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EFFECT OF ABSORPTION IN TIME-RESOLVED OPTOACOUSTIC TOMOGRAPHY

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The reconstructive problem of time-resolved optoacoustic tomography is solved taking into account the absorption of initiating (laser) and secondary (acoustic) radiations. Numerical results that confirm theoretical data are presented. A relatively simple relation between the unknown and the experimental functions of spatial distribution of the absorption coefficient is obtained.

To solve the problem of tomography diagnostics, recently a number of methods have been proposed, including the investigation of the velocity (momentum) space [1–3] and taking time as an additional coordinate axis [4–8]. One of these methods is time-resolved optoacoustic tomography [8–11], which is based on the analysis of the secondary acoustic radiation generated by an ultra-short laser pulse for obtaining the distribution of the coefficient of laser-radiation absorption due to the optoacoustic effect.

A simple method for solving the inverse optoacoustic problem with absorption of the initiating radiation was proposed in [8, 9]. In the present paper, we discuss a more general case with two absorption components — optoacoustic and nonoptoacoustic.

As was shown in [8], in general, the time profile of an acoustic signal has the form

$$G_s(t) = \int_0^l X_1(x) T\Big(t - \frac{x}{v_s}\Big) dx, \tag{1}$$

where

$$CX_1(x) = X(x) \exp\Big(- \alpha \int_0^x X(x)\, dx\Big). \tag{2}$$

if the laser and receiver of the secondary acoustic radiation are located at the point $x = 0$, or

$$X_1(x) = X(x) \exp\Big(- \alpha \int_{l-x}^l X(x)\, dx\Big), \tag{3}$$

if the laser is located at the point $x = l$ and the receiver of the secondary acoustic radiation is located at the point $x = 0$. Below, we investigate the first case, assuming that the function $X_1(x)$ is given by formula (2). In Eqs. (1)–(3), l is the length of the object of investigation along the direction of transmission, x is the spatial coordinate, t is time, v_s is the velocity of the acoustic signal, $T(t)$ is the known time profile of the laser pulse, $X(x)$ is the unknown function of the distribution of the absorption coefficient, $G_s(t)$ is the experimental time profile of the secondary (acoustic) signal, $\alpha = \ln(I/I_0)$ is the total absorption coefficient, I_0 is the intensity of the initiating pulse, I is the intensity of the pulse transmitted through the object, the functions $X(x)$ and $X_1(x)$ are normalized by unity, and C is the normalization constant.

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Equation (1) is a Fredholm equation of the first kind, and generally it can be solved using standard methods. If the laser-pulse duration is $\Delta t \ll l/v_s$, the function $T(t - x/v_s)$ can be expressed in terms of the δ-function. In this case, the equality $X_1(x) = AG_s((t - t_0)/v_s)$ is satisfied, where t_0 is the time corresponding to the peak of the function $T(t)$ and A is a constant.

Thus, if the initiating pulse is sufficiently short and the absorption of the laser radiation by the object under investigation is sufficiently weak, the time profile follows the acoustic response of the spatial distribution of the optoacoustic source.

Let the function $CX_1(x)$ be known up to a constant factor. To solve Eq. (2), where the function $X_1(x)$ and the coefficient α are specified, constant C is unknown, and the function $X(x)$ is required to be determined, we introduce the functions

$$F(x) = \int_0^x X(x)\,dx, \qquad F_1(x) = \int_0^x X_1(x)\,dx.$$

We assume that $\alpha \neq 0$ (otherwise, the equation which must be solved becomes an identity). Then, it follows from (2) that $CX_1(x) = (dF/dx)\exp(-\alpha F)$. Separating the variables and integrating, we obtain

$$F(x) = -\frac{1}{\alpha}\ln(1 - \alpha C F_1(x)). \tag{4}$$

Differentiating Eq. (4), we find that

$$X(x) = \frac{CX_1(x)}{1 - C\alpha F_1(x)}. \tag{5}$$

From the normalization conditions, we determine C:

$$C = \frac{1}{\alpha}(1 - \exp(-\alpha)). \tag{6}$$

Formulas (5) and (6) allow one to determine the function $X(x)$ for $\alpha \neq 0$ if the function $X_1(x)$ is known. [For $\alpha = 0$, the function $X_1(x)$ coincides with the function $X(x)$ with a calculation error.]

Above, we have considered a simplified problem. In real physical objects under investigation, in addition to the absorption of the initiating (laser) radiation whose energy is expended for generation of acoustic waves, there is an absorption [of both the initiating (optical) and the secondary (acoustic) radiations] of different nature.

