal back-scatterers in the medium, as

\[ n(t) = \sum_{k=1}^{K} \sigma_k \exp(-\alpha \tau_k) s(t - \tau_k), \]  

where \( s(t) \) is an ultrasonic signal, \( K \) is the number of reflectors, \( \sigma_k \) and \( \tau_k \) are the reflection coefficient and the time delay associated to the \( k \)-th reflector and \( \alpha \) is the attenuation coefficient of the medium. These models consider a far-field approximation and are limited to longitudinal waves. They do not take account of multiple diffraction.

In a more general way, Gustafsson and Stepinski [8] introduce the frequency dependence of \( \sigma_k \). In the frequency domain, the back-scattered noise can be written as

\[ N(f) = \sum_{k=1}^{K} \sigma_k f \exp(-2j\pi f \tau_k) S(f) = H(f)S(f). \]  

The frequency response \( \sigma(f) \) of a discontinuity is given by [8]

\[ \sigma(f) = K \frac{Vf^2}{xc^2}, \]

where \( V \) is the volume of the scatterer, \( x \) its distance to the transducer, \( K \) a constant and \( c \) is the wavespeed of the ultrasonic wave considered. This model has been implemented in \textit{Méphisto}. The inspected component is supposed to include a set of randomly distributed scatterers with specific reflectivity. The crystallographic structure of the component is supposed to be homogeneous, so that the spatial distribution of scatterers is assumed uniform with a given density. Several regions with different spatial distributions could be used to represent a heterogeneous component. Assuming the medium is isotropic, the crystallographic axes of the grains are uniformly distributed and the grain size and density are also uniform. Applying the central limit theorem, the reflectivity of the scatterers is supposed to be a zero mean Gaussian distribution [8]. Therefore, such a structure is simply described by two parameters: the scatterer density and the variance of reflectivity distribution, directly proportional to the noise level.

**SIMULATION OF ULTRASOUNIC ATTENUATION**

Attenuation in metals is mainly due to diffusion phenomena at grain bounds, attenuation due to absorption being negligible [9]. When a wave propagates along a distance \( d \), its amplitude is attenuated by a factor

\[ \exp(-\alpha(\lambda, \bar{D})d), \]  

where \( \alpha \) is the attenuation coefficient. Its frequency dependence has been widely studied. Three domains are classically described, depending on the ratio of average grain size \( \bar{D} \) to wavelength \( \lambda \):

- for \( \lambda \gg \bar{D} \) (Rayleigh regime): \( \alpha(f) = C_1 \bar{D}^3 f^4 \),
- for \( \lambda \approx \bar{D} \) (stochastic regime): \( \alpha(f) = C_2 \bar{D} f^2 \),
- for \( \lambda \ll \bar{D} \) (diffusion regime): \( \alpha(f) = C_3 / \bar{D} \).
The determination of parameters $D$ and $C_i$ is difficult. Theoretical work is available giving analytic formulas of $C_i$ in the case of ideal polycrystalline metals (see [9] for example). Assumptions made in deriving these formulas may be critical. The other parameter $D$ (geometric) is even more difficult to access due to variability of grain size distribution (see [10]). Reliable data are those one can get from experiments. It must be noticed that only specific experiments for attenuation measurement can lead to acceptable values [11].

In most cases encountered in the nuclear industry, for a coarse-grained steel, the ratio between wavelength and grain size leads to attenuation typical of the Rayleigh regime.

In case of immersion testing, attenuation coefficient in the liquid coupling medium mainly depends on temperature. For water at room temperature, the coefficient is $f^2$ dependent and given by

$$\alpha_{\text{water}}(f) = 25.3 \times 10^{-6} f^2 \text{ (neper.mm}^{-1}, \text{ with } f \text{ in MHz}).$$  \hspace{1cm} (6)

A similar law, with a different coefficient, can be used to model attenuation in the solid wedge of a contact transducer.

This model of attenuation has been implemented in the Champ-Sons software in terms of a time convolution of the impulse response of the transmitted field with the inverse Fourier transform of the frequency dependent filter of attenuation. For each calculation point in the component, this filter is computed taking into account the paths through the different media from each source point.

As an illustration, Fig. 1 shows the field transmitted by a 45° shear wave transducer in a steel component for three different attenuation coefficients (0, 5 and 10 dB/m measured at 1.0 MHz). Effects of attenuation such as amplitude loss (-2.2 dB for the 5 dB/m and -3.6 dB for the 10 dB/m) and frequency shift are clearly observed.

![Fig. 1](image)

**FIGURE 1.** Top: Fields transmitted by a 45° shear wave probe in steel for three different attenuation coefficients. -2.2 dB and -3.6 dB correspond to the normalization for the whole computation zones as compared to the non-attenuating case. Bottom: superimposition of spectra of displacement at a point on the acoustical axis at the bottom of the computation zone, showing frequency shift (for the maximum amplitude).
MODEL-BASED INVERSION OF NOISE PARAMETERS FROM ULTRASONIC IMAGES

The two parameters defined in the forward model of noise are not predictable under simple modeling approaches. Producing synthetic images comparable with experiments in terms of noise requires the determination of the two parameters from experiments. To achieve this, a model-based inversion process has been developed.

The procedure is based on the segmentation algorithm, developed in the Civa system, applied on a Bscan image. This algorithm consists in extracting from a Bscan image the echoes using amplitude, time, and orientation criteria. An indication is then represented by a so-called “segment” made of a set of points (one per scanning position), and an amplitude (the maximum amplitude among the amplitudes at the points accounted for). This technique can be viewed as a time and spatial deconvolution of the image. Assuming that each segment corresponds to the contribution of one scatterer, a statistical analyze of the various segments can be applied to extract the parameters of interest.

