ABSOLUTE MEASUREMENT OF ULTRASONIC ATTENUATION

BY ELECTROMAGNETIC ACOUSTIC RESONANCE

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INTRODUCTION

The accurate measurement of ultrasonic attenuation is very important, since it has a great utility in the wide area of materials characterization. In this paper, a new method of measuring the attenuation is presented, which employs electromagnetic acoustic resonance (EMAR) [1-3]. The EMAR is a combination of resonance method and electromagnetic acoustic transducers (EMATs). At a resonance, many reflection echoes are coherently overlapped each other, which serves to provide an easily measurable signal intensity, compensating in excess for the inefficient transduction with EMATs. Use of a noncontacting or weakly coupling EMAT for the attenuation measurement has a pronounced advantage of eliminating the extra energy losses, which otherwise occur with the conventional contacting or immersion tests based on the piezoelectric transducers.

In the attenuation measurement using a contacting transducer with well finished sample surfaces, the ultrasonic beam will lose its energy due to five factors: (1) attenuation in the sample; (2) damping through in the transducer, the couplant, and the buffer, if any; (3) reflection and transmission losses at the interfaces; (4) energy leakage into the transducer; and (5) the beam spreading (diffraction). Being interested only in factor (1), we must remove other losses by proper correcting procedures. Many authors have already investigated the diffraction phenomena for factor (5) in pulse-echo measurements [4-7]. The correction for factors (2) through (4) has not been successful so far in reality, because the acoustic parameters of all the components involved have to be determined a priori. It is not practical to know, for example, the thickness and the acoustic velocity in the couplant, which depend on the temperature, the applied pressure, the surface condition, etc.

The measurement with an EMAT is inherently free from factors (2) and (3). In this case, the ultrasonic wave loses the energy due to factors (1), (5), and additionally (6) electromagnetic loss. It will be shown later that factor (6) is negligible compared with (1) and also we can correct for factor (5) numerically at a resonance, thus isolating factor (1). It is then accomplished to evaluate an absolute value of ultrasonic attenuation based on the EMAR. Furthermore, a larger number of echoes involved in the resonance contribute to improve the accuracy and the reproducibility to a remarkable extent.
LORENTZ FORCE MECHANISM

The shear wave EMATs are used throughout this study (Fig. 1). An EMAT has a pair of permanent magnets, which have the opposite magnetization directions normal to the sample surfaces, and a flat elongated coil. When the coil is placed near the surface of a conducting material and is driven by an rf burst current, eddy currents are induced in the near surface region. These currents interact with the static magnetic field applied by the magnets and generate the Lorentz forces upon electrons carrying the eddy currents. Through the collision with ions and other transformation mechanisms, the Lorentz forces are coupled to the mechanical body forces and generate an ultrasonic vibration. In the room temperature and with a lower frequency (< 50 MHz), the amplitude of the ultrasonic thus generated is linear to the Lorentz force [8]. For the EMAT with the geometry in Fig. 1, the direction of Lorentz force is principally parallel to the surface and results in the polarized shear wave propagating the thickness direction of the sample. The receiving principle is based on the reverse process of the generation.

MEASUREMENT OF RELAXATION TIME COEFFICIENT

Our attenuation measurement proceeds in three steps. It is an absolute measurement in that other damping mechanisms can be eliminated and the evaluation is independent of the measuring conditions including the EMAT used, the specimen thickness, the surface condition, the liftoff, the operator, etc. First, we measure a series of resonance frequencies to the accuracy in the 10 Hz order, by sweeping the operating frequency and obtaining the amplitude spectrum [9]. Secondly, we determine the relaxation time coefficients at the measured resonance frequencies. Finally, we correct for the diffraction effect by numerically incorporating the effect to the echoes that make up the ringdown signals.

