SCATTERING INDUCED ATTENUATION OF ULTRASONIC BACKSCATTERING

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INTRODUCTION

Scattering induced ultrasonic attenuation offers a simple way to characterize material inhomogeneities. This method has a wide range of applications from tissue characterization [1,2] to ultrasonic NDE, such as grain size measurement in polycrystalline materials [3,4], structural diagnostics in ceramics [5,6], porosity assessment in cast metals [7,8] and composites [9], etc. The scattering induced attenuation of a through transmitted coherent ultrasonic wave can be readily related to certain characteristics of the average inhomogeneity via its total scattering cross-section. In many cases however, ultrasonic attenuation measurement is not feasible except from the backscattered signal. For want of better approximation, the scattering induced attenuation is presumed to have the same relation to the average inhomogeneity as if it were measured by the simpler transmission technique. It was recently reported [10] that this approximation breaks down in porosity assessment, and it probably does not work in many other NDE applications either.

Due to the inherent technical difficulties associated with backscattering measurements, it is rather hard to experimentally verify or contradict the above presumption, i.e. that the backscattered wave is attenuated in the same way as a coherent plane wave. Of course, whenever absorption dominates the total attenuation, like in biological tissues, the attenuation is the same regardless of whether it is measured from the backscattered signal or from the transmitted one by a phase-sensitive (or even by a phase-insensitive) detector. On the other hand, our experimental results show that the backscattered signal is much less attenuated by scattering than the transmitted coherent wave. It will be shown that this is due to the incoherent nature of the backscattered waves and that the effect is present from the very beginning of the backscattered signal, i.e. well before the field becomes completely diffuse.

ULTRASONIC ATTENUATION MEASUREMENT

The numerous ultrasonic attenuation measurement techniques can be divided into two basic categories: coherent methods and incoherent methods. The coherent techniques measure the attenuation of a well-collimated ultrasonic beam by a phase-sensitive transducer of large aperture. The ultrasonic attenuation coefficient can be written as follows:

$$\alpha(k) = \alpha_a(k) + \alpha_s(k), \tag{1}$$

where α_a is the absorption coefficient, α_s is the scattering induced attenuation coefficient, and k is the wave number. Due to the large aperture phase-sensitive detection, all scattered energy will be missing from the detected, strictly coherent wave, therefore the scattering induced plane wave attenuation cofficient will be

$$\alpha_s^{pl}(k) = \tfrac{1}{2}\, n\, \gamma(k), \tag{2}$$

where $\gamma(k)$ is the total scattering cross-section of the average scatterer and n is the number density of the scatterers. This very simple relation offers a direct way to characterize the inhomogeneity via the frequency dependence of $\gamma(k)$.

Ultrasonic attenuation measurement from the penetrating coherent wave is often hindered or even rendered completely useless by the lack of parallel smooth surfaces and the necessity of one-sided access. Considerable effort has been made in many areas to measure the ultrasonic attenuation from the backscattered signal [10-14]. The backscattered signals emanating from deeper regions of the sample are obviously weaker than those originating from shallow depths and the difference is regarded as apparent attenuation. Due to the incoherent nature of the back-scattered signals, this technique inherently invokes spatial averaging to recover the statistical expectation value of this difference. Otherwise, the various techniques are quite different, e.g. narrow-band tone-burst methods are based on the exponentially decaying envelope of the back-scattered signal [11,12], while broadband techniques usually use some combination of time-gating and frequency analysis [10,13,14].

A more detailed description of the often used spectral difference technique can be found in Reference 10. The backscattered power spectrum from a certain layer is determined by averaging the power spectra of numerous time-gated A-scans at different spatial positions [15,16]. Assuming even inhomogeneity distribution, the backscattering coefficient must be the same at different depths, therefore the difference between the power spectra of layers at shallow and deep depths yields the apparent ultrasonic attenuation of the backscattered signal.

