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On the Specifics of Measuring Attenuation and Velocity of Ultrasound in Media with Microstructure

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Abstract—We examine specific problems of measuring attenuation and velocity of ultrasound in engineering materials using the pulse method of exciting and receiving elastic oscillations. These problems are related to the influence of the internal structure of metals and alloys on the propagation in them of elastic longitudinal and shear waves in the megahertz frequency range. Using the example of a probing signal in the form of a radio pulse with a smooth envelope of Gaussian shape, additional sources of measurement error of the echo method of evaluation of the main acoustic characteristics used in problems of nondestructive testing and ultrasonic diagnostics of materials with microstructure were revealed.

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Attenuation and propagation velocity of ultrasonic waves are at present very important informative characteristics of nondestructive testing and diagnostics of engineering materials. The use of these characteristics in the audible frequency range began neither today nor even yesterday—at large installations, maintenance personnel check the operability of train car wheels by ear using hammers and salespeople in stores listen to the sound of music that plates and glasses make when stroking a finger around the rim. Clearly, professionals in this area take into consideration the duration (attenuation of oscillations) and the timbre of sound (the main frequency proportional to the velocity of sound, and its harmonics). Modern ultrasonic and electronic radio equipment is quite capable of implementing calibrating impact action and the "sensitive ear" of a professional. High accuracy has been achieved in measuring frequency (time) intervals characterizing frequency (time) shifts of electric signals. At the same time, the abundance of papers and inventions is simply surprising, in which the same high accuracy is ascribed to determination of the physical parameters of oscillations and waves based on these measurements. This especially refers to the pulse method—the most widespread in the ultrasonic testing of manufactured products for various purposes.

So, the physical basis of traditional nondestructive testing is reflection and refraction of elastic waves at the interface of two media. The fact and time of an echo signal arriving is usually fixed, and on this basis, the presence and location of a defect are evaluate, but however much we increase the accuracy in measuring the intervals between electric pulses, because of signal distortion in the material, we can hardly evaluate the time interval between sent and received ultrasonic pulses with an error much less than the pulse duration. In order to achieve the desired effect, we can move away from using video pulses actually applied in nondestructive testing, as well as measuring the casing wall thickness, and switch to so-called radio pulses with clearly expressed high-frequency filling. It then becomes possible to follow more accurately the movement of some "fixed" point of the pulse profile, for instance, of a certain amplitude maximum of the carrier frequency. But how do we choose this point and compare the results of our measurements to those made by other authors? Which point did they choose? Don't the measurement results depend on the choice of the fixed point?

In order to evaluate the size of the defect, attenuation of the sound signal is determined. From attenuation of the probing signal, we evaluate not only the "size" of the defect, but also the attenuation of elastic waves deep in the material. The majority of ultrasonic testing methods are based on examined preliminarily "calibrated" dependences of ultrasound attenuation on particular characteristics of the material [1]. This is a result of the fact that attenuation is much more sensitive to changes in the structural and stress-strain properties of the material than the wave velocity. However, the number of factors decreasing the accuracy of its determination is much larger. Since the accuracy of amplitude measurements itself is at least an order less than frequency (time, phase) measurements, it is clear that reliable determination of the ultrasonic attenuation coefficient in the material is relatively complicated. In determining the size of ultrasonic attenuation by the decrease in amplitude of echo pulses, the

final result is affected not only by absorption (scattering) of elastic waves in the material, but also by the state of the reflecting surface and diffraction spreading of the ultrasonic beam, energy losses in the contact layer, and other factors. A characteristic difference in the propagation of acoustic pulses from propagation of radio waves or signals in electric circuits is the frequency dependence of the wave attenuation coefficient, the physical mechanisms of which can be different depending on the structure of the material and wavelengths.

Here, we limit ourselves to the influence of the internal structure of the material on the accuracy of measuring the speed and attenuation of elastic waves, since among other sources of errors in ultrasonic measurements this question has been explicitly considered by researchers. In implementing precision ultrasonic measurements in metals and alloys, they cannot be considered a continuous medium of elastic wave propagation in the megahertz range (millimeter wavelengths) without loss of accuracy in determining the acoustic characteristics. In this specific idea, it can be characterized, in my opinion, by two basic properties:

—the presence of scale parameters related to the dimensions of crystals, grains, inclusions, and other features of the structure;

—the presence of sharp boundaries between components of the structure.

