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LASER PHOTOACOUSTIC MONITORING OF PIEZOELECTRIC ELEMENTS OF HYDROACOUSTIC TRANSDUCERS

M. L. Lyamshev
Wave Research Center, General Physics Institute, Russian Academy of Sciences,
ul. Vavilova 38, Moscow, 117942 Russia
e-mail: lyamshev@kapella.gpi.ru

Excitation of flexural vibrations of a bounded thin plate by laser radiation is considered. The relations connecting the parameters of the laser radiation and the plate are obtained. Opportunities for remote laser photoacoustic monitoring and identification of piezoelectric elements of hydroacoustic transducers (arrays) are discussed.

Hydroacoustic transducers (arrays) are frequently lattices of single piezoelectric elements made of piezoceramic plates for example. The diversity of their parameters leads to deterioration of array characteristics and, in particular, to the increase of the level of the so-called sidelay of a hydroacoustic array. This may reduce the signal-to-noise ratio of a hydroacoustic system.

Further we consider excitation of flexural vibrations of a bounded plate by a harmonically modulated laser radiation. The relations connecting the parameters of the laser radiation and the plate are obtained. Opportunities for remote laser photoacoustic monitoring and identification of the parameters of elements of hydroacoustic transducers (arrays) are discussed.

Let a harmonically modulated laser radiation be incident upon the surface of a thin bounded plate. We consider flexural oscillations of the plate and do not take into account its piezoelectric properties. This does not restrict the generality of the problem treatment.

The following equation is valid for the displacements $w(r)$ of the plate surface [1]:

$$(\Delta^2 - \kappa^4) w(r) = \frac{F(r)}{g}, \tag{1}$$

where

$$\Delta \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial t^2},\ r(x,y),\ g = \frac{Eh^3}{3(1-\nu^2)},\ \kappa^4 = \frac{[3\omega^2\rho(1-\nu^2)]}{Eh^2},$$

g is the flexural rigidity, $m_s = 2h\rho$ is the mass per unit area, $F(r)$ is the function characterizing the external dynamic force due to the effect of laser radiation incident on the plate, ω is the circular frequency of modulation of the laser radiation intensity, ρ is the material density, $2h$ is the thickness, E is Young's modulus, and ν is the plate Poisson ratio.

We assume that the laser radiation is absorbed in a thin surface layer of the plate, and the distribution of its intensity I_0 is described by Gaussian law. We can write for $F(r)$ [2]

$$F(r) = -\frac{E\alpha\mu m}{C_p} I_0 \exp\left(-\frac{r^2}{a_0^2}\right), \tag{2}$$

where α is the coefficient of cubic thermal expansion, C_p is the specific heat capacity of the plate material, μ is the absorption coefficient, m is the modulation coefficient of laser radiation ($0 \le m \le 1$), and a_0 is the radius of the laser spot at the plate surface.

Let us consider further as an example the vibrations of a circular plate with the radius a. We write down the solution to Eq. 1 in the form

$$w(r) = \int_S F(r_0) G(r_0 / r) ds(r_0), \tag{3}$$

where $G(r_0/r)$ is Green function that represents the solution to the equation

$$(\Delta^2 - k^4) G(r_0 / r) = -\delta(r_0 - r) \tag{4}$$

and obeys the boundary conditions or the conditions of fixation at the plate edge.

Using a standard procedure for solving Eq. 4, we obtain [1]

$$G(r_0 / r) = \sum_n \frac{\psi_n(r_0)\psi_n(r)}{\kappa_n^4 - \kappa^4}, \tag{5}$$

where $\psi_n(r)$ are the normalized eigenfunctions of plate vibrations, which satisfy the equation

$$(\Delta^2 - k_n^4)\psi_n(r) = 0, \tag{6}$$

the boundary conditions, and the normalization conditions

$$\int_S \psi_n(r)\psi_l(r) ds(r) = \delta_{nl}, \tag{7}$$

where δ_{nl} is the Kronecker delta.

