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Transverse-to-Transverse Diffuse Ultrasonic Double Scattering

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ABSTRACT

Diffuse ultrasonic backscatter techniques are commonly used for microstructure evaluation and defect detection, however, the sensitivity of these measurements is highly dependent on grain noise. Traditional single scattering models have been very effective for a large class of weakly scattering materials including magnesium and aluminum alloys. However, while it appears to break down for strong scattering materials. Longitudinal-longitudinal double scattering response models have been established for strongly scattering materials such as iron, copper and nickel-based alloys. In order to complete this double scattering theory, the transverse-to-transverse double scattering model is developed within the previous formalism based on Wigner distribution functions. This model is then combined with extreme value statics to detect the sub-wavelength, near-surface flaws in strongly scattering material. Experiments show that the developed method has good performance for suppressing both missed detections and false positives.

Keywords: Transverse-to-transverse (T-T) double scattering; Strongly scattering material; Time-dependent threshold; sub-wavelength near-surface flaws;

1. INTRODUCTION

The ultrasonic backscatter, also known as grain noise, can be used as a tool for microstructure characterization. In the past few decades, statistical method is used to quantify the diffuse scattering from the background, heterogeneous medium such that deviations from this response can be predicted and related to the presence of defects. Ghoshal and Turner [1] followed with a model specific for the case of longitudinal scattering in a pulse-echo configuration through planar and curved interfaces. Hu et al 2,3] expanded to the case of longitudinal-to-shear (L-T) scattering and shear-to-shear (T-T) scattering.

However, the above ultrasonic scattering models are based on the single scattering assumption, and the ultrasonic noise received by the ultrasonic probe in the strongly scattering material theoretically contains the second or even higher scattering of the grain boundaries. Therefore, Turner and HU proposed a multiple scattering theory framework [4], and derived the L-L double scattering model based on the Wiener distribution function by simplifying the hypothesis [5]. The results show that for high-scattering steels, the theoretical prediction error of grain noise can reach 52% if the high-order scattering component is ignored [4], which verifies the necessity of multiple scattering correction for high scattering materials.

In order to complete this double scattering system, the transverse-to-transverse double scattering model is developed within the previous formalism based on Wigner distribution functions. This model is then combined with extreme value statics to detect the sub-wavelength, near-surface flaws in strongly scattering material. Experiments show that the developed method has good performance for suppressing both missed detections and false positives

2. MATERIALS AND METHODS

2.1 Theory

Doubly-scattered response (DSR) is derived under the assumption that the ultrasound scatters only twice in the time between excitation and detection. Its general expression is written as [4]

$$\begin{aligned}\Phi(t) &= \Phi^1(t) + \Phi^2(t) \\ &= \int \frac{d\omega}{(2\pi)^4} d^3p d^3q d^3X dT W^R_{\beta j}(\mathbf{X}, t-T, \mathbf{p}, \omega)^{\mathbf{p}}_{\mathbf{p}}{}^{\beta}_{j} K^{\gamma q}_{k\,q} W^S_{\gamma k}(\mathbf{X}, T, \mathbf{q}, \omega) \\ &+ \int \frac{d\omega}{(2\pi)^4} d^3p d^3q d^3s d^3X d^3X' dT' dT^* W^R_{\gamma k}(\mathbf{X}, t-T'-T^*, \mathbf{p}, \omega) \\ &\times {}^{\mathbf{p}}_{\mathbf{p}}{}^{\gamma}_{k} K^{\delta \mathbf{s}}_{l\,\mathbf{s}} W^G_{\delta\tau lm}(\mathbf{X}-\mathbf{X}', T^*, \mathbf{s}, \omega)^{\mathbf{s}}_{\mathbf{s}}{}^{\tau}_{m} K^{\pi \mathbf{q}}_{n\,\mathbf{q}} W^S_{\pi n}(\mathbf{X}', T', \mathbf{q}, \omega)\end{aligned} \tag{1}$$

After a series of simplifications and mathematical derivations, we got the final expression of DSR:

