Anomalies of Reflection of Acoustic Pulses from Boundary with Strong Dissipative Medium

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Abstract

In given work the longitudinal acoustic waves reflection from boundary of a solid body with dissipative liquid theoretically is considered. The essential dependence of factor of signal reflection and its phase from factor of absorption of ultrasound in dissipative medium is shown. The experimental confirmation of conclusions of the theory is carried out by consideration of reflection of an acoustic pulse from the boundary of plexiglass - epoxy pitch while the last is loaded, shown essential reduction of reflection factor and of acoustic pulse duration while epoxy pitch is hardening.

Keywords: acoustic wave, reflection, dissipative medium.

1. Theory

The reflection of continuous and pulse acoustic signals from boundary of mediums is investigated theoretically and experimentally rather in detail [1]. Nevertheless, the case of reflection of an acoustic wave from medium having strong absorption of sound waves is unknown to us and can appear interesting both in scientific, and in the practical plan. In that work we consider reflection of an acoustic longitudinal wave (LW) from flat boundary of a solid body with strong dissipative medium, as which the viscous liquid can serve.

Let continuous harmonic LW is spread in a solid body without attenuation, which at normal fall on boundary with a viscous liquid partially is reflected, and past LW in a liquid rather quickly fades (fig. 1).

The wave equation for LW in dissipative medium looks like:

$$\rho\, \ddot{u}_x = c u_{x,xx} + b u_{x,xxt}\ , \qquad (1)$$

where u_x - component of longitudinal displacement in LW, c - elasticity module, ρ - density, b - dissipative losses parameter, determined in factors of shift η and volumetric ξ viscosity and thermal conductivity factor χ according to a ratio [2]:

$$b = \tfrac{4}{3}\eta + \xi + \chi(c_v^{-1} + c_p^{-1})\ , \qquad (2)$$

in which c_p and c_v are thermal capacities of medium at constant pressure and volume accordingly.

Thus factor of absorption of sound α is unequivocally expressed through the parameter of dissipative losses b according to expression $\alpha=\omega^2/2\rho S_l^3$, where $\omega=2\pi f$ - cyclic frequency of a sound wave, S_l - speed of a longitudinal sound. Let's note, that at $b=0$ these equation determines the acoustic oscillations in a solid body with the appropriate material constants.

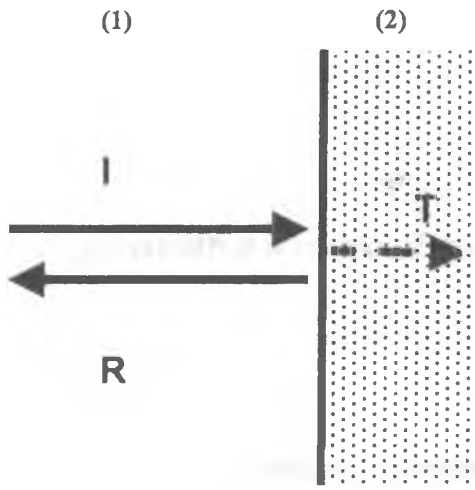

Fig.1. Reflection of an acoustic signal from boundary of mediums

The decisions for falling, reflected and past waves are searched in a standard kind [2]:

$$u^I = u^I_{01}\exp[i(k_1 x - \omega t)]$$
$$u^R = u^R_{01}\exp[i(-k_1 x - \omega t)] \qquad (3)$$
$$u^T = u^T_{02}\exp[-\alpha x + i(k_2 x - \omega t)]$$

where $k_1=\omega/S_{l1}$, $k_2=\omega/S_{l2}$ - wave numbers, S_{l1} and S_{l2} - speed of a longitudinal sound in a solid body (1) and liquid (2), t - time.