We consider the case when the plate edges are supported. We have for $\psi_n(r)$ [1]

$$\psi_n(r) = \frac{1}{a\sqrt{\pi\Lambda_n}} \left[I_0\left(\frac{\pi\beta_n r}{a}\right) - \frac{J_0(\pi\beta_n)}{I_0(\pi\beta_n)} I_0\left(\frac{\pi\beta_n r}{a}\right) \right], \tag{8}$$

where

$$\Lambda_n = 2\{[J_0(\pi\beta_n)^2 + [J_0^{'}(\pi\beta_n)]^2\}, \; J_0^{'}(n) = \frac{\partial}{\partial n} J_0(n), \tag{9}$$

$\beta_1 = 1.015$, $\beta_2 = 2.007$, $\beta_3 = 3.000$, and $\beta_n \to n$ at $n \to \infty$; $J_0(n)$ is the Bessel function of the zero order and $I_0(n)$ is the imaginary Bessel function.

Using Eqs. 2—7 we obtain for the plate displacements

$$w(r) = \frac{3(1-\nu^2)\alpha\mu m a_0^2}{a^2h^3\rho C_p} I_0 \sum_{n=1}^{\infty} \frac{1}{\Lambda_n(\kappa_n^4 - \kappa^4)} \times$$

$$\times\left[\exp\left(-\frac{\pi^2\beta_n^2 a_0^2}{4a^2}\right) - \frac{J_0(\pi\beta_n)}{I_0(\pi\beta_n)}\exp\left(\frac{\pi^2\beta_n^2 a_0^2}{4a^2}\right)\right]\left[J_0\left(\frac{\pi\beta_n r}{a}\right) - \frac{J_0(\pi\beta_n)}{I_0(\pi\beta_n)} I_0\left(\frac{\pi\beta_n r}{a}\right)\right]. \quad (10)$$

Now let us consider Eq. 8. First of all, one can see that, when the modulation frequency of laser radiation ω coincides with some frequency of natural oscillations of the plate ω_n, the resonance of oscillations is observed, and the plate performs intense vibrations corresponding to the resonance of the normal mode. Indeed, the condition for the resonance follows from the equality $\kappa^4 - \kappa_n^{\ 4} = (\kappa^2 + \kappa_n^{\ 2})(\kappa^2 - \kappa_n^{\ 2}) = 0$. Form the condition $\kappa = \kappa_n$ it follows $\omega = \omega_n$, where for ω_n the following expression corresponding to the functions $\psi_n(r)$ is valid (see Eq. 9) [1]

$$\omega = \frac{\pi h}{2a^2}\sqrt{\frac{E\beta_n^2}{3\rho(1-\nu^2)}}. \quad (11)$$

A laser vibrometer may be used for remote detection of plate vibrations [3]. Using Eqs. 8 and 9 and knowing the characteristics of a laser vibrometer it is possible to estimate the parameters of a laser and a modulator of laser radiation necessary for remote photoacoustic monitoring of the plate parameters. It is necessary to note that taking into account the piezoelectric properties of the plate will lead only to insignificant corrections to the values of the eigenfrequencies of plate vibrations and taking into account losses in the plate material will lead to ω_n taking on complex values that will characterize the quality factor of an oscillating system, i.e. a vibrating plate.

A scheme of laser photoacoustic monitoring of plate vibrations and some experimental results on the influence of temperature on vibrations of ceramic plates are given in [3].

Above we have considered excitation of flexural vibrations of a circular plate by harmonically modulated laser radiation. The obtained results may be easily extended, for example, to the case of generation of oscillations by a periodic sequence of laser pulses. It is possible to demonstrate that in the case of a certain frequency of pulse repetition one can excite plate oscillations at several eigenfrequencies simultaneously. Comparing the pattern of oscillations of a plate under test to that of a standard plate it is possible to perform nondestructive evaluation and identification of the plate (an element of a hydroacoustic transducer, i.e. array).

We have considered laser thermooptical excitation of oscillations in a bounded plate as an example. The results would not be changed fundamentally if we take a piezoceramic sphere or cylinder as an array element.

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REFERENCES

1. P. M. Morse and K. U. Ingard, Theoretical Acoustics, McGraw-Hill, N.Y., 1968
2. L. M. Lyamshev, Thermooptical Laser Excitation of Sound, Nauka, Moscow, 1989 [in Russian]
3. G. Busse, M. L. Lyamshev, and J. Stanullo, Acoustical Physics, Vol. 42, 28, 1996