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THERMOELASTIC GENERATION OF ULTRASONIC BY PULSE LASER

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The hyperbolic thermal diffusion equation and Navier-Stokes equation are used to find the temperature field and normal displacement field generated by a laser pulse in a semi-infinite medium. The theoretical results are presented. Using correlation method and spectrum analysis technique, the ultrasonic group and phase velocity in several samples are measured with laser-ultrasound technique.

L'équation hyperbolique de diffusion thermique et l'équation de Navier-Stokes sont utilisées pour trouver le champ de température et champ de déplacement normal produits par un impulse de laser dans un medium semi-infini. Les resultats theoriques sont presentes. Utilisant la methode de correlation et la technique de l'analyse spectrale, les vitesses ultrasoniques de groupe et de phase dans queleques échantillons sont mesurées avec la technique de laser-ultrason.

1. Temperature Field

When a $\delta(t)$ laser pulse is incident on a sample surface, a pulse heat source is formed and a rapid thermal expansion can be produced to generate detectable ultrasonic waves in the sample. The thermal power density of the heat source is given by

$$g(\vec{r}, t) = \delta(r)\delta(z)\delta(t) / 2\pi r \quad (1)$$

Instead of the traditional parabolic thermal diffusion equation [1,2], the hyperbolic thermal diffusion equation is used to find the temperature distribution in a semi-infinite homogeneous and isotropic medium in order to avoid getting the impossible physical result that the thermal wave velocity would be larger than sound velocity in the medium when the laser pulse width is short enough. Then the temperature increment $T(\vec{r}, t)$ is determined by

$$(1/C_T^2)(\partial^2 T / \partial t^2) + (1/\alpha)(\partial T / \partial t) = \nabla^2 T + g(\vec{r}, t) / k, \quad (2)$$

and

$$T(\vec{r}, 0) = \partial T(\vec{r}, 0) / \partial t = 0, \quad (2a)$$

where C_T is thermal wave velocity, α and k are thermal diffusivity and conductivity of the medium, respectively.

Using Laplace-Henkel transform, the transform solution $\bar{T}^*(s, p, z)$ is obtained from Eq.(2):

$$\bar{T}^*(s, p, z) = \exp(-K_i z) / 4\pi k K_i, \quad (3)$$

where

$$K_i^2 = (s/C_T^2)^2 + (s/\alpha) + p^2, \quad (3a)$$

$$T(s) = \int_0^\infty T(t) \exp(-st) dt, \quad T^*(p) = \int_0^\infty T(r) J_0(pr) r dr, \quad (3b)$$

Therefore the temperature field is obtained by inverse transform:

$$T(r, z, t) = [H(t - z/C) \exp(-C_T^2 t / 2\alpha) / 4\pi k] \int_0^\infty J_0[(p^2 C_T^2 - C_T^4 / 4\alpha)^{1/2} (t^2 - z^2 / C_T^2)^{1/2}] J_0(pr) p dp \quad (4)$$

where $H(t)$ is Heaviside step function.

2. Normal displacement field

The Navier–Stokes equation for displacement $\vec{U}(r, z, t)$ at point $\vec{r}(r, \theta, z)$, when the temperature field is restricted on the sample surface, is

$$\mu \nabla^2 \vec{U} + (\lambda + \mu) \nabla(\nabla \cdot \vec{U}) - \rho \partial^2 \vec{U} / \partial t^2 = 0, \quad (5)$$

where λ and μ are Lamé constants, and ρ is density.

Introducing the scalar and vector potential ϕ and $\vec{A}$, such that

$$\vec{U} = \nabla \phi + \nabla \times \vec{A}, \quad \nabla \cdot \vec{A} = 0 \quad (6)$$

Let $A_\theta = -\partial \psi / \partial r$, we get

$$\nabla^2 \Phi - (1/C_1^2) \partial^2 \Phi / \partial t^2 = 0, \quad \nabla^2 \psi - (1/C_2^2) \partial^2 \psi / \partial t^2 = 0, \quad (7)$$

and the initial conditions and boundary conditions are

$$\Phi(r, z, 0) = \partial \Phi(r, z, 0) / \partial t = 0, \quad \psi(r, z, 0) = \partial \psi(r, z, 0) / \partial t = 0, \quad (8)$$

$$\tau_{zz}(r, 0, t) = \lambda \nabla^2 \Phi + 2\mu(\partial / \partial z)[\partial \Phi / \partial z + \partial^2 \psi / \partial z^2 - (1/C_2^2) \partial^2 \psi / \partial t^2] - (3\lambda + 2\mu) \alpha_T T = 0, \quad (9)$$

$$\tau_{rz}(r, 0, t) = \mu(\partial / \partial r)[2\partial \Phi / \partial z + 2\partial^2 \psi / \partial z^2 - (1/C_2^2) \partial^2 \psi / \partial t^2] = 0 \quad (10)$$

where $C_1^2 = (\lambda + 2\mu) / \rho$, $C_2^2 = \mu / \rho$, and α_T is thermal expansion coefficient.