The boundary conditions at $x=0$ are representing the continuity of displacement and stress in an acoustic wave and will be written down as follows:

$$u^I_x + u^R_x = u^T_x,$$
$$c_1(u^I_{x,x} + u^R_{x,x}) = c_2 u^T_{x,x} + b_2 u^T_{x,xt} \qquad (4)$$

That decisions (3) satisfy to the appropriate wave equations, and being substituted in (4), give the system of the linear equations to define the factors of reflection $R = u^R_{01}/u^I_{01}$ and transition $T = u^T_{02}/u^I_{01}$ (T=1+R). Reflection factor has the following kind [3]:

$$R_\omega = \frac{R_0\left[1+(1+x^2)^{1/2}\right] + \frac{T_0}{2}x^2 + i\frac{T_0}{2}x(1+x^2)}{1+(1+x^2)^{1/2} + \frac{T_0}{2}x^2 + i\frac{T_0}{2}x(1+x^2)} \qquad (5)$$

where $R_0=(Z_2-Z_1)/(Z_2+Z_1)$ and $T_0=2Z_2/(Z_2+Z_1)$ are reflection and transition factors of acoustic wave accordingly (when $\omega \to 0$), $x=\omega/\omega_c$, $Z_1=\rho S_{l1}$ and $Z_2=\rho S_{l2\,0}$ are acoustic impedances of solid and liquid mediums (without dissipation), $\omega_c=\rho_2 S^2_{l2,0}/b$ is some effective frequency to characterize the dissipative medium, $S_{l2,0}$ is sound velocity (when $\omega=0$).

Starting from (5), a statement for a reflected signal phase can be followed:

$$tg\Psi^R_\omega = \frac{(1-R_0)T_0 x(1+x^2)^{1/2}\left[1+(1+x^2)^{1/2}\right]}{2R_0\left[1+(1+x^2)^{1/2}\right]^2 + T_0(1+R_0)x^2\left[1+(1+x^2)^{1/2}\right] + \frac{T_0^2}{2}x^2(1+2x^2)} \qquad (6)$$

Thus, accordingly to (5) and (6) at reflection of an acoustic wave from dissipative medium its amplitude and phase varies.

Below the factor of passage T_ω and phase Ψ_ω of the passed LW are also shown:

$$T_\omega = \frac{(1+R_0)\left[1+(1+x^2)^{1/2}\right] + T_0 x^2 + i\frac{T_0}{2}x(1+x^2)^{1/2}}{1+(1+x^2)^{1/2} + \frac{T_0}{2}x^2 + i\frac{T_0}{2}x(1+x^2)^{1/2}} \qquad (7)$$

$$tg\Psi_{\omega}^{T} = \frac{\frac{T_0}{2}x(1+x^2)^{1/2}\left[R_0(1+(1+x^2)^{1/2})+\frac{T_0}{2}x^2\right]}{2R_0\left[1+(1+x^2)^{1/2}+\frac{T_0}{2}x^2\right]+\left[(1+R_0)(1+(1+x^2)^{1/2})+T_0x^2\right]+\frac{T_0^2}{4}x^2(1+x^2)} \tag{8}$$

2. Computer experiment

Proceeding from the given dependence R_ω and using direct and inverse Furier transformations with the help of the computer the form of the reflected signal from boundary of plexiglas - epoxy pitch was estimated for model and real acoustic pulses. The results are given in a fig. 2, 3. The changes of amplitude and phase can be unequivocally connected to properties of a contact liquid and superficial layers of a body and contra-body, for example in tribological research of pairs friction.

If the reflection occurs from less dense acoustic medium ($Z_2 < Z_1$), at $\omega<<\omega_c$ then there is an inversion of a signal ($\Psi^R=\pi$). In a vicinity $\omega\sim\omega_c$ the minimum of reflection factor is observed at the further increase of a phase of the reflected signal concerning a phase of a signal, falling on boundary. Further at $\omega>>\omega_c$ $R_\omega\to 1$ and $\Psi^R\to 2\pi$. There is a complete reflection of a signal. Otherwise at reflection from more dense medium the inversion of a signal does not occur ($\omega>>\omega_c$, $R_\omega\to R_0$ and $\Psi^R\to 0$). Similarly at $\omega\sim\omega_c$ the minimum of reflection factor R_ω is observed at a maximum of a phase Ψ^R_ω. Further at $\omega>>\omega_c$ $R_\omega\to 1$ and $\Psi^R\to 0$.

3. Real experiment

To confirm the theoretically predicted above phenomenon - dependence of the reflection factor from the dissipation of ultrasonic energy in reflecting medium the following experiment was carried out. The pulse generator feeds ultrasonic piezoceramical transducer (UPT) with resonance frequency of 3.5 MHz. An acoustic pulse close to the theoretically considered form was radiated into the structure of plexiglass - epoxy pitch. Radiated and reflected signals were registered by oscillograph.