In comparison to the dimensions of grains, inclusions, and pores in common engineering materials, these are "long" waves. However, at the contemporary developmental level of ultrasonic technique, it becomes noticeable how the frequency dependence of the velocity and/or attenuation of ultrasound affect the propagation of elastic waves related to the presence of "internal" scale parameters in the medium. The existence in the medium of a scale parameter much less than the wavelength leads to weak dispersion of a high-frequency wave and to their predominant Rayleigh-type scattering.

In this case, common pulse methods of measuring the velocity and attenuation of ultrasound have not always been at the necessary level. This is because propagation in such a medium of frequency packets in the time domain of corresponding pulses with a smooth envelope, sufficiently long in comparison to the period of the carrier (radio pulse analogues), already finds specific features not characteristic of harmonic waves [2]. What can we say about pulses of more complex shape, moreover, video pulses. Application of relatively short pulses in comparison to the period of the main frequency results in sufficient signal power and high-resolution capability of the pulse method in testing components of relatively small thickness. As well, however, the procedure of obtaining information on state of the material becomes complicated in comparison to, for instance, resonance or interference methods due to pulse distortion in a structurally inhomogeneous medium. There should be more focus on allowance for how the pulse characteristics and the medium influence the accuracy in determining the velocity and attenuation of ultrasound in a material with a frequency dependence on the velocity and/or attenuation of ultrasound.

Study [3] addressed the question of errors in measuring the ultrasonic attenuation coefficient, which were determined by the pulse shape and the character of wave attenuation in the material. For a bell-shaped (Gaussian-shaped) pulse of the form

$$R(t) \sim \exp\left(i\omega_0 t - \frac{t^2}{2\tau_0^2}\right) \quad (1)$$

propagating in a medium with an attenuation coefficient of $\alpha = \alpha_0\left(\frac{\omega}{\omega_0}\right)^s$ (s is even), approximate expressions were obtained determining the dependence of the main frequency ω_0 and the inverse pulse duration on the path x traveled by it. Introducing in them an effective pulse duration of $2\tau_0$ instead of its inverse value, we obtain

$$\omega(x) = \omega_s = \omega_0[1 - s(\omega_0^2\tau_0^2)^{-1}\alpha_0 x], \quad (2)$$

$$\tau^2(x) = \tau_s^2 = \tau_0^2[1 + s(s-1)(\omega_0^2\tau_0^2)^{-1}\alpha_0 x]. \quad (3)$$

Formulas were obtained in the smallness approximation of $2(\omega_0^2\tau_0^2)^{-1}$, which with reference to ultrasonic testing was taken at 10^{-2}–10^{-4} (a dimensionless effective pulse duration of $n = 2\tau_0/T_0$ near 2–20 periods T_0 of the main frequency). The value of the attenuation coefficient measured over the amplitude maximum in the pulse in this case is determined by the formula

$$\alpha(x) = \alpha_0[1 + s(s-1)(2\omega_0^2\tau_0^2)^{-1} - s^2(2\omega_0^2\tau_0^2)^{-1}\alpha_0 x].$$

Formula (3) shows the influence of two competing effects on the measurable value of the attenuation coefficient: its increase due to pulse spreading and decrease due to a decrease in the main frequency. In [3], a quantitative estimate of the relative error in measuring attenuation by a pulse with an effective duration of nearly two periods of the main frequency, the amplitude of which decreased by a factor of e^5 ($\alpha_0 x = 5$): at $s = 2$, the error is 18%; at $s = 4$, it reaches 70%.

In this, the measuring attenuation is less than the actual attenuation, since the value of $\alpha_0 x = 1 - 1/s$ at which the measured attenuation coefficient coincides with the actual one is, respectively, 0.5 and 0.75. Obviously, to increase measurement accuracy, we should choose such a range of changes in signal amplitude that this equality will be approximately satisfied, although this is not always possible during strong signal attenuation or large dimensions of the samples under

study. For steel in the megahertz frequency range $\alpha \approx 3\ m^{-1}$ and the corresponding distance is 15–25 cm, which is feasible to implement even at a large thickness and during multiple passes of the pulse through a relatively small thickness of the material. At the same time, for pig iron, attenuation can be 10–20 times greater and this distance is 1–2 cm.