Figure 2 shows the measurement setup, which is based on the spectrometer system produced by RITEC, Inc. Resonance frequencies are easily measured by activating the EMAT with long, high-power rf bursts gated coherently, sweeping the operation frequency, and acquiring the amplitude spectrum. Amplitude spectrum is calculated from the in-phase and quadrature outputs of overlapped echoes (reverberation) after the superheterodyne process. We then bring the sample plate into the ultrasonic resonance by driving the EMAT with the measured resonance frequency. At a resonance, all echoes reflected at the sample surfaces become coherent; that is, the echoes possess a constant phase regardless of the echo number, m. In this case, the in-phase integrator outputs \( A_m \cos \Phi_m \) decays exponentially with time, depending on a time constant \( \tau \) as shown in Fig. 3. The outputs of quadrature components \( A_m \sin \Phi_m \) also decay with \( \tau \), but with much less amplitude. We obtain the ringdown curve by sweeping a short integrator gate (instead of a long one for obtaining the spectra) along the time axis, integrating both in-phase and quadrature out-
Figure 2. Amplitude spectrum detection by superheterodyne phase sensitive detector. The diagram includes phase modulation at each step. $A_m$ is the amplitude of m-th reflected echo and $\Phi_m$ its phase.

Figure 3. Time response of coherent signals at a resonance after the superheterodyne processing (in phase components). $A_1$ is the amplitude of the first echo and $\Phi_1$ is its phase shift. $T$ is the round-trip time in the sample and $T_B$ the width of the input rf burst.

Figure 4. Measured ringdown curve with a low carbon steel sample (6 mm thick) at the 10-th resonance frequency (around 2 MHz).
puts, and calculating the root of the sum of the squares of these responses [3]. Figure 4 presents an example of the measured ringdown curve from a 6 mm thick carbon steel at the tenth resonance frequency around 2 MHz. We obtain the relaxation time coefficient at the resonance, which is defined as the exponential decay constant of the curve, by fitting an exponential curve to it. It is shown numerically and experimentally that the coefficient equals τ if the input burst is much longer than the round-trip time T and the integrator gate is short enough. The resonant sharpness (or Q value) also indicates τ, but its measurement depends on the geometry.

Thus measured τ consists of three elements: the attenuation during the propagation in the sample (α), which is related to the material attribute of interest; the beam spreading due to diffraction (τd); and the electromagnetic energy loss (τe). Namely,

$$\tau = \alpha + \tau_d + \tau_e \quad (1)$$

CORRECTION FOR DIFFRACTION LOSS IN EMAR

Ultrasonic beam radiated from a finite transducer spreads perpendicular to the propagation direction and a part of the incident energy will not return to the sending transducer. This is called diffraction and causes the amplitude losses and phase shifts in received echo signals. Following Seki et al. [4], several authors [5-7] have studied the phenomena for longitudinal wave radiated from a circular piston source transducer. But, the solution has been unavailable for the EMAR because of the non-circular geometry and a strength distribution over the EMAT's radiating area; and highly overlapped echoes at a resonance.

Diffraction Phenomena Radiated by an EMAT

We first calculated the Lorentz force distributions in a sample induced by an EMAT through a quasi-nonlinear FEM analysis [10]. Figure 5 is an example of the calculated Lorentz force distribution. This distribution is assumed to represent the shearing force distribution on the radiating area. We next simulate three-dimensional ultrasonic diffraction to calculate the amplitude and

![Figure 5. Lorentz force distribution generated in a low carbon steel by an shear wave EMAT. Two-dimensional quasi-nonlinear FEM analysis was performed assuming a permanent magnet of 2.4mm wide and 2.0mm high with 1T, coil (cupper) of 0.2mm diameter with 6 turns, driving current density of 1.6x10^6 A/m^2, frequency of 1 MHz, and 0.1 mm liftoff.](image)

![Figure 6. Amplitude losses due to diffraction in pulse-echo measurements. λ is wavelength, z the propagation distance, r the equivalent radius of equal area. Solid line is for a shear-wave EMAT whose effective area is 14x20 mm^2. Broken line is for the case of circular piston transducer presented by Seki et al.](image)
phase profiles on the receiving area at a distance. The radiation into the sample is considered by integrating the radiation fields from the all source elements, oscillating with the prescribed strengths, over the sending surface. The amplitude loss is reduced from the ratio of total power over the receiving area to that on the radiating one in a pulse-echo configuration. Figure 6 shows a calculated result for the shear wave EMAT, whose effective area is 14x20 mm². For a comparison, we also give the classical solution by Seki et al. [4]. The phase shift due to diffraction causes little influence on the attenuation measurement, because the variation is limited within the 0 to π/2 range and it is asymptotic to the maximum π/2 as S increases.