In a fig. 4 the dependence of reflection factor R of a pulse signal in arbitrary units is presented during hardening of epoxy pitch prepared accordingly to the state standard (10 g of epoxy pitch to 1.2 g of curing agent). Let's note that acoustic impedances of liquid and hard phase of epoxy pitch are differing no more than 100%. During the mix hardening temperature grew no more 10^{o}C in comparison with room, that practically did not influence on the acoustic parameters of the mix. It is possible to explain the reduction of reflection factor in 2,5 times on our sight only by the theory advanced here, namely sharp change of energy dissipation in an epoxy layer while hardening. In a fig. 3 theoretical dependence of reflection factor (represented by dot lines) at Z_1=3.1·10^6 kg/(m^2 s), Z_2 =3.25·10^6 kg/(m^2 s), for the basic frequency of a pulse signal at ω_c=10 MHz for a solid phase. Also at hardening of the epoxy pitch the duration of the reflected acoustic signal changed from τ=3 μs up to τ=2 μs, that will be coordinated to conclusions of the advanced here theory.

The most unexpected results appeared when on 4 volumetric parts of epoxy pitch 1 volumetric part of curing agent was added. The process of hardening of epoxy pitch occurred very intensively and non-uniformly with the change of volume up to 10 % and increase of temperature of a mix up to 80^{O} C. The results of experimental researches are given in a fig. 5, whence it be visible, that the change of reflection factor of an acoustic pulse signal had maximum change in 8.5 times and qualitatively coincided with the advanced here theory. For the quantitative coordination of the theory with experiment the study of dynamics of viscosity and of some physical-chemical factors of hardened epoxy pitch is necessary, that is an independent task and serious experimental efforts are required for that.

It is necessary to make a conclusion, that the condition of reflecting dissipative medium essentially influences the reflection factor and phase both continuous and pulse acoustic signals. As the phase measurements are rather exact in comparison with amplitude ones, so on them we can estimate the sound absorption in strong dissipative medium and to carry out the direct measurements of viscosity of liquids.