The amplitude distribution of the segments depends on the amplitude distribution of the incident beam and on that of the scatterers. Let us now assume the amplitude distribution of the scatterers is gaussian. It is possible to measure its variance by a model-based inversion process. A Bscan is first simulated, given an arbitrary distribution of scatterer, the transducer used for the simulation having the same characteristics as that used in the experimental image to inverse. Then, amplitude histograms of the segmented measured Bscan is compared to that of the segmented simulated one. Then, the aim is to minimize the difference between the two histograms by changing from one realization to another in the simulations the scatterer distribution. During this first step, the number of scatterers is not of interest. However, to ensure the robustness of the method, it must be sufficiently high so that simulated results do not significantly change from one realization to another.

Once the variance of the amplitude distribution has been extracted, density parameter is varied to obtain a simulated noise level similar to the experimental one. To this aim, a specific image has been developed, that represents the energy averaged for all scanning positions, versus time-of-flight. An example is given on Fig. 2 where measured Bscan and

![Experimental Bscan and Simulated Bscan](image1)

![Experimental segmented Bscan and Simulated segmented Bscan](image2)

**FIGURE 2.** Experimental and simulated Bscans and segmented Bscans. Simulated results shown are that corresponding to the best match with experiments resulting from the inversion procedure.
FIGURE 3. Left: comparison of the simulated and measured histograms of segment amplitudes. Right: comparison of the simulated and measured energy versus time of flight.

segmented Bscan are compared to the simulated ones. For the extracted couple of parameters, very good agreement between measured and simulated results is observed. Fig. 3 compare simulated and measured histograms of segment amplitudes and simulated and measured energy versus time-of-flight.

EXAMPLE OF APPLICATION

The model of noise with its two parameters determined as explained can then be used for simulations with other transducers, since it is not specific to the transducer used in the measure. This is particularly useful when various transducers are to be compared to achieve the best performances for testing one given component. The various signal-to-noise levels one gets with the various transducers are directly comparable.

To illustrate this, a study has been performed to simulate the inspection of a component made of coarse-grained steel using three different transducers. In a first step, the parameters of the noise models (scatterers density and variance of the amplitude distribution) are extracted according to the acquisition performed with an immersed focused transducer. In a second step, these parameters are used to simulate the inspection of this component using three different L-45° contact transducers (T1, T2, T3). They differ only by the shape of their piezo-element. T1 is flat whereas T2 is cylindrical and T3 is bifocal (torus). The fields they radiate are shown on Fig. 4.

From Fig. 4, maximum amplitude for each transducer is compared to that of the flat one (reference). The bifocal transducer achieves the best energy focusing in both the plane of incidence and the plane perpendicular to it. This results in an amplitude 9 dB higher than that of reference. The cylindrical one only achieves good focusing in the plane of incidence.

Now, a component made coarse-grained steel is successively inspected with the three transducers. The component contains two artificial defects. The first is a notch (4-mm-height and 15-mm-long), modeling a surface-breaking crack and positioned perpendicularly to the surface opposite to the surface where the transducers radiate. The second is a side-drilled hole of 2-mm-diam.

Fig. 5 displays the component containing the two defects and the transducer scan. The notch plane as well as the SDH generatrix are both perpendicular to the plane of incidence. Fig. 6 shows the results of the three simulated inspections in the form of both the Bscan and the echodynamic curve resulting from it.

It is observed from the simulated results that noise level considerably varies from one transducer to another. For T1, the poor focusing in both the plane of incidence and the plane perpendicular to it leads to poor S/N. The best results are obtained with transducer T2, for which the beam radiated is focused in the plane of incidence and unfocused in the plane perpendicular to it. Therefore, a coherent integration takes place in this latter plane. Such an effect cannot take place in scattering by grain boundaries behaving as point-like defects. Transducer T3 is focused in both planes. No integration effect takes place and amplitude level of defect indications decreases as compared to grain scattering noise. Table 1 gives quantitative results of S/N for the two defects and the three different transducers. It is observed that S/N variations can be as high as 14 dB.

![FIGURE 6](image)

**FIGURE 6.** Simulated Bscans and resulting echodynamic curves for the three transducers: Left: T1, Center, T2 and Right: T3. Black ellipses indicate where indications from both defects are found.

**TABLE 1.** Simulated Signal-to-Noise ratios for the three inspections and the two defects.

<table>
<thead>
<tr>
<th>Signal-to-Noise ratios (dB)</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Side-Drilled-Hole</td>
<td>0</td>
<td>14</td>
<td>6</td>
</tr>
</tbody>
</table>
CONCLUSION

Models developed at CEA [1, 2] can now deal with materials in which noise due to coarse-grained structure and associated attenuation play important roles. This allows one to quantify the sensitivity of UT methods. A model of attenuation based on a time filtering approach and a model to simulate the backscattered noise assuming randomly distributed scatterers [8] have been implemented in *Champ-Sons* and *Méphisto* models. In the model accounting for noise, the structure is essentially described by two parameters: the density of the scatterers and the distribution of their reflectivity. A procedure (model-based inversion) to extract these two parameters from experimental results has been presented. Example given deals with the inspection of a component made of coarse-grained steel with three different probes. It explains how the various beams radiated by various transducers result in different signal-to-noise ratios. It becomes therefore possible in UT simulation to associate a signal-to-noise ratio to a transducer, given a component made of a material for which the two parameters would have been extracted from an experimental image.

REFERENCES