Quantity s is related to physical mechanisms of attenuation of elastic waves in a medium; so, at $s = 2$, signal attenuation is determined by the presence of dislocations or coherent scattering of waves; $s = 4$ corresponds to the region of Rayleigh scattering [4, 5]. In addition to scattering caused by multiple reflections of an elastic wave at the boundaries of the structural components, in a real medium, there can be wave absorption, for instance, hysteretic losses and other forms of internal friction. This mechanism is characterized by a linear dependence of ultrasonic attenuation on frequency, i.e., $s = 1$.

In the long term, theoretical studies of the problem were implemented for problems of medical diagnosis in studying ultrasonic attenuation in biological objects. Experiments have shown that with such objects, condition $1 \le s \ge 2$ is almost always satisfied [6]. In [6], an equation was found for evaluating the main frequency of a pulse in such a medium, and in [7] for a narrowband frequency packet, an analytical solution to this equation was obtained. For cases $s = 1$ and $s = 2$, this solution in fact coincides with formula (1), although s is odd. However, for these cases, it is possible to find exact solutions using inverse Fourier transform, leading to generalized Poisson integral [8].

The mechanism of the linear frequency dependence of attenuation is not directly related to the presence or absence of microstructure; however, it can make its own contribution to the experimental value of the attenuation coefficient in the medium. One can see from formulas (2), (3) or the result of special consideration of the question [9] that in this case "dissipative" pulse spreading is absent; therefore, the measured attenuation will always be less than the actual attenuation.

In a real material, there are usually several mechanisms of ultrasonic attenuation and quantity s is determined as the result of their competition. Judging from the results of experimental study [10], for steels in the frequency range of 5–20 MHz, its value is between 2 and 4 (in steel 40X3 it lies between 3 and 4, and for steel 12X18H10T, it can be taken as 2).

Thus, the dynamic range for measuring the attenuation coefficient in materials with microstructure should be chosen such that the amplitude of echo signals by which the value of the attenuation coefficient is judged differs by roughly a factor of 2. If this is impossible under the experimental conditions, then to estimate the true value of the frequency-dependent attenuation in a material, formula (2) should be used.

In applying "velocimetric" methods of studying the properties of a medium, obviously the most suitable informative parameter is the phase velocity. Strictly speaking, it is not related at all to the spatial displacement of any substance if the value of the "phase of oscillations" cannot be considered as such. The phase velocity is associated with a harmonic wave and is relatively easily determined in standing wave systems and in interferometers [11]. As is known, its physical sense is as follows: if at the selected point of space the phase of oscillation with frequency $f = \omega/2\pi$ is equal to φ, then after the time $nT = n/f$ or at the moment in time at distance $n\Lambda$ it will be equal to $\varphi + 2\pi n$. The ratio of the space and time period of oscillations of the medium naturally has the dimensionality of speed. However, it does not determine any material motion (it is not at all surprising that the propagation "velocity" of electromagnetic waves along a waveguide can exceed the speed of light, because this is "apparent" motion, like blinking Christmas tree lights or moiré patterns).

However, as a consequence, quantity $V_f = \Lambda/T = \Lambda f$ for a given frequency of oscillations excited in the medium is determined exclusively by the properties of the medium. For instance, the propagation velocities of bulk longitudinal and shear waves in an isotropic solid not possessing an internal structure do not depend on frequency and are determined by elastic moduli and the density of the medium. Resonance methods of measuring the phase velocity are based on using this definition and fixing the frequency of this wave, the wavelength of which and the length of the resonator are found in the relation $n\Lambda = 2L$. However, to support resonance oscillations of a solid medium, larger energy expenditures are required; in addition, vibrations of complex-shaped details of require a quite cumbersome description.

The simplest and most economical way to excite elastic waves in a material is impact excitation (if maintenance personnel use a hammer for this, then a salesperson needs only two fingers!). In pure form, this method is used in nondestructive testing, but the sensitive ear is replaced by a microphone and frequency meter (or a spectrum analyzer). The most widespread, however, are pulse-echo methods, where the role of a wheel or a plate is played by an electromechanical transducer excited by a powerful electric pulse and connected (in the oscillation sense, because there are noncontact transducers) to the surface of the studied material.

