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Directivity patterns of laser-generated sound in solids: Effects of optical and thermal parameters

Victor V. Krylov

Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

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ABSTRACT

In the present paper, directivity patterns of laser-generated sound in solids are investigated theoretically. Two main approaches to the calculation of directivity patterns of laser-generated sound are discussed for the most important case of thermo-optical regime of generation. The first approach, which is widely used in practice, is based on the simple modelling of the equivalent thermo-optical source as a mechanical dipole comprising two horizontal forces applied to the surface in opposite directions. The second approach is based on the rigorous theory that takes into account all acoustical, optical and thermal parameters of a solid material and all geometrical and physical parameters of a laser beam. Directivity patterns of laser-generated bulk longitudinal and shear elastic waves, as well as the amplitudes of generated Rayleigh surface waves, are calculated for different values of physical and geometrical parameters and compared with the directivity patterns calculated in case of dipole-source representation. It is demonstrated that the simple approach using a dipole-source representation of laser-generated sound is rather limited, especially for description of generated longitudinal acoustic waves. A practical criterion is established to define the conditions under which the dipole-source representation gives predictions with acceptable errors. It is shown that, for radiation in the normal direction to the surface, the amplitudes of longitudinal waves are especially sensitive to the values of thermal parameters and of the acoustic reflection coefficient from a free solid surface. A discussion is given on the possibility of using such a high sensitivity to the values of the reflection coefficient for investigation of surface properties of real solids.

1. Introduction

Laser generation of sound is a convenient non-contact method of sound generation in air, liquids, and solids. The possibility of generation of sound in solids by transient surface heating has been first described by White more than 50 years ago [1]. Since then, following rapid development of lasers as efficient non-contact sources of heat, this method of generating surface and bulk acoustic waves has been studied widely in respect of its applications to non-destructive testing of materials and to experimental solid state physics (see, e.g. monographs [2–4]). One should keep in mind that this method of elastic wave generation is truly non-destructive only in the so-called thermo-optical regime of generation that takes place if the intensity of laser light is not too high to cause the surface damage and material ablation.

To describe the behaviour of laser-generated sound in the thermo-optical regime of generation it is often assumed that, e.g. in the case of two-dimensional geometry of laser-illuminated area, the equivalent laser-induced source of acoustic waves (a line source) can be modelled as a dipole-type source comprising two horizontal forces applied to the surface in opposite directions (see Fig. 1). The calculated radiation patterns of bulk longitudinal and shear acoustic waves generated by such a pair of forces are shown in Fig. 2. In the case of three-dimensional geometry of a laser beam (a point source) a second pair of horizontal forces should be added in the perpendicular direction, which results in similar radiation patterns in vertical cross-sections.

This very simplified theoretical model has been introduced on the intuitive basis in the early 80-ies (see e.g. [2,3,5]), and it is still used by the theorists [6]. In the same time, a number of papers based on a rigorous approach to the developing of the theory of laser generation of sound in solids have been published in the eighties and nineties [7–13]. These papers, that take into account light absorption and thermal wave generation and propagation, show that there is more to the phenomenon than just a response of the medium to a pair of opposite forces. Attention to the effects of thermal and optical parameters of solids on laser generation of sound continued to be paid also in more recent publications (see e.g. [14,15]).

E-mail address: V.V.Krylov@lboro.ac.uk

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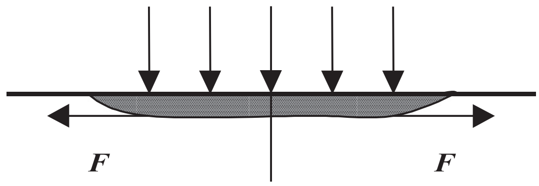

Fig. 1. Modelling a laser-induced line source as a pair of horizontal forces.

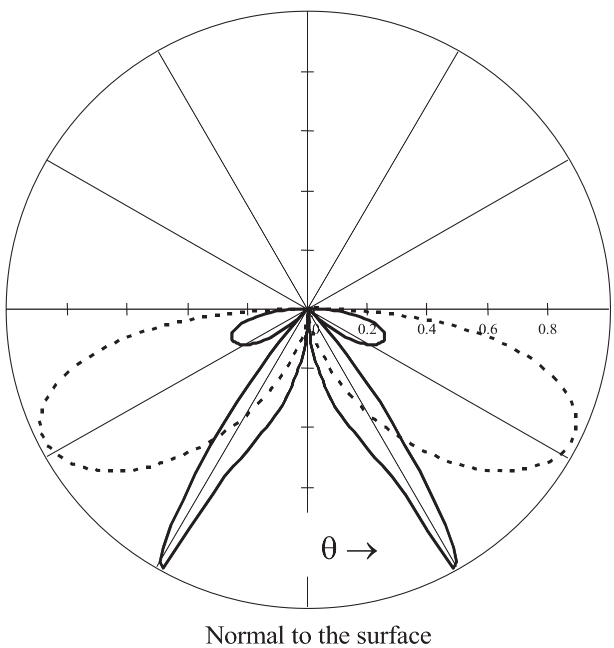

Fig. 2. Dipole-type radiation patterns for a pair of horizontal forces applied to the surface: dashed curve corresponds to bulk longitudinal waves, and solid curve indicates shear waves.