Applying Laplace–Henkel transform to Eqs. (7)–(11), we obtain

$$\begin{aligned} \bar{U}_z = & -[(3\lambda + 2\mu) / 4\pi k \mu] * \\ & \int_0^\infty \frac{k_1 \{[(s/C_2)^2 + 2p^2] \exp(-k_1 z) - 2k_1 p^2 \exp(-k_2 z)\} p J_0(pr) dp}{K_1 \{[(s/C_2)^2 + 2p^2]^2 - 4k_1 k_2 p^2\}} \end{aligned} \quad (11)$$

where $k_i = p^2 + (s/C_i)^2$, $i = 1$ or 2 .

Using Cagniard method and $K_1^2 \cong (s/C_T)^2 + p^2$, the epicenter displacement $U_z(r=0)$ is obtained:

$$\begin{aligned} U_z = & B' * C_2 \tau^2 (2\tau^2 + \delta_2) H(t - z/C_1) / [\tau^2 + (C_2/C_T)^2 - (C_2/C_1)^2]^{1/2} \{ (2\tau^2 + \delta_2)^2 - 4\tau(\tau^2 + \delta_1)^{1/2} [\tau^2 \\ & - (C_2/C_1)^2] \} \\ & - B' * 2C_2 \tau (\tau^2 - 1)(\tau^2 - \delta_1) H(t - z/C_2) / [\tau^2 + (C_2/C_T)^2 - 1]^{1/2} \{ (2\tau^2 - 1)^2 - 4\tau(\tau^2 - 1)(\tau^2 - \delta_1)^{1/2} \} \end{aligned} \quad (12)$$

where $\tau = C_2 t / r$, $\delta_1 = 1 - (C_2/C_1)^2$, $\delta_2 = 1 - 2(C_2/C_1)^2$, $B' = B/Z$ and $B = -(3\lambda + 2\mu) / 4\pi k \mu$.

The surface displacement $U_z(z=0)$ can also be found by means of residual theorem. In the case of $C_T < C_2 < C_1$, we get

Fig.1—Normal displacement waveforms

(a) and (b) are theoretical results $U_z(r=0)$ and $U_z(z=0)$
 (c) and (d) are experimental results $U_z(r=0)$ of AL
 and $U_z(z=0)$ of Steel measured by interferometer.

Fig.2— Laser-Ultrasound system.

$$U_z = \begin{cases} 0, & (0 < \tau < C_2 / C_1), \\ -\frac{2B}{\pi r} \int_0^\tau \frac{C_2 y (1-2y^2)^2 [y^2 - (C_2 / C_1)^2]^{\frac{1}{2}} dy}{[(C_2 / C_T)^2 - y^2]^{\frac{1}{2}} \{(1-2y^2)^4 + 16y^4 (1-y^2) [y^2 - (C_2 / C_1)^2]\} (\tau^2 - y^2)^{\frac{1}{2}}}, & (C_2 / C_1 < \tau < 1), \\ -\frac{2B}{\pi r} \int_0^\tau \frac{C_2 y [y^2 - (C_2 / C_1)^2]^{\frac{1}{2}} \{(1-2y^2)^2 + 4y^2 [y^2 - (C_2 / C_1)^2]^{\frac{1}{2}} (y^2 - 1)^{\frac{1}{2}}\} dy}{[(C_2 / C_T)^2 - y^2]^{\frac{1}{2}} \{(1-2y^2)^4 + 16y^4 (1-y^2) [y^2 - (C_2 / C_1)^2]\} (\tau^2 - y^2)^{\frac{1}{2}}}, & (1 < \tau < C_2 / C_T), \\ 0, & (C_2 / C_T < \tau). \end{cases}$$

The normal displacement waveforms $U_z(r=0)$ and $U_z(z=0)$ are shown in Fig.1(a) and (b), respectively. They are in good agreement with the experimental results Fig.1(c)[3] and (d)[4].

3. Measurement of ultrasonic velocity

A laser-ultrasound experimental system is shown in Fig.2. The ultrasound pulse generated by a N_2 pulse laser (337nm, 8ns and 6-8mJ) and the train of echo pulses in the sample are detected by a PVDF film or PZT coupled with the sample. The ultrasonic pulses are recorded by a digital oscilloscope Gould 4072 and sent to a microcomputer to process. The correlation method and spectrum analysis technique are used to obtain the group and phase velocity of several samples. The experimental values of group velocity of Al and Steel are

$$C_{AL} = (6.438 \pm 0.029) \text{ km/s}, \quad C_{Steel} = (6.005 \pm 0.005) \text{ km/s},$$

respectively. The phase velocity of Al and Steel are shown in Table 1. They are in good agreement with the theoretical values:

$$C_{AL} = 6417.74 \text{ km/s} \quad \text{and} \quad C_{Steel} = 5.941 \text{ km/s}.$$

Table 1 Experimental results of phase velocity

Sample	f(MHz)	20.5	22.1	24.4	25.9	26.6	30.7	32.3	33.9
AL	C(km/s)	6.40	6.41	6.41	6.40	6.41	6.40	6.39	6.40
	f(MHz)	21.3	22.8	24.4	27.6	29.9	31.5	33.9	35.4
Steel	C(km/s)	5.96	5.95	5.96	5.97	5.95	5.95	5.96	5.96

Therefore the laser-ultrasound method is a very powerful new technique for nondestructive testing.

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