EXCESS SCATTERING INDUCED LOSS AT A ROUGH SURFACE
DUE TO PARTIALLY COHERENT DOUBLE-REFLECTION

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INTRODUCTION

Transmission (and retransmission) through rough surfaces degrades ultrasonic flaw detection and materials characterization. The flaw signal as well as reference signals (e.g. reflections from the front-surface or back-surface of the specimen) become difficult to interpret. In the simplest case, we make two assumptions in order to model the ultrasonic pulse-echo signal. Our first assumption is that the scatterer is large in the sense that it extends laterally for many surface correlation lengths. In this case, the signal has a small variance and is well described by its average value that will be referred to as the "specular" signal. Our second assumption is that the flaw is far from the surface, in a sense to be defined below. Given these two assumptions, the rough surface introduces a loss that is proportional to the square of the rms height, \( h \), and the frequency, \( f \). Further, the loss due to a double-transmission, \( L_d \), is just twice the loss due to a single-transmission, \( L_s \), i.e.,

\[
L_d \approx 2 L_s.
\]

In this paper we show that the signal can be understood using simple physical arguments based on local changes in the phase even if the assumptions stated above are not satisfied. In particular, suppose that the second assumption is violated and the scatterer is near the surface of the specimen. The initial transmission, as the ultrasound enters the part, becomes statistically correlated with the final transmission, as the ultrasound exits. In this case the loss is a complicated function of the frequency, the rms height as well as the surface autocorrelation length and can be as high as \( 4 L_s \). We show that specular signals from subsurface defects in shot blasted samples can be understood in terms of roughness-
induced changes in the phase. The observed signals (both for the near-surface and the far-surface regime) are quantitatively described by simple analytic formulas derived using the phase-screen approximation (PSA) [1].

We will use the words "specular" and "diffuse" to describe the average and randomly varying components of the wavefield. In order to avoid confusion, we use the words "coherent" and "incoherent" to describe the presence or lack of correlation in the transmission and retransmission of ultrasound through the rough surface.

BASIC IDEA

Although surface roughness affects both the phase and amplitude of the sound wave as it crosses the surface, the change in phase dominates the physics since the phase appears in an exponential, while the amplitude is a slowly varying prefactor. The simplest possible approximation is to ignore the amplitude variation altogether and to concern ourselves entirely with the phase variation. This idea is expressed via the phase-screen approximation, which relates the field just before the surface, \( z = 0^- \), to the field just after the surface, \( z = 0^+ \), as

\[
\psi(\omega, r, z = 0^+) = T_0 \exp\{i\phi(r)\} \psi(\omega, r, z = 0^-).
\]

Here, \( \omega \) denotes the angular frequency, \( r \) the coordinate parallel to the surface and \( \phi(r) \) the change in phase due to the local surface height variation at \( r \). Finally, \( T_0 \) denotes the appropriate plane wave transmission coefficient for a smooth planar surface.

SINGLE-TRANSMISSION/REFLECTION

The roughness-induced loss (single-transmission or reflection) can be calculated analytically in the PSA for surfaces described by a Gaussian random process and is given by \( L = \frac{1}{2} \langle \phi^2 \rangle \) [1]. That is, the loss is proportional to the square of the rms value of the phase perturbation \( \phi \). In this approximation the magnitude of the phase perturbation is always proportional to both the frequency, \( f \), and the rms roughness, \( h \). Consequently, the scattering induced loss for the reflected \( L_R \) and longitudinal \( L_L \) and transverse \( L_T \) transmitted waves can be written in the following general form

\[
L_{R,L,T} = A_{R,L,T}(f, h, \theta) f^2 h^2,
\]

where \( A_R, A_L, \) and \( A_T \) are known functions of the sound velocities in the solid and the fluid and the angle of incidence, \( \theta \) [2, 3]. Eq. (1) has the interesting feature that the loss depends separately on \( f^2 \), \( h^2 \) and a function of the angle of incidence, \( A \).

Losses for transmitted waves can be predicted once the loss for a normally incident reflected wave is measured. This follows from Eq. (2) and the fact that the \( A \)'s are simple known functions (tabulated in Ref. 3). The losses for the transmitted waves are given by

\[
L_{S,L,T} = \frac{A_{L,T}(\theta)}{A_R(\theta = 0)} L_R(\omega, h, \theta = 0).
\]
These angle-dependent normalized losses can be easily calculated for both longitudinal and transverse waves from the known sound velocities in the solid and the fluid [3].

