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Thermoelastic Waves Generated by Line-focused Laser Sources

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1. Introduction

Laser-based ultrasonics has many industrial application in the area of nondestructive testing and evaluation (NDT&E), laser ultrasonic velocity and attenuation measurements to determine elastic constants and grain size of materials. The laser-generated ultrasonics has several advantages in NDT&E over many conventional transducers, such as the ability to achieve broad-banded excitation with high signal reproducibility and the possibility of generating a truly remote source of ultrasound by optical means on hot or rough samples and in hostile environments. The characteristics of the laser-based ultrasonic wave depend strongly on the optical penetration, thermal diffusion, elastic properties and geometry of materials as well as parameters of the exiting laser pulse including the shape, focus spot, and pulse width [1].

A numerical analysis formulation is developed to simulate a generation of thermoelastic waves in homogeneous isotropic elastic half-space under a line-focused laser irradiation. Analytic solutions for surface displacements are obtained by employing integral transform methods to the transient elastodynamic equations. Inverse Fourier transform is numerically evaluated by making use of Filon's method and numerical inversion of the Laplace transform is performed on the basis of Crump-Durbin technique. The numerical results of the displacements and the tractions generated by a line-focused laser pulse on the surface of an aluminum block.

2. Theory and Results

In this section some of the theories involved in generating thermoelastic waves are briefly described.

Table I: Symbols of parameters and values of material constants for aluminum.

Symbol	Parameter	Aluminum
c_1	Compression wave speed	6400 m/s
c_2	Shear wave speed	3150 m/s
c_R	Rayleigh wave speed	2940 m/s
ρ	Density	2700 kg/m^3
α	Linear expansion coeff..	2.31 10^{-5} K^{-1}
κ	Thermal diffusivity	6.58 10^{-5} m^2/s
k	Thermal conductivity	240 W/mK
R	Reflectivity	0.94
μ	Shear elastic modulus	26.1 GPa
λ	Lame elastic modulus	58.1 GPa
ν	Poisson ratio	0.345

2.1 Governing Equations

The.hyperbolic time-dependent thermal diffusion equation for the temperature Θ [2]:

$$\nabla^2\theta - \frac{1}{\kappa}\frac{\partial\theta}{\partial t} - \frac{1}{c_1^2}\frac{\partial^2\theta}{\partial t^2} = -\frac{q}{k}. \quad (1)$$

The symbols of parameters are listed in Table I.

The elastodynamic equation [3]:

$$\mu\nabla^2\vec{u} + (\lambda+\mu)\nabla\nabla\cdot\vec{u} = \rho\frac{\partial^2\vec{u}}{\partial t^2} + \beta\nabla\theta \quad (2)$$

2.2 Spatial and Temporal Laser Profile

The spatio-temporal profile of the laser pulse:

$$q = E(1-R)f(x)g(t) \quad (3)$$

$$f(x) = \frac{2}{\sqrt{2\pi}\varpi}e^{-2x^2/\varpi^2} \quad (4)$$

$$g(t) = \frac{8t^3}{\upsilon^4}e^{-2t^2/\upsilon^2} \quad (5)$$

where ω is the Gaussian width, and υ is the pulse duration time of the laser beam.

2.3 Wave Equations with Boundary-Initial Contidtions

For our analysis, we introduce displacement potential,

$$\vec{u} = \nabla\varphi + \nabla\times\psi \quad (6)$$

Substitution of (6) into (2) yields the wave equation:

$$\nabla^2\varphi - \frac{1}{c_1^2}\frac{\partial^2\varphi}{dt^2} = \frac{\beta}{c_1^2\rho}\theta \quad (7)$$

$$\nabla^2\psi - \frac{1}{c_1^2}\frac{\partial^2\psi}{dt^2} = 0 \quad (8)$$

The boundary and initial conditions read

$$\vec{n}\cdot\nabla\theta(\vec{x},t) = 0 \quad \text{and} \quad \theta(\vec{x},0) = 0 \quad (10)$$

$$\sigma_{zx} = \mu\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) = 0 \quad (11)$$

$$\sigma_{zz} = \lambda\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_z}{\partial z}\right) + 2\mu\frac{\partial u_z}{\partial z} - \beta\Delta\theta = 0 \quad (12)$$