As mentioned above, ultrasonic attenuation measurement by backscattering is strictly limited to samples of evenly distributed inhomogeneity. This restriction applies to both axial and lateral directions because of the necessity of having a constant backscattering coefficient and using spatial averaging. Consequently, the technique works better on inherently inhomogenous materials such as polycrystalline metals where the grain structure and size distribution is more or less homogeneous, than on less natural inhomogeneities like gas porosity which tends to be unevenly distributed. It is obvious that the accuracy of the attenuation measurement from backscattering is inevitably lower than that of a more conventional coherent transmission technique even in poly-crystalline materials where the number of statistically identical, but uncorrelated A-scans can be as high as a few thousands.

Fig. 1 shows the line-of-sight propagation through tenuous distribution of scatterers in a low absorption medium. The forward propagating total wave becomes dominantly incoherent after only two optical distances, but a large aperture phase-sensitive detector has much higher sensitivity to the smaller coherent term than to the strongly diverging incoherent one. We can measure the weak coherent term even after 50-60 dB attenuation, when it has lost more than 99.999% of its energy to the scattered field.

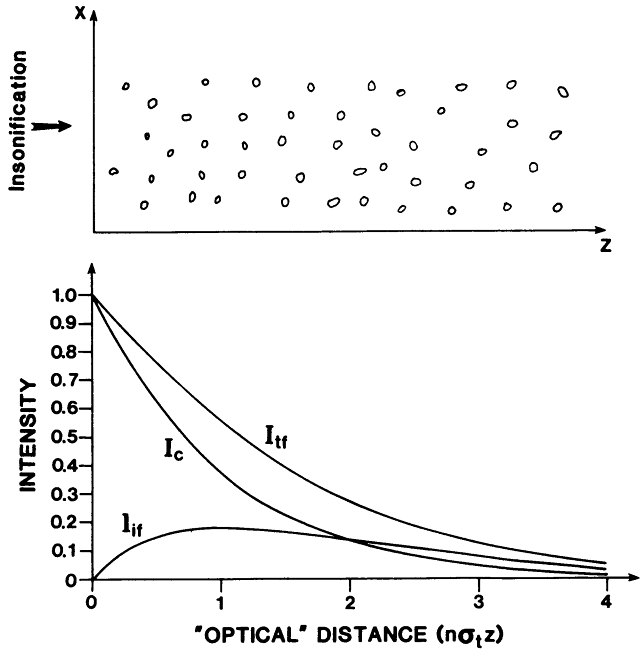

Fig. 1. Approximate behavior of the coherent intensity I_c, the forward propagating incoherent intensity I_{if}, and the total forward propagating intensity I_{tf} for an absorption free medium in the case of isotropic scattering.

On the other hand, there is no way to distinguish between backscattering components due to coherent and forward scattered incoherent waves. Therefore, there is only a very short exponentially decaying part at the very beginning of the backscattered signal where the principal source of the forward scattered field is still the weakening coherent wave. In non-absorbing media this range is not longer than the optical distance, and it is followed by a diffuse region where the non-exponential decay yields no other information than absorption [18]. In some applications, the inhomogeneity simply provides a means to measure the ultrasonic attenuation through the backscattered waves, but does not contribute to the attenuation itself. In such cases, e.g. in biological tissues, the backscattering technique yields comparable results to the coherent transmission methods in a wide attenuation range. In mostly scattering media, there is only a short (less than 10 dB) attenuation range where scattering induced attenuation can be measured at all. This rather small measuring range, together with the inevitably low accuracy, greatly limits the feasibility of scattering induced attenuation assessment from backscattering. Furthermore, the question arises whether the attenuation coefficient in this exponentially decaying beginning part of the backscattered signal is the same as that of the coherent wave or not.

This generic problem was analyzed by the authors in a separate paper [17]. According to their results, as opposed to absorption, scattering always has a weaker effect on the ability of a collimated beam to generate incoherent backscattering than to generate a coherent echo. The total scattering cross-section can be written as the sum of inward and outward components:

$$\gamma = \gamma_{in} + \gamma_{out}, \qquad (3)$$

where γ_{in} denotes the forward scattered portion of the total scattering cross-section, which does not diverge out of the coherent beam. The scattering induced attenuation of the backscattered signal:

$$\alpha_s^{bs} < \tfrac{1}{2}\, n\, \gamma_{out} < \alpha_s^{pl} \qquad (4)$$

is always smaller than the corresponding plane wave attenuation, and in the case of strongly forward scattering inhomogeneity, the difference can be substantial.