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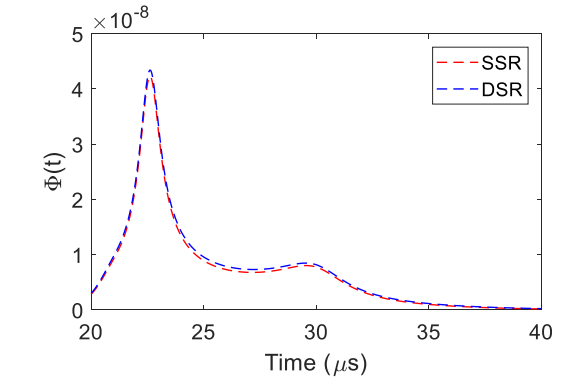
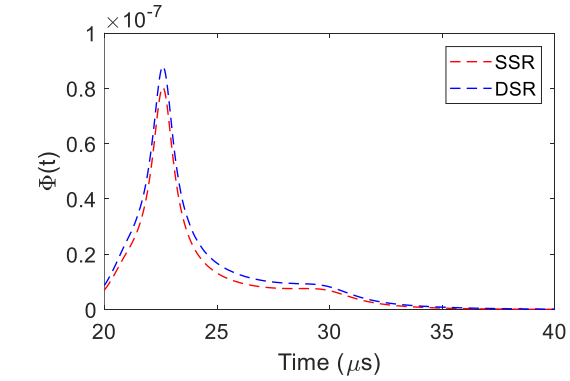
3. RESULTS AND DISCUSSION

In order to explore the DSR in detail, polycrystalline steel with density of $\rho = 7836\,\mathrm{kg/m^3}$, and single crystal elastic constants $c_{11} = 219.2\,\mathrm{GP}a$, $c_{12} = 136.8\,\mathrm{GP}a$, $c_{44} = 109.2\,\mathrm{GP}a$ is used for the following numerical analysis because it represent strongly material. Water is used as the couplant, and its density and velocity are assumed as $\rho_f = 998\,\mathrm{kg/m^3}$ and $c_f = 1486\,\mathrm{m/s}$. The transducers are assumed to have matched center frequencies $\omega_0 = 10\,\mathrm{MHz}$ and pulse widths $\sigma = 0.57\,\mu\mathrm{s}$, respectively, as well as the same nominal focal length and element radiu, $F = 50.8\,\mathrm{mm}$ and $a = 12.7\,\mathrm{mm}$. The water path for the transducer is assumed to be $z_f = 14.86\,\mathrm{mm}$, and the material path in the sample is obtained through $z = \left(F - z_f\right)\cdot c_f / c_L$ (where F is the focal length of the transducer). The longitudinal and transverse material attenuations for these calculations are based on the theory developed by Weaver.

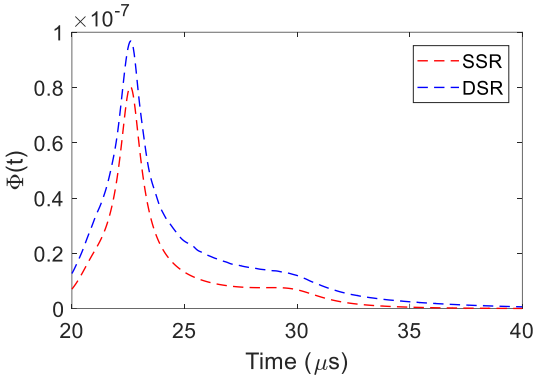
The correlation length used to generate Fig. 3 are $L = 10, 15,$ and $20\ \mu\mathrm{m}$. It is note that the changes between SSR and DSR for iron increase as L increases.



(a)



(b)



(c)

FIGURE 1: Comparisons between normalized SSR and DSR with varied L for iron. (a) $L = 10\ \mu\mathrm{m}$; (b) $L = 15\ \mu\mathrm{m}$; (a) $L = 20\ \mu\mathrm{m}$;

4. CONCLUSION

(1)The T-T DSR is developed under the same formalism of L-L DSR based on Wigner distribution functions.

(2)Higher-order scatterings are necessary to model the grain noise in materials with coarse grains such steel, titanium alloy.

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