Correction at a Resonance State

Figure 7 sketches the algorithm for correcting the diffraction effect at a resonance. The correction proceeds as follows; (1) We measure a resonance frequency and then the relaxation time coefficient τ. (2) We assume a trial time coefficient τ' (τ'<τ), which is supposed to be free from the diffraction effect. (3) We calculate the amplitudes of echoes Eₘₙ(t), which decrease with τ' as in Fig.3; Eₘₙ(t) can be expressed as

\[ Eₘₙ(t) = AₘH(t - mT)e^{-\tau'(m-1)T} \]

where H(t) is the function defined by

\[ H(t) = \begin{cases} 
0 , & t \leq 0 \text{ or } t \geq T_B \\
1 , & 0 < t < T_B 
\end{cases} \]

and Aₘ, m, T and Tᵣ have been defined in Fig.3. (4) We give further damping to Eₘₙ(t) by incorporating the calculated diffraction data in Fig.6. It should be noted that the diffraction effect causes different losses to individual echoes, because they propagate the different distances. (5) We then have the ringdown curve by numerically integrating the superimposed Eₘₙ(t) with a short gate. The gate width and the sweeping steps follow the actual experiments. We obtain the time constant τ' by again fitting the curve to an exponential decay. Now, if the trial τ' is the diffraction-free time constant, then τ'' must equal as-measured τ, because the diffraction effect has been included in τ''; τ''=α+τᵣ. This series of calculation (1)-(5) is repeated until τ''=τ is realized within an error budget.
ELECTROMAGNETIC ENERGY LOSSES

The last term $\tau_e$ refers to the electromagnetic loss, which occurs when the ultrasonic travels through the static magnetic field, giving rise to the inverse Lorentz force mechanism. To estimate $\tau_e$, we consider a simple model that the shear wave, polarized in the x direction, is propagated along the z axis into a sample having a bias field applied by a permanent magnet; the magnetic flux density has a uniform value of $B_0$ along the z direction (Fig. 8). Thus the displacement $u$ and the magnetic flux density $B$ have the forms of

$$u = (u_0 e^{i(ax - k_x)}, 0, 0)$$
$$B = (0, 0, B_0)$$

where $u_0$ is a constant amplitude, $\omega$ the frequency and $k$ the wavenumber. In this situation, an electric field $E = u \times B$ is induced in the sample with the only nonzero component $E_y$, which generates an electric potential $V_y = B_0 E_y$. As the sample is a conductive material, the current $I_y = adzE_y$ arises across the small area $adz$, where $\sigma$ is the electrical conductivity. The average energy $W_E$ spent per unit time in a small rectangular cube (axbxdz) becomes

$$W_E = \frac{1}{2} A\sigma\omega^2 u_0^2 B_0^2 dz$$

where $A = ab$. On the other hand, the energy $W_U$ of shear wave incident in the area $A$ per unit time is

$$W_U = \frac{1}{2} A c_s \rho \omega^2 u_0^2$$

where $c_s$ is the shear wave velocity and $\rho$ is the density. Therefore, the rate of energy loss, $\alpha_e$, spent per unit time, per unit length in the z direction, and per unit incident ultrasonic energy, becomes

$$\alpha_e = W_E/(W_U dz) = \sigma B_0^2/(c_s \rho)$$

This means that the ultrasonic beam will lose the energy during the propagation from $z$ to $z + \Delta z$ by the amount $\alpha_e W_U \Delta z$.