EXPERIMENTAL RESULTS

The seriousness of the above discussed inherent difference between α_s^{bs} and α_s^{pl} cannot be regarded generally because of the strong dependence on the scattering directivity. Most inhomogeneities such as porosity and composite and ceramic materials are strongly scattering in every direction, therefore the inhomogeneity attenuates the transmitted energy, too, by scattering the incident energy into backward directions. Slight surface roughness, on the other hand, acts like a thin phase-plate, causing only phase modulation in the transmitted wave without reducing the energy transmission of a smooth interface. It should be mentioned that a practical rough-interface tends to be a liquid-solid one where the velocity difference is accompanied by acoustic impedance difference as well. Therefore, as opposed to an ideal phase-plate, we have backward scattering as well, but the source of this diffuse reflection is the reduced specular reflection rather than the transmitted energy. Consequently, as for the field in the second medium, the surface roughness causes forward scattering only. Because of this particular scattering directivity, surface roughness induced attenuation seems to be the best example to indicate the difference between α_s^{pl} and α_s^{bs}.

Fig. 2 shows the schematic diagram of the surface roughness induced attenuation measurement. The front and backwall echoes are coherent specular reflections since the ultrasonic transducer is quite insensitive

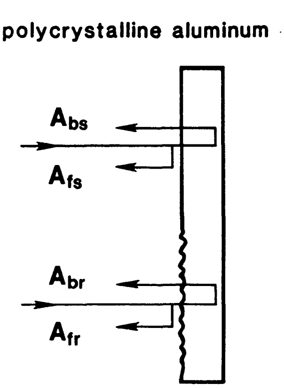

Fig. 2. Schematic diagram of the surface roughness induced attenuation measurement.

to the surface roughness induced incoherent field. Both coherent waves are attenuated by the surface roughness in a similar way although to a different degree. The surface roughness induced attenuation of the front and backwall echoes [18]

$$L_{front} = \ln \frac{A_{fs}}{A_{fr}} = 2h^2k_1{}^2, \tag{5}$$

$$L_{back} = \ln \frac{A_{bs}}{A_{br}} = h^2(k_1 - k_2)^2, \tag{6}$$

where h is the rms roughness of the immersed sample, and k_1 and k_2 denote the wave number in the liquid and the sample, respectively. In spite of the double interaction with the rough surface, the backwall echo is somewhat less attenuated, but both coherent waves are sharply reduced at sufficiently high frequencies.

Fig. 3 shows the backreflected and backscattered signals from an immersed polycrystalline aluminum sample. The rms roughness of the shot-blasted part on the front surface was about 30 μm. Here, and in all the following experiments, a ½" diameter immersion type broadband transducer of 15 MHz center frequency was used to interrogate the sample. The specular front and backwall reflections were attenuated by as much as 60 and 20 dB, respectively. On the other hand, even without spatial averaging, it is obvious that the backscattered signal did not reduce by more than a few dB, i.e. much less than the coherent backwall echo. This result is in good agreement with our prediction that forward directed scattering causes but very small attenuation.