2.4 Fourier-Laplace Transforms, Numerical Inversion

Analytic solution of (1) can be obtained in a integral-transformed form by exploiting Fourier and Laplace transforms. These solutions involve integrals of highly oscillatory functions over semi-infinite intervals and inversion of one-sided Laplace transform. The computational schemes employed are on the bases of Filon's method [4] and a Fourier-series technique for evaluating the numerical inversion of the Fourier-Laplace transform [5].

2.5 Results: Displacement and Traction

A series of numerical computations are carried out to compute the displacements and tractions at the surface of aluminum block. The results are plotted in Figs. 1-5.

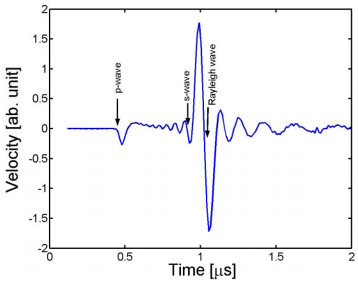

Figure 1. Vertical velocity of the surface at distance 3 mm.

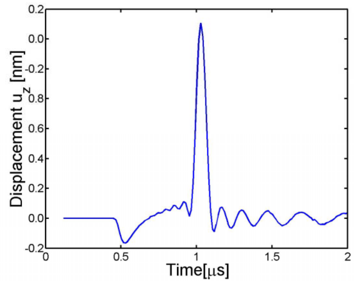

Figure 2. Vertical displacement at distance 3 mm.

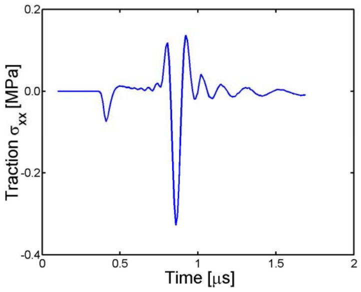

Figure 3. . Traction σ $_{xx}$ on the surface at distance 3 mm...

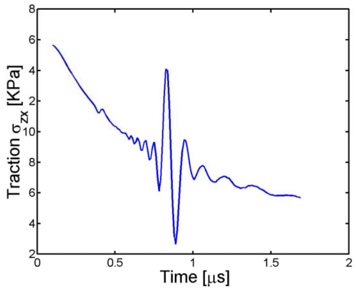

Figure 4. Traction σ $_{zx}$ on the surface at distance 3 mm..

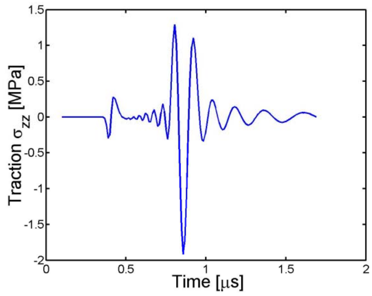

Figure 5. . Traction σ $_{zz}$ on the surface at distance 3 mm..

3. Conclusion

A set of elastodynamic eqauations are solved by use of integral transformations. The computational schemes employed are on the bases of Filon's method and a Fourier-series technique for evaluating the numerical inversion of the Fourier-Laplace transform.

Physical processes involved in generating the thermoelastic waves can be described by a thermal dipole model [6]. The branch points and real poles in the integral-transformed solution of the elastodynamic equation determine the arrival time of compression, shear, and the Rayleigh waves, respectively. The use of the Rayleigh surface wave may have a great advantage in NDT&E since it decays much less than that of the compression wave with distance.

In a thermoelastic regime of laser ultrasonics, the thermal wave equation plays a key role in description of the source term. Since the speed of the Rayleigh surface wave is much slower than that of the heat wave, the temporal profile of the displacement is mainly determined by the material properties rather than that of the laser pulse. Therefore, it is very hard to broadent he frequency spectrum of the ultrasonic wave in the thermoelastic regime. In an ablative reigme, however, broad-band ultrasonic waves can be generated by use of ultrashort laser pulses.

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