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On the validity and improvement of the ultrasonic pulse-echo immersion technique to measure real attenuation

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ABSTRACT

A fundamental assumption embraced in conventional use of the ultrasonic pulse-echo immersion technique to measure attenuation in solid materials is revisited. The cited assumption relies on perfect and immutable adhesion at the water to sample interface, a necessary condition that allows calculating the reflection coefficient at any interface from elastic wave propagation theory. This parameter is then used to correct the measured signal and obtain the *real* attenuation coefficient of the sample under scrutiny. In this paper, cases in which the perfectly cohesive interfacial condition is not satisfied are presented. It is shown also that in those cases, the repeatability of the conditions at the interface is always uncertain. This implies that the reflection coefficients are unknown, even when density is known. A new method of simultaneously measuring the reflection coefficients for both exposed interfaces that are normal to the transducer, and the attenuation coefficient of the specimen is developed and is presented here. The robustness of the new method is proven, as we demonstrate that the proper value of attenuation is achieved independently of the continuously varying interfacial conditions of these non-ideal cases.

1. Introduction

The ultrasonic immersion technique has a very wide range of applications. It is commonly used to determine the elastic constants of homogeneous, heterogeneous, isotropic, and anisotropic composites [1,2]. It can also be used for material inspection, to detect defects within materials, lack of bonding, voids, or cracks [3,4]. Within our sphere of interest, it is also frequently used to measure wave velocities, attenuation, density, and thickness [5,6].

The present work will focus on the application of the technique to measure the attenuation coefficient of materials which, as referred in this work, is a material property, in contrast to the apparent attenuation measured by other practices such as described in ASTM Standard E664 [6]. This property is also referred to as real or true attenuation.

There exist alternate techniques capable of measuring the attenuation coefficient of solid materials, which are based on the use of direct contact instead of immersion transducers. One such technique developed by Treiber et al. [7] is able to calculate the attenuation coefficient of any material even when reflection coefficients are unknown. This technique overcomes the unknown conditions at the three-media-interface formed by the transducer, the coupling agent, and the specimen by using an additional transducer to measure the reflection coefficient at that interface. This provides a valid measurement of the real attenuation of the material. However, based on the authors' experience, direct contact transducers are not always as reliable as immersion transducers, sometime producing highly distorted second and third echoes that lend themselves poorly to analysis. Inconsistencies associated with the contact transducers led us to adopt immersion transducers in the measurement of attenuation coefficients of solid materials under the well-known pulse-echo immersion technique.

The ultrasonic pulse-echo immersion technique uses a broadband immersion transducer positioned perpendicularly to the specimen and records the successive reflections occurring at the front and back walls of the specimen [8,9]. The spectrums of the first and second echoes are typically used to calculate the attenuation coefficient. In addition, the reflection coefficients at both faces of the sample are needed to correct the measured signals. Sometimes, the transmitted pulses are used instead of the reflected ones and the process is applied with the only difference that the transmission coefficients might be needed, depending on the setup of the test [10]. This variant of the immersion technique is known as through transmission mode. In both test setups, the reflection and transmission coefficients are calculated from elastic wave propagation theory [8–10] for the case of a plane dilatational wave impinging upon a plane interface between two media under the condition of a perfectly bonded interface [11,12]. In this paper, this assumption is analyzed by performing experiments in different

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materials for which the reflection coefficients are measured and compared to those predicted by the theory. It is shown how, for some cases, the reflection coefficients do not match the theoretical ones and therefore, care must be taken when calculating the attenuation coefficient to avoid introducing large errors. Some relatively recent versions of the classical immersion technique are able to provide the attenuation coefficient without the knowledge of the reflection or transmission coefficients [13–15]. However, these versions require equal, [14,15], or consistent, [13], reflection coefficients at both faces of the specimen in order to proceed with the calculations to obtain the attenuation coefficient. The question, indeed, is whether these assumptions do hold true during the execution of the ultrasonic immersion technique, especially for those cases in which the reflection coefficients do not match the theoretical calculation.

2. Theory

Since this work is based on the pulse-echo mode of the Ultrasonic immersion technique, only one transducer is necessary, which works alternatively as an emitter and a receiver. Fig. 1 illustrates the supposed trajectory of both emitted and received pulses, as interactions take place between the ultrasonic pulse generated by the transducer, V_0, and the specimen immersed in the liquid medium. The inclined pulse trajectory illustrated in Fig. 1 is so rendered to assist with the conceptual clarity of the phenomenon, as the actual paths would be directed perpendicularly with respect to the face of the specimen. The chosen notation defines V_0 as the emitted pulse; V'_0 corresponds to the front wall (A) reflection; V_1 and V_2 are the first and second echoes reflected off the back wall (B), respectively. The magnitudes of these reflections, as a function of that of the emitted pulse, are derived presently, as shown. In the relations presented below, the following phenomena are taken into account:

- The pulse will partially transmit and partially reflect at the liquid to solid specimen interfaces.
- Attenuation will occur only within the specimen's internal boundaries, and is neglected as the pulse traverses the liquid medium.
- The traveling pulses will diverge with distance.