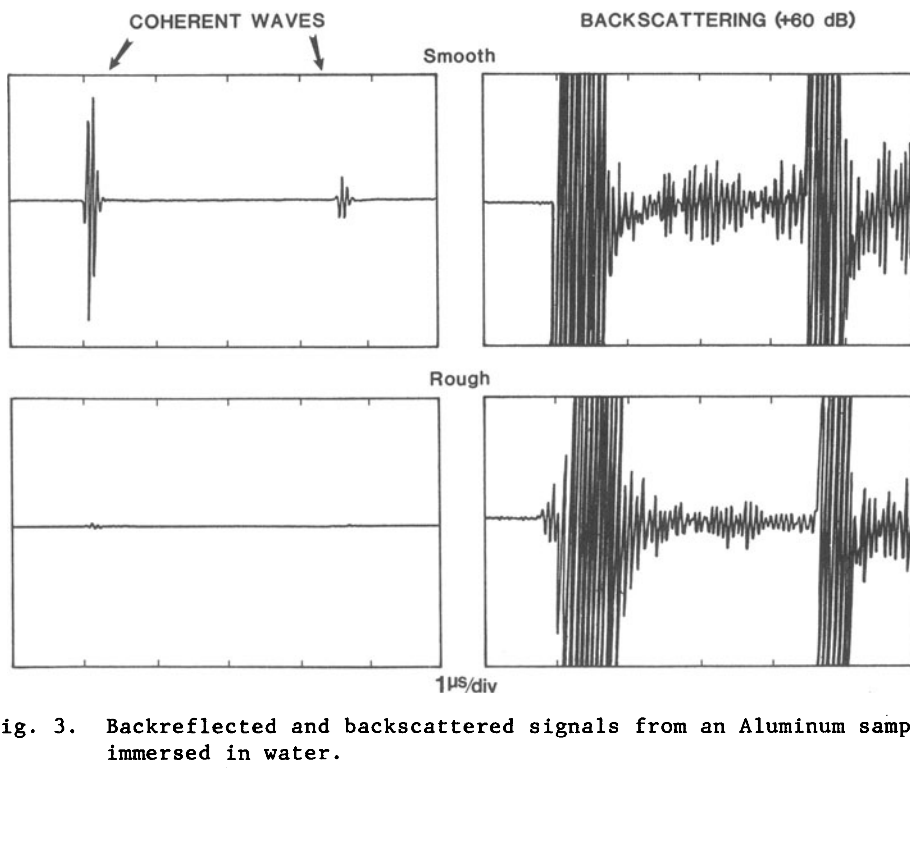

Fig. 3. Backreflected and backscattered signals from an Aluminum sample immersed in water.

Since volume inhomogeneities usually scatter fairly evenly in both forward and backward direction, the scattering induced attenuation of the backscattered signal tends to be approximately half of the plane wave attenuation. Fig. 4 shows the scattering induced attenuation in polycrystalline copper as measured by the coherent transmission and the broadband backscattering techniques. The attenuation coefficient versus frequency curves show the expected result and the difference between the two results is obviously too big to attribute to experimental errors and uncertainties. Fig. 5 shows the result of a similar experiment on a carbon steel sample. The backscattered power from layers at different depths was averaged at 100 different positions. The average backscattering was calculated from the Fourier spectra of these time gated sections by summing all components from 14 to 16 MHz. The slope of the best fitting line to the resulting 17 data points is 1.2 dB/cm, roughly half of the 2.2 dB/cm attenuation coefficient measured by coherent transmission in the same sample.

These results are especially interesting, since backscattering techniques are widely used to measure scattering induced attenuation for grain size assessment in polycrystalline materials [11], Although Guo, Höller, and Goebels [19] raised serious doubts about the feasibility of this technique because of the lack of sufficiently long exponentially decaying part in the backscattered signal before it becomes diffuse, they did not examine the slope in this first part where the principal source of the scattered field is still the forward propagating coherent wave. The rather short exponential part is usually not available by narrow-band tone-burst techniques because the strong interface signal results in a so-called blind zone, and the backscattering becomes partially coherent at the start due to the long pulse time. On the other hand, the backscattering technique proved to be a fairly accurate one in grain size determination, which seems to be in contradiction with our roughly 50% underestimation in the ultrasonic attenuation measurement. The explanation lies in the statistical nature of the grain size and its very strong effect on ultrasonic attenuation. Ultrasonic grain size determination is usually carried out in the so-called Rayleigh region where the scattering induced attenuation is proportional to the volume of the average grain.