In this case, a wave train propagates in the medium; i.e., something is already "in actuality" displaced in space. The speed of displacement of the envelope maximum of a quasi-harmonic wave, in a medium without dissipation coincides with the group velocity of the main frequency corresponding to the maximum of the amplitude spectrum. If in the medium there is not only no dissipation, but also no dispersion (all the

harmonics "travel" at the same speed), the phase velocity coincides with the group velocity, assuming in such an indirect way a certain physical sense. As well, any point of the wave train corresponding to a certain phase of oscillation "moves" at this speed.

In a dispersive medium, a specific phase velocity corresponds to each harmonic; therefore, tying ourselves to a certain phase of oscillation in the wave train, it is not so easy to forecast when and at what point in space we will again see this phase. For a narrowband frequency packet of Gaussian form (1) in a medium with weak dispersion, fully characterized by dispersion parameter $D = d^2q/d\omega^2$ [12] (q is the propagation constant) at the frequency range occupied by the pulse, it is possible to show that these are only two points equidistant from the "amplitude center" ($R'(t) = 0$) of the pulse, determined by the equation [13]

$$(t - t_0)^2 = 2\tau_0^4 (Dx)^{-1} (1 + \tau_0^{-4} D^2 x^2) \arctan(0.5\tau_0^{-2} Dx).$$

Here, $2\tau_0 \gg T_0$ is the effective duration of the wave train, and quantity $\tau_D^2 = \tau_0^2 (1 + \tau_0^{-4} D^2 x^2)$ corresponds to the pulse half-duration squared in a weak dispersion medium. At a small value of parameter $\tau_0^{-2} Dx$, these are points $\tau \approx t_0 \pm \tau_0$ (here the pulse envelope has the largest derivative). We call these the pulse "phase centers" (in review [2], these are "frequency centers," but here it is more logical to call a frequency center the point of the pulse profile where the equality $\omega = \omega_0 = 2\pi f_0$ is satisfied). Their location is symmetrically relative to the frequency center coinciding in a conservative medium with an amplitude center. By analogy, it is possible to assume that for a pulse with a meander-type envelope, the so-called "velocity of front propagation" will be the closest to the phase velocity of the main frequency (if this inflection point of the envelope is considered the "front line" ($R''(t) = 0$)). In the adopted approximation of a sufficiently long pulse, the location of phase centers is determined only by the function of their envelope. During further pulse propagation, the phase centers "shifting" from the amplitude center in opposite directions.

In a medium without frequency-dependent attenuation, the amplitude center of the pulse coincides with the frequency center ($\omega = \omega_0$) and is displaced with the group velocity of frequency ω_0. If the high-frequency components of the spectrum of the signal attenuate more quickly than the low-frequency components, but there is no dispersion, then the main frequency in the pulse increases everywhere according to formula (2). When there are in the medium both dispersion and frequency-dependent attenuation of ultrasound, it is convenient to characterize wave processes via a complex propagation constant, the real part of which is determined by dispersion properties, and the imaginary part, by the dissipative properties of its structure.

During propagation of a narrowband frequency packet in such a medium, the "balance" of the harmonics is violated and the amplitude–frequency center splits into an amplitude ($R'(t) = 0$) and a frequency ($\omega = \omega_0$) center. In the case of linear dependence of attenuation on frequency ($s = 1$), this point on the time axis is determined by the equality [9]:

$$t_3 \approx t_{gr} + \frac{\alpha_0 \tau_0}{D\omega_0} \tau_0. \quad (4)$$

Here for t_{gr} we take the time by which the amplitude maximum in the conservative medium would have arrived ($R'(t) = 0$, $\omega = \omega_0$). The pulse duration does not change owing to the presence of "linear" attenuation in the medium. If the influence of dispersion on propagation of the wave train is more than, or comparable to, the influence of absorption, then it is possible to find this point in the area of the "main part" [2] of the pulse.

From the condition of equality of the derivative of the pulse envelope to zero, it is possible to find the point of its profile where the amplitude of oscillations reaches the maximum value [9]:

$$t_0 = t_{gr} - \frac{\alpha_0 \tau_0}{D\omega_0} \frac{D^2 x^2}{\tau_0^4} \tau_0. \quad (5)$$

In a medium with small-scale inhomogeneity ($D > 0$), the maximum of the envelope moves more quickly than in an absorptionless medium and vice versa. In a weakly dispersive medium with absorption, the pulse amplitude center still moves at a velocity close to the group velocity of the carrier frequency.