We now consider the case where, along with the absorption related to the optoacoustic effect, there is absorption with the differential coefficient $\alpha' X'(x)$, where $\alpha' = \text{const}$ and $X'(x)$ is a known normalized function. We note that absorption of both the initiating (laser) radiation and the secondary (acoustic) radiation can be considered in this manner. In this case, $\alpha' X'(x)$ represents the sum of both components because both absorptions are ultimately expressed in the same form:

$$CX_1(x) = X(x)\exp\left(-\alpha\int_0^x X(x)\,dx - \alpha'\int_0^x X'(x)\,dx\right).$$

We introduce the function

$$F'(x) = \int_0^x X'(x)\,dx.$$

Similarly to the preceding case, we obtain

$$CX_1(x) = \frac{dF}{dx}\exp(-\alpha F - \alpha' F'(x)). \tag{7}$$

Let $X_1' = X_1\exp(\alpha' F'(x))$ and $F_1'(x) = \int_0^x X_1(x)\exp(\alpha' F'(x))\,dx$. Solving Eq. (7) similarly to the example considered above, after simple transformations, we obtain $X(x) = CX_1'(x)/(1 - C\alpha F_1'(x))$.

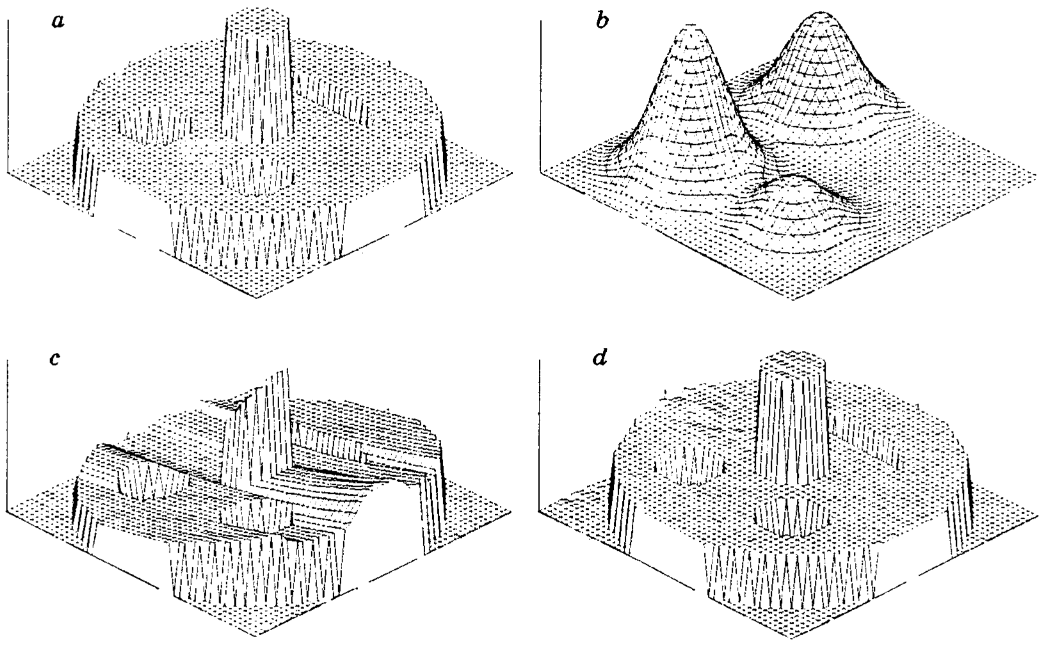

Fig. 1. Numerical results: (a) the distribution of the optoacoustic component of absorption; (b) the distribution of the nonoptoacoustic component of absorption; (c) the numerical function of optoacoustic response; (d) the reconstructed function of optoacoustic distribution.

If we treat α' and $X'(x)$ as known and normalize $X_1'(x)$, then the constant C can be calculated from formula (6). The coefficient α' can be obtained using the absolute value of the total energy of the received acoustic signal (up to this point, this quantity is leveled by normalization). For that, a real experimental facility must be calibrated using reference patterns with different ratios between α and α'. In general, the function $X'(x)$ is not known but, in several cases, it can be obtained. In particular, if the additional absorption is independent of the coordinate, the function $X'(x)$ can be identically equal to the constant l^{-1}. If the additional absorption is proportional to the optoacoustic absorption, then, as follows from (7), the problem can be solved using Eqs. (5) and (6) where α is replaced by the sum $\alpha + \alpha'$.

Since an acoustic signal can be transmitted only by the excited part of the object under investigation, the object can be step-by-step scanned by a laser along other spatial directions (see [9]).

Using the results obtained above, we carried out several numerical experiments. For clarity and objectivity, we assumed that the object was scanned along an additional spatial coordinate; the optoacoustic and nonoptoacoustic components of absorption were different from each other. The characteristic conditions of the experiments were typical: the dimensions of the specimen were 0.1×0.1 m, the duration of the initiating laser pulse was $\Delta t = 10^{-7}$ sec, and the velocity of the secondarily ultrasonic wave was $v_s = 10^3$ m/sec. The dependence of the velocity on the coordinate was neglected.

Typical calculation results are shown in Fig. 1. In this case, $\langle \alpha'(y) \rangle = 1$ and $\langle \alpha(y) \rangle = 1$. The stochastic noise with a relative magnitude of 3% was added to the function $G_s(t)$. All these functions were normalized by unity. The theoretical conclusions are confirmed by the numerical data. Good restorability of the unknown function is observed even for considerable external noise.

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