In the present paper, the behaviour of directivity patterns of laser-generated sound in solids is examined on the basis of the rigorous approach developed in [7–12]. The theory takes into account all acoustical, optical and thermal parameters of a solid material and all geometrical and physical parameters of a laser beam. By analysing the expressions for laser-generated longitudinal, shear and Rayleigh waves, the applicability of the simplified dipole-source representation is discussed for all these cases. It is also shown that, for radiation in the normal direction to the surface, the amplitudes of longitudinal waves are very sensitive to the values of thermal parameters and of the acoustic reflection coefficient from a free solid surface. Finally, a discussion is given on the possibility of using such a high sensitivity to the values of the reflection coefficient for investigation of surface properties of real solids.

2. Theoretical background

Let us assume that a two-dimensional laser beam (a line source) is incident in normal direction onto the surface of a solid, which for simplicity is considered as elastically isotropic (see Fig. 3). The problem of laser generation of sound in such a system can be described by the following governing equations [7–9].

The components of the displacement vector of laser-generated elastic waves u_i must satisfy the equation of mechanical motion,

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \sigma_{ij,j}, \tag{1}$$

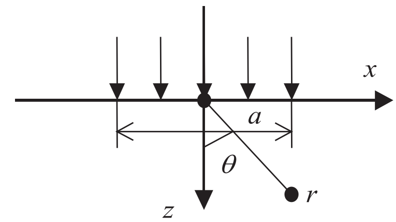

Fig. 3. Geometry of the problem of laser generation of sound in solids.

and the linearised constitutive equation that takes into account temperature effects,

$$\sigma_{ij} = 2\mu u_{ij} + [\lambda u_{kk} - \gamma K(T - T_0)]\delta_{ij}. \tag{2}$$

Here σ_{ij} are components of the elastic stress tensor, ρ is the mass density of the medium, $u_{ij} = (1/2)(u_{I,j} + u_{j,i})$ are components of the linearised strain tensor, λ and μ are the elastic Lame constants, $K = \lambda + 2\mu/3$ is the elastic compression modulus, γ is the thermal expansion coefficient and T_0 is the initial temperature.

Eqs. (1) and (2) should be supplemented by the linearised equation of thermal balance, in which we ignore the effects of viscosity:

$$\rho c_v \frac{\partial T}{\partial t} - \kappa T_{,ii} + \gamma K T_0 \frac{\partial u_{ii}}{\partial t} = -\frac{\partial}{\partial z}[\beta I(x) f(t) exp(-az)]. \tag{3}$$

Here c_v is the material's specific heat at a constant volume, κ is the coefficient of thermal conductivity, β is the coefficient of laser light energy transmission into the medium, α is the light energy absorption coefficient, $I(x)$ is the spatial distribution of the intensity of laser radiation over the surface, and $f(t)$ describes the intensity modulation law. In what follows we assume for simplicity that modulation is time-harmonic, i.e. $f(t) = 1 + m\cos\omega t$, and the modulation index m is equal to unity.

The resulting field of generated acoustic waves must also satisfy the stress-free boundary conditions on the solid surface (at $z = 0$):

$$\sigma_{ij} n_j = 0, \tag{4}$$

where n_j are components of the normal unit vector to the surface. The generated temperature field must satisfy the condition of continuity of the thermal flow on the surface (at $z = 0$):

$$\frac{\partial T}{\partial z} = 0. \tag{5}$$

Rigorous analysis of the system of simultaneous Eqs. (1)–(3) and the boundary conditions (4) and (5) is rather complex. A traditional simplification is in ignoring the small dilatational term $\gamma K T_0 \partial u_{ii}/\partial t$ in (3). In this case Eq. (3) does not contain mechanical displacements u_i and can be solved independently versus T. Note that such an approximation is equivalent to ignoring the difference between isothermal and adiabatic values of the elastic constants λ and μ.

In what follows we limit our consideration to the case of laser generation of sound in metals and consider a typical case of the laser light penetration depth into the metal, $2\pi/\alpha$, being much smaller than the length of the thermal wave, $\lambda_T = 2\pi/k_T = 2\pi/(\omega\rho c_v/2\kappa)^{1/2}$. Then, the solution of (3) subject to the boundary condition (5) results in the following expression for $\partial T/\partial t$ away from the boundary:

$$\frac{\partial T}{\partial t} = [(1 - i)k_T \beta I(x)/\rho c_v] exp[-(1 - i)k_T z - i\omega t]. \tag{6}$$

Expressing particle vibration velocity in the medium $v_i = \partial u_i/\partial t$ via potentials φ and ψ,

$$v_x = \frac{\partial \varphi}{\partial x} - \frac{\partial \psi}{\partial z}, \tag{7}$$