Thus,

$$V'_0 = V_0 R_A D(s'_0), \tag{1}$$

$$V_1 = V_0 T_A^2 R_B D(s_1) \exp\{-2h\alpha\}, \tag{2}$$

$$V_2 = V_0 T_A^2 R_B^2 R_A D(s_2) \exp\{-4h\alpha\}, \tag{3}$$

where R_A, R_B, T_A are the reflection and transmission coefficients of faces A and B, respectively. $D(s)$ stands for the beam spreading of the pulse, α is the attenuation coefficient of the specimen, and h is the thickness of the specimen. For a description of the beam spreading function, $D(s)$, the reader is directed to the derivation given by Rogers and Van Buren [16]. It is a function of the wavelength of the ultrasound in liquid medium (λ_w) and within the specimen (λ_s), as well as the transducer size (a), and the distance between the transducer and the closest face of the specimen (L):

$$D(s) = \sqrt{\left[\cos\left(\frac{2\pi}{s}\right) - J_0\left(\frac{2\pi}{s}\right)\right]^2 + \left[\sin\left(\frac{2\pi}{s}\right) - J_1\left(\frac{2\pi}{s}\right)\right]^2},$$

where the s variables are described as $s'_0 = 2L\lambda_w/a^2$, $s_1 = (2h\lambda_s + 2L\lambda_w)/a^2$, $s_2 = (4h\lambda_s + 2L\lambda_w)/a^2$. The functions J are Bessel functions.

2.1. Attenuation coefficient calculation

Dividing Eq. (2) by Eq. (3) and performing the requisite simplifications and reformulation, an expression for the attenuation coefficient α is obtained as shown below:

$$\alpha = \frac{1}{2h} \ln\left[\frac{V_1}{V_2} R_A R_B \frac{D(s_2)}{D(s_1)}\right], \tag{4}$$

where V_1 and V_2 are known, since they are direct readings of the transducer. If the reflection coefficients were to be calculated following conventional methodologies, that is to say, according to elastic wave theory, then:

$$R_A = R_B = \frac{Z_s - Z_w}{Z_s + Z_w}, \tag{5}$$

where Z_s is the acoustic impedance of the specimen, and Z_w is the acoustic impedance of the water. In the above equation, directionality is irrelevant.

2.2. Measurement of reflection coefficient

As discussed in the Introduction, the main three assumptions used by current methodologies to calculate the attenuation coefficient of a material are being tested. On the one hand, it is desired to know if the reflection coefficients match the value given by Eq. (5) for all materials. On the other hand, it is desired to know if the reflection coefficients are equal at both faces of the specimen during a particular instance of immersion and if they are consistent between consecutive immersions. In order to ascertain the veracity of these assumptions, it is necessary to measure the reflection coefficients. This measurement was performed by the method illustrated in the first two subsets of Fig. 2. The method is capable of measuring the reflection coefficients at both faces of the specimen for a unique immersion and is expounded upon in depth in Section 3.2. By means of Steps 1 and 2, the reflection coefficient at face B, R_B, can be measured. Likewise, using Steps 3 and 4, the reflection coefficient at face A, R_A can be measured. The mathematical fundamentals behind this measurement are relatively simple and proceed as follows: In the process pertaining to each of the previous steps, one signal is recorded. Though several options present themselves, the first echo of each signal was chosen to evaluate the reflection coefficients. Referring to Eq. (2), it is clear that the only parameter altered between the two configurations of Steps 1 and 2 is R_B since the transducer and the specimen were never moved. In the configuration corresponding to Step 1, it is assumed that exposure to air results in complete reflection, i.e., $R_B = 1$. Therefore, utilizing Eq. (2), and taking the ratio of the respective first echoes from Step 2 and Step 1, yields the water–specimen reflection coefficient at side B, R_B. Alternatively, use of Steps 3 and 4 would yield R_A.

$$R_B = \frac{V_1^{(2)}}{V_1^{(1)}}; \quad R_A = \frac{V_1^{(3)}}{V_1^{(4)}}. \tag{6}$$

where the subscripts stand for the first echo and the superscripts stand for the corresponding step in the experimental sequence.

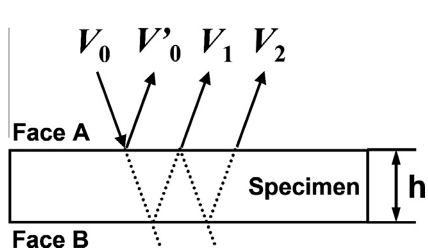

Fig. 1. Interaction between an emitted pulse V_0 and a specimen immersed in water.