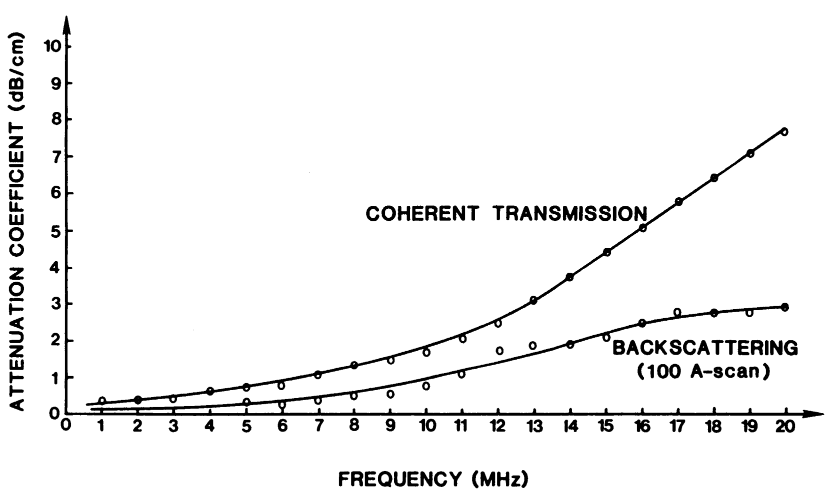

Fig. 4. Grain scattering induced attenuation in polycrystalline Copper.

Consequently, even 50% uncertainty in the measured attenuation would cause only about 15% error in the grain size assessment, while "fairly good agreement" with other, e.g. metallurgical results means no better than 15-30% fit.

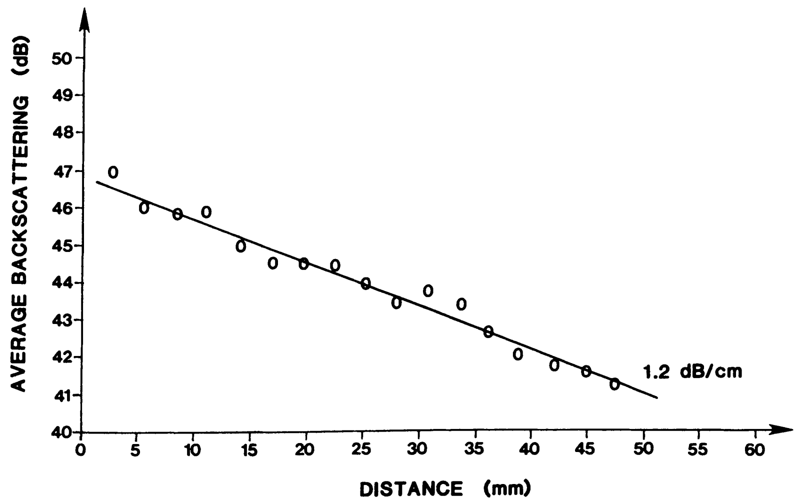

Fig. 5. Average backscattering power from Carbon Steel at 15 MHz as a function of distance from the surface. The grain scattering attenuation coefficient by coherent transmission is 2.2 dB/cm.

CONCLUSIONS

Different techniques for measuring ultrasonic attenuation in inhomogeneous media were compared by experimental means, and the scattering induced attenuation was shown to be highly dependent on the measuring methodology. For instance, the coherent transmission measurement yields the highest possible scattering induced attenuation, while at the other end of the wide scale, backscattering techniques in the diffuse region give zero scattering induced attenuation. The actual value is always somewhere between these limiting cases. Of particular interest is the scattering induced attenuation of the backscattered signal in its first, exponentially decaying portion. Since the dominant component in this region is the forward propagating coherent wave, it is usually presumed that the backscattering is attenuated in the same way as the coherent wave. Theoretical considerations indicate that this is not the case and that the backscattered signal is considerably less attenuated, even in this region, than the coherent transmission. Experimental results were presented on different types of inhomogeneities to verify this conclusion. Scattering induced attenuation measurement plays a very important role in quantitative nondestructive evaluation, therefore these conclusions should be taken into account whenever absorption is negligible.

ACKNOWLEDGEMENT

This work was sponsored by the Center for Advanced Nondestructive Evaluation, operated by the Ames Laboratory, USDOE, for the Air Force Wright Aeronautical Laboratories/Materials Laboratory under Contract No. W-7405-ENG-82 with Iowa State University. The authors also are grateful to James Rose of Iowa State University for his useful suggestions and many interesting discussions.

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