DOUBLE-TRANSMISSION

Roughness-induced losses for transmitted waves are described in a remarkably simple and useful way by Eq. (3). Experimental tests of this equation are reported in Ref. 3 and a short synopsis of these experiments is as follows. We measured the losses for reflected and doubly-transmitted waves for a series of shot-blasted aluminum plates, which are described in greater detail in Ref. 3. The double-transmission loss was measured in a pulse-echo arrangement by placing the specimen between a 1/2-inch-diameter transducer and a plane reflector app. 500 mm apart. That is, the experiment was carefully prepared so that the assumptions of the first paragraph were completely satisfied and consequently the losses for double-transmission are expected to be just twice the loss for single-transmission. The results are shown in Fig. 1, which shows that Eq.(3) is quantitatively accurate for those values of the frequency and the angle of incidence that are shown. Note that Eq. (3) will fail near the critical angle and that it is expected to be best for samples whose rms height is much less than the surface autocorrelation length.

It has been recently recognized, that the two-way phase-perturbation is not necessarily the incoherent sum of the two one-way perturbations if the propagation distance between the two interactions is small [4,5]. Clearly, partial coherence between the two interactions can significantly increase the double-transmission loss. In the case of completely coherent interactions, the rms value of the combined phase-perturbation is twice as much as

![Figure 1](image_url)

Figure 1. Scattering loss as a function of frequency for the reflected and double-transmitted waves at given angles of incidence (h = 25.6 um, aluminum). The solid lines are theoretical predictions based on the phase-screen approximation and the symbols represent the experimental data.
that of a single interaction, i.e., $\phi_d = 2\phi_s$. Since the loss of the specular component is proportional to the square of the rms value of the combined phase-perturbation, the total loss caused by the double-interaction is four times higher than the loss of the single-interaction, i.e., $L_d = \frac{1}{2}(\phi_d^2) = 4L_s$. In comparison, in the case of completely incoherent interactions discussed above, the rms value of the combined phase-perturbation is only $\phi_d = \sqrt{2}\phi_s$, and therefore the total loss caused by the double-interaction is twice the loss of the single-interaction, i.e., $L_d = \frac{1}{2}(\phi_d^2) = 2L_s$.

The transition between completely coherent interactions at close distances to completely incoherent interactions at large distances is demonstrated by Figure 2, which shows the calculated double transmission loss of the longitudinal wave at normal incidence for an aluminum specimen immersed in water. The rms roughness and the coherence length of the specimen were $h = 20 \mu m$ and 1.5 mm, respectively. Both Gaussian and exponential auto-correlation functions were considered. These calculations were made by using the phase-screen approximation and assuming a Gaussian beam profile of $a = 10 mm$ radius and an operation frequency of $f = 10 MHz$. For this combination of parameters, the reflection loss, $L_r$, at normal incidence is 12.2 dB. The normalized longitudinal transmission loss for aluminum in water is 0.151. The double-transmitted loss can be estimated from the reflection loss in the incoherent repetition approximation as $L_d^L(\theta = 0) \approx 3.69 dB$ (dashed line in Fig. 2). At very large depths below the rough surface, the loss of the double-transmitted signal asymptotically approaches this "incoherent" limit. However, at smaller depths, the actual loss is much higher. For example, the excess loss with respect to the incoherent approximation is app. 2 dB at 5 mm below the surface. At very small depths, the loss of the double-transmitted signal approaches the "coherent" limit of $L_d^L(\theta = 0) \approx 7.38 dB$, i.e., twice the value of the incoherent limit.

Figure 2 Calculated double-transmission loss of the longitudinal wave at normal incidence for an aluminum specimen immersed in water ($h = 20 \mu m$, correlation length = 1.5 mm, $a = 10 mm$, and $f = 10 MHz$).
The partial coherency between subsequent phase-perturbations experienced by the ultrasonic wave upon repeated interaction with the same rough surface is obviously a general phenomenon affecting both reflected and transmitted waves. Of course, in typical NDE applications we are mainly interested in the transmitted wave. In the commonly used pulse-echo mode of operation the transmitted wave always interacts twice with the same rough surface; first time as it enters the specimen and second time when it leaves it. An analogous phenomenon occurs when multiple-reflection takes place between parallel reflectors. We found that the effect of partial coherency between repeated interactions with a rough surface can be more easily studied experimentally using the reflected part of the wave than on the transmitted component.