Dominance of the dispersive or absorption properties in a medium is determined by the value of dimensionless parameter $N = \alpha_0 \tau_0 / D\omega_0$, which at the given parameters of pulse is a characteristic of the material. If this parameter is on the order of unity, then the deviation of the amplitude ($R'(t) = 0$) and frequency ($\omega = \omega_0$) pulse centers becomes significant.

$$t_3 - t_0 = \frac{\alpha_0 \tau_0}{D\omega_0} \left(1 + \frac{D^2 x^2}{\tau_0^4}\right) \tau_0 = N\tau_D.$$

As well, neither is displaced with the group velocity of the main frequency, which is shown by formulas (4) and (5). The positions of phase centers remaining symmetrical relative to the frequency center are also shifted relative to the amplitude center.

For the other mechanisms of wave attenuation in the medium ($s = 2$ or $s = 4$), expressions (4) and (5) take the form

$$t_3 - t_{gr} = \frac{s\alpha_0\tau_s}{D\omega_0}\tau_s = sN\frac{\tau_s^2}{\tau_0^2}\tau_0,$$

$$t_0 - t_{gr} = sN\frac{D^2x^2\tau_s^2}{\tau_0^4\tau_0^2}\tau_0,$$

and the value of deviation of the amplitude and frequency centers is determined by a formula

$$t_3 - t_0 = sN\left(1 + \frac{D^2x^2}{\tau_0^4}\right)\frac{\tau_s^2}{\tau_0^2}\tau_0 \approx sN\frac{\tau_{s,D}^2}{\tau_0^2}\tau_0.$$

However, in this case for a sufficiently long wave train, it is possible to find the fixed points being displaced as though they belonged to the harmonic wave of frequency ω_0 [13]. Since their position relative to the amplitude center is asymmetrical, during propagation of the pulse one of them will go beyond its limits earlier than the other. In a medium with positive dispersion ($D > 0$), as a characteristic point for media with a microstructure, it is preferable to use a fixed point located in the area of inflection of the envelope in the first half of the pulse, for determining the phase velocity. This is because, in this part, the amplitude center of the pulse is displaced toward the phase center and the indicated point goes beyond the pulse limits later. It coordinates are determined by the negative root of the equation

$$(t - t_3)^2 = 2\tau_0^4(Dx)^{-1}(1 + s(s-1)(\omega_0^2\tau_0^2)^{-1}\alpha_0 x + \tau_0^{-4}D^2x^2)\arctan[0.5\tau_0^{-2}Dx],$$

where the value $\tau_{s,D}^2 = \tau_0^2(1 + s(s-1)(\omega_0^2\tau_0^2)^{-1}\alpha_0 x + \tau_0^{-4}D^2x^2)$ corresponds to the pulse half-duration squared in the medium under consideration.

In practice it is possible to isolate certain groups of materials for which larger or smaller parameters N are characteristic. The dominant influence of dispersion on the pulse propagation of shear waves with a frequency of 5 MHz in an aluminum–magnesium alloy ($N \leq 1$) has been mentioned. As well, the difference in the displacement velocities of various points of the pulse profile attains 0.1% [13]. An increase in the period of oscillations is observed at the onset of the pulse and a decrease in it at the end ($D > 0$). From the experimentally observed change in the frequency modulation index in the pulse, it was possible to determine the value of dispersion parameter D characterizing the microstructure of the material [14].

For maraging steel, the indicated difference in velocities is five times less, but the frequency-dependent attenuation exerts a substantial influence on wave processes ($N \geq 1$). Estimation of its value helped in increasing accuracy of the ultrasonic method of mechanical stress measurement in a medium with microstructure [15].

Thus, in studying the physical effects characterized by relative changes in the phase velocity of ultrasound on the order of 0.01–0.001% (for instance, the phenomenon of acoustoelasticity), the influence of the microstructure of engineering materials on ultrasonic pulse propagation becomes noticeable. Therefore, the considered specific features of methods for measuring the phase and group velocity and the attenuation of elastic waves and their frequency dependence at the contemporary level of ultrasonic technique developing are becoming of particular interest for media with microstructure.

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