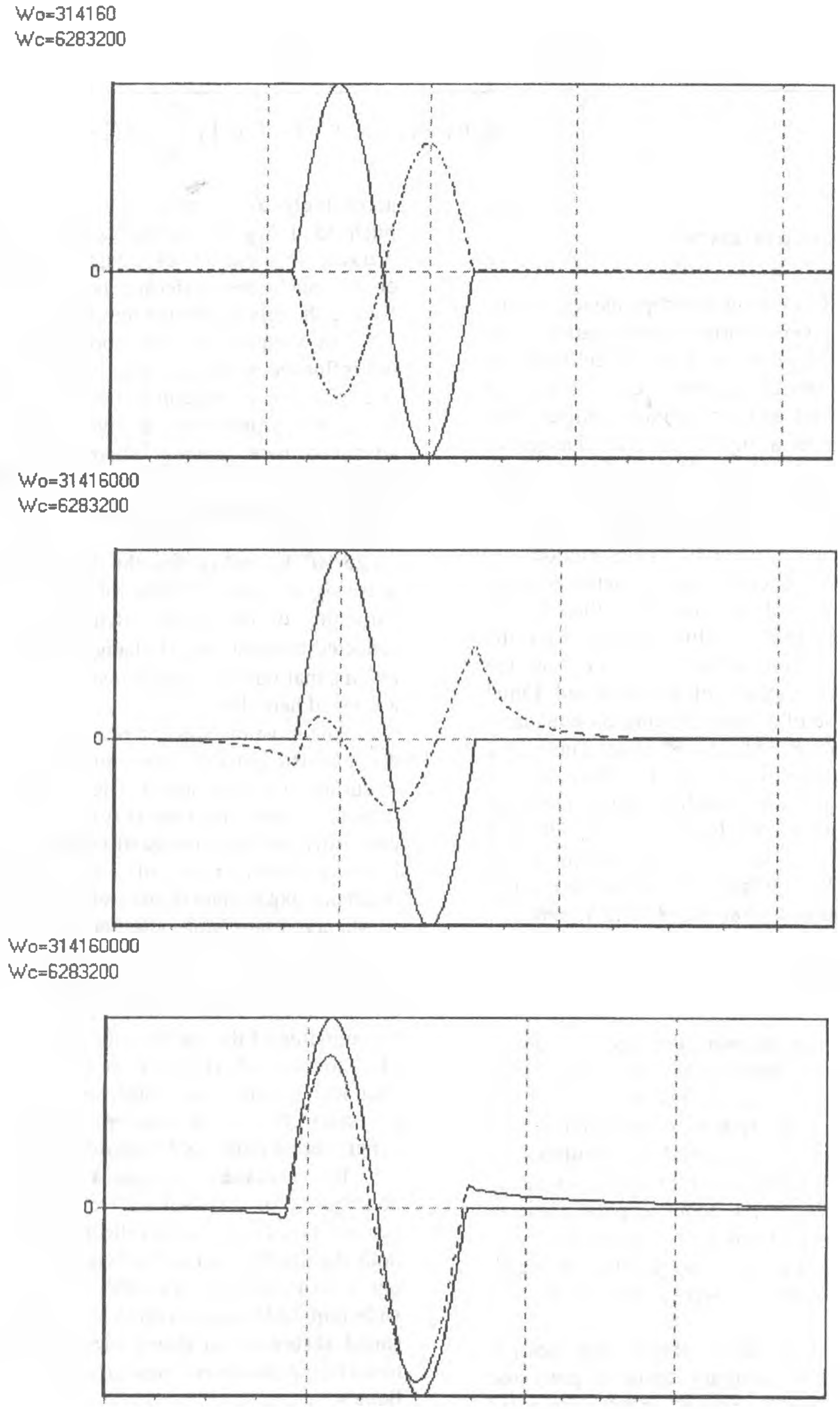

Fig. 2. Reflection of model pulses:
—— falling pulse, ... reflected pulse

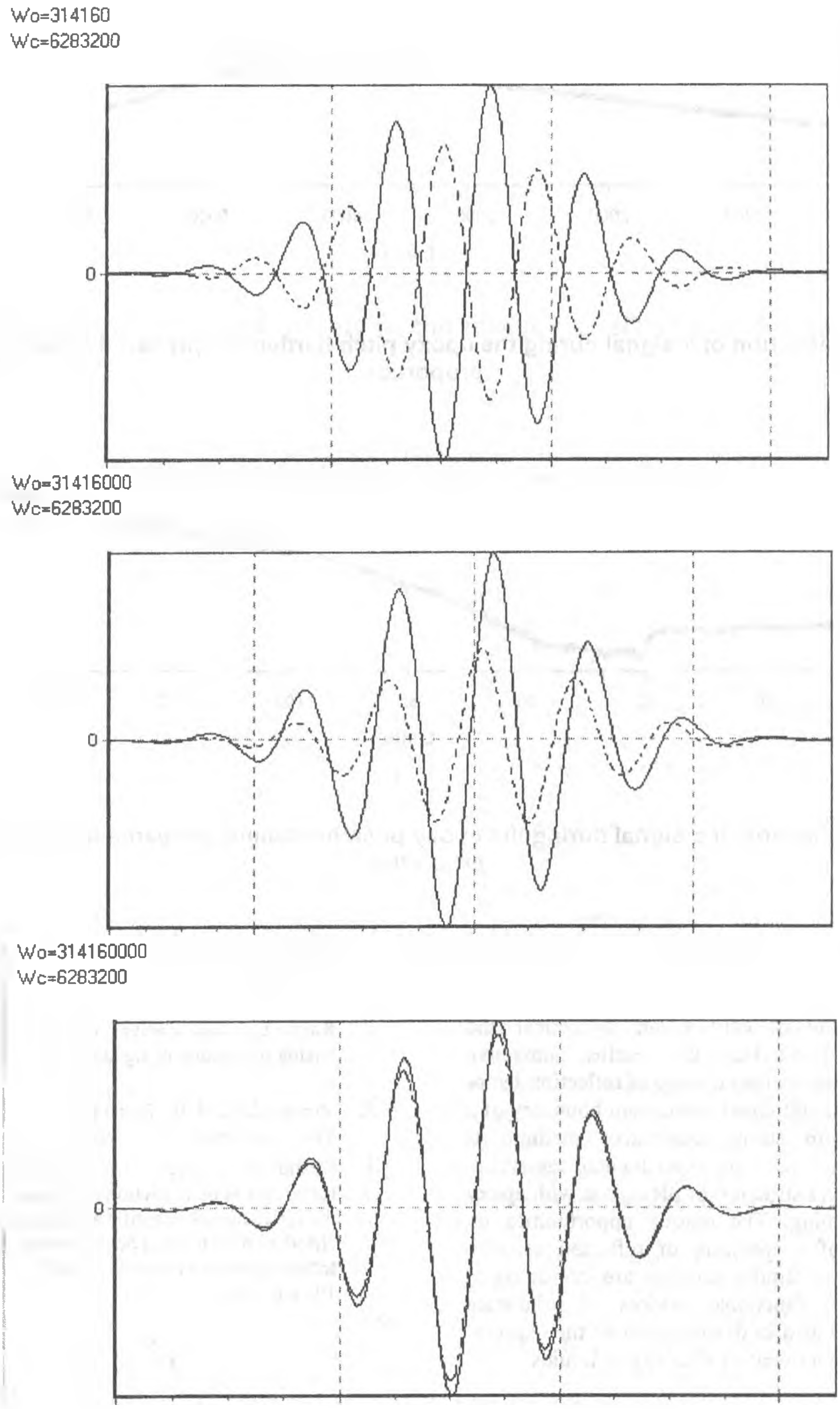

Fig. 3. Reflection of real pulses:
——— falling pulse, ·········· reflected pulse

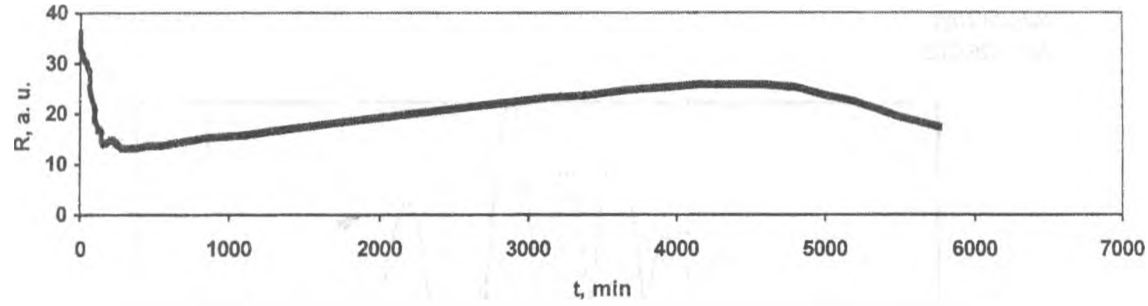

Fig. 4. Reflection of a signal during the epoxy pitch hardening, prepared in 10/1.2 weight proportion.

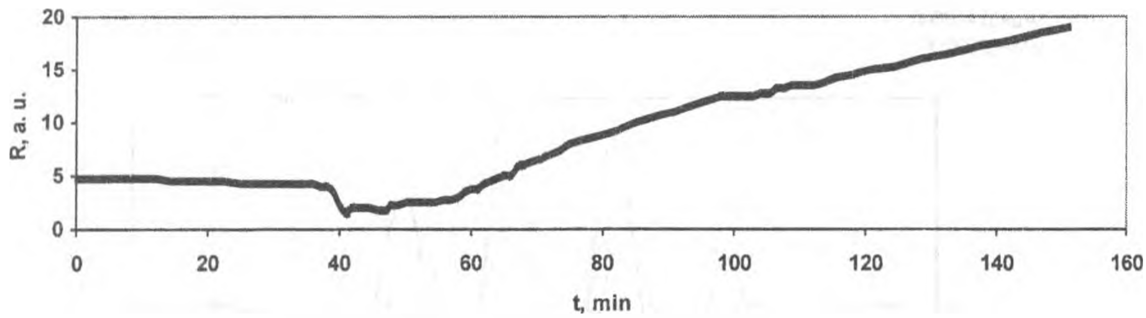

Fig. 5. Reflection of a signal during the epoxy pitch hardening, prepared in 4/1 volumetric proportion.

Conclusion

As a result of carried out theoretical and experimental researches the earlier unknown phenomenon - anomalous change of reflection factor of an acoustic longitudinal wave from boundary of a solid body with strong dissipative medium is established. Its model in experimental researches was the two-layer structure of plexiglass with epoxy pitch at hardening. The unique opportunities on measurement of a spectrum of reflected acoustic signals in such or similar structure are interesting in development of functional devices of solid-state electronics, and also in development of the express-method of measurement of viscosity of liquids.

References

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