$$W_U - \alpha_e W_U \Delta z = W_U + \frac{dW_U}{dz} \Delta z$$

or

$$W_U = W_0 e^{-\alpha_e z}$$
indicating that $\alpha$ stands for the energy attenuation rate for the propagated distance. To convert $\alpha$ to $\tau$, in Equation (1), we divide $\alpha$ by two and multiply by $c$, to have

$$\tau = \frac{\alpha c_s}{2} = \frac{\sigma B_0^2}{2\rho}. \quad (9)$$

Taking up a steel, for example, where $B_0=0.1T$, $\sigma=3.0\times10^6$ S/m and $\rho=7900$ kg/m$^3$, we have $\tau=2\times10^6$ 1/$\mu$s. Because the static field is not uniform though the sample in practice but is confined to within the near surface region, $\tau$ will be smaller than this estimation. As shown later and in [3], $\alpha$ is larger than $10^3$ 1/$\mu$s in most steels for frequencies beyond 1 MHz. This leads to the estimation that $\tau/\alpha < 0.2$ % and $\tau$ is negligible relative to $\alpha$ for steels. But, $\tau$ has to be taken into account for a material with a high conductivity and for a strong magnetic field.

EXPERIMENTAL RESULTS

Figure 9 shows the attenuation measurements by the EMAR at a series of resonance frequencies for a 25 mm thick carbon steel $(100\times100\times25^\circ)$. We used two EMATs; they are large EMAT of 14x20 mm$^2$ and small EMAT of 5x6 mm$^2$. We used burst signals of 120$\mu$s wide and swept the integrator gate of 5$\mu$s every 1$\mu$s. We plotted the as-measured time constants ($\tau$) and the attenuation coefficients ($\alpha$) after being corrected for the diffraction effect. It is seen that $\alpha$ takes the same value for the two EMATs, while $\tau$ differs each other, reflecting the difference of the diffraction losses involved. The EMAR method is independent on the EMAT geometry after the diffraction correction is performed.

We also make the conventional pulse-echo measurement of attenuation coefficient at the same resonance frequencies. Figure 10 compares them with the EMAR for a 6 mm thick carbon steel sample $(100^2 \times 100^2 \times 6^2)$. In EMAR, we used the large EMAT, the rf bursts of 40$\mu$s duration, and the sweeping gate of 5$\mu$s long. In the pulse-echo method, we used a piezoelectric shear-wave transducer of 12 mm diameter and 5 MHz center frequency. We applied the transducer/buffer/sample system proposed by Papadakis [11], where the effects of boundaries (factor (3)) can be
approximately eliminated. For both methods the diffraction effects were corrected. We tried five
times at the same position for each measurement. It is obvious that the EMAR method is superior
to the pulse-echo method in reproducibility. This occurs not only because of using the contactless
EMAT but also because a large number of echoes participate in the resonance, making the mea-
asurement stable and also robust against the noises.

CONCLUSION

The EMAR is revealed to be ideally suited to the ultrasonic attenuation measurements.
Owing to the use of noncontacting EMATs, it conveniently excludes the interfering effects which
occur with the conventional techniques. The measurement is only influenced by the diffraction
phenomena, but the effect can be strictly corrected using the numerical iteration procedure de-
scribed, resulting in an evaluation of the absolute attenuation coefficient. The measurement can be
done with much ease and high reproducibility, accommodating unprepared samples as well.

The EMAR, however, is restricted to the plate geometry of samples. The diffraction
correction is unavailable for other geometries at present. In case of a thick sample, the intervals of
neighboring resonant peaks become narrower and eventually they are overlapped, making the the
resonance frequency measurement inaccurate or infeasible. When the plate is too thin, the reso-
nance peaks are disperse. The measurable thickness is between 0.5 mm and 50 mm for common
metals, but it depends mainly on the attenuation character in the metal. Discrete measurement of
attenuation at the resonances can be a problem. Interpolation is available to have the attenuation
for intermediate frequencies.

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