The asymptotic behavior of the double-reflection loss can be readily predicted from simple physical considerations for either very low or very high values of standoff distance, frequency and autocorrelation length. It is much more difficult to quantitatively describe the transition from dominantly incoherent repetition to dominantly coherent repetition. However, the phase-screen approximation provides simple explicit results for both Gaussian and exponential correlation functions [5].

EXPERIMENTAL TECHNIQUE AND RESULTS

Figure 3 shows (a) the schematic diagram of the experimental arrangement used to investigate the effect of coherency on the scattering induced loss of the double-reflected specular wave from a rough surface and (b) the multiple echoes received from the smooth and rough sides of the specimen. One of the main advantages of this arrangement is that the standoff distance \( z_o \) can be varied easily over a wide range. Details of the experimental setup and sample preparation and characterization are given in Ref. 5. A 1/2"-diameter collimated-beam broadband immersion transducer was used in the measurements. The transducer had a 1/2"-long glass buffer which plays an essential part in this experiment. The perfectly smooth, polished water/glass interface encountered by the back reflected ultrasonic waves from the surface of the specimen acts like an ideal mirror. The scattering induced loss of the first and second (or any higher order) reflection can be easily measured by comparing the spectra of the same signal from the smooth and rough sides as the specimen is flipped over. Of course, the reflection coefficient of the water/glass boundary is only about 80% but, because of the way we measure the scattering induced loss of the specular signals, this small frequency-independent loss has no effect on our results. In order to measure the specular and only the specular component of the reflected signal, we should measure the reflection from a large number of specimens and calculate the ensemble average. Instead, we did spatial averaging over the whole 2"-by-2" roughened area of the specimen.

Measurements of the scattering-induced loss of the singly- and doubly-reflected specular waves were made on an aluminum specimen of \( h = 5.2 \mu \text{m} \) rms roughness and 730 \( \mu \text{m} \) correlation length. The measurements were made for six standoff distances of 2.5, 5.25, 8, 11, 16, and 22 mm between 5 MHz and 50 MHz (subject to a dynamic range of app. 40 dB). Figure 4 shows the measured loss as a function of frequency for different standoff distances. The solid lines show the best fitting \( f^2 \) curves matched to the frequency-dependent loss of the first reflection. The two dotted lines simply show twice and four times this best fitting loss spectrum to indicate the incoherent and coherent limits of the double-
Figure 3 Schematic diagram of (a) the experimental arrangement used to investigate the effect of coherency on the scattering-induced loss of double-reflection from a rough surface and (b) the multiple echoes received from the smooth and rough sides of the specimen.

The open boxes indicate the measured single-reflection loss, while the open circles show the measured double-reflection loss. The double-reflection loss is four times the single-reflection loss either for small standoff distances or high frequencies, i.e., when coherent repetition occurs. Figure 4a is for our smallest standoff distance of 2.5 mm. As can be seen, the measured double-reflection loss is nearly four times higher than the single-reflection loss over the whole frequency range. On the other hand, Figure 4f shows the results for our largest standoff distance of 22 mm. In this case the measured double-reflection loss is approximately twice the single-reflection loss over the whole frequency range. For intermediate standoff distances, the double-reflection losses are twice the single-reflection losses for low frequencies but switch to four times the single-reflection losses at high frequencies.
Figure 4  Measured loss as a function of frequency for six different standoff distances (see explanation in the text).
CONCLUSIONS

The scattering induced loss of a specular ultrasonic wave interacting with a rough surface is proportional to the square of the rms roughness-to-acoustic-wavelength ratio. Under most ordinary circumstances, a second interaction with the same rough surface is incoherent with respect to the first one and the losses can be simply added. However, when the second interaction occurs within the coherence length of the scattered diffuse field from the first interaction, the total scattering induced loss is not twice but four times the loss incurred during a single interaction. As a first experimental step in studying the generic problem of partially coherent double-interaction with a rough interface, we measured the scattering induced loss of singly- and doubly-reflected specular waves from a carefully prepared rough specimen. We varied the degree of coherency between the two interactions by changing the propagation distance and the frequency. Our experiments show that at close distances and high frequencies, when the interactions are coherent, the doubly-reflected wave is four times more attenuated than the singly-reflected one. In comparison, at large distances and low frequencies, when the interactions are incoherent, the doubly-reflected wave is two times more attenuated than the singly-reflected one. It has been shown recently [5], that the transition region between coherent and incoherent interactions as either the propagation distance or the frequency varied can be used to characterize the autocorrelation function of the surface and assess the autocorrelation length.

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REFERENCES