

PACS numbers: 42.30.Wb; 43.60.Rw
DOI: 10.1070/QE2000v030n12ABEH001875

Some aspects of optoacoustic tomography

A A Aliverdiev, A A Amirova, M G Karimov

Abstract. An inverse problem of optoacoustic tomography is solved within the framework of chronotomography, and two-component absorption of the exciting laser emission is analysed. The numerical experiments are performed which confirm theoretical conclusions.

1. Introduction

Optoacoustic tomography is a comparatively new field lying between tomography and optoacoustic (photoacoustic) spectroscopy. It is based on the analysis of the time profile of acoustic radiation induced by a short laser pulse and the reconstruction of the spatial structure of the object under study. The first paper on optoacoustic tomography seems to be Ref. [1]. This field has been further developed in papers [2 – 5].

In this paper, we present our approach to optoacoustic tomography as a space-time tomography that uses the propagation velocity of a signal being detected [5, 6]. Within the framework of this approach, we solve the problem of an analytic calculation of absorption of laser radiation, in particular, in the presence of additional absorption with a different spatial distribution. The results of our numerical simulations confirm the theoretical conclusions.

2. General problem of optoacoustic tomography

We will not consider here in detail the nature of the optoacoustic interaction. This has been well done in Ref. [3]. In addition, unlike [3], where the direct problem was formulated using the method of the transfer function, we propose a simpler approach in which the intensity of sound coming from all excited regions is integrated taking into account the time delay caused by the sound speed finiteness. Because sound is excited independently in different regions, this approach is quite adequate to the reality. In addition, we assume that the sound speed is constant within an object under study, which is also justified in most cases.

A A Aliverdiev, A A Amirova Institute of Physics, Dagestan Scientific Centre, Russian Academy of Sciences, ul. M Yaragskogo 94, 367003 Makhachkala, Russia; e-mail: aliverdi@datacom.ru
M G Karimov Dagestan State University, ul. Gadzhieva 43a, 367000 Makhachkala, Russia

Received 3 December 2000; revision received 11 October 2000
Kvantovaya Elektronika **30** (12) 1115 – 1117 (2000)
Translated by M N Sapozhnikov

Therefore, our assumptions allow us to consider optoacoustic tomography, which uses the propagation velocity of a signal being detected, within the framework of spectrotomography [7] and chronotomography [8]. Note that we use, as in [1 – 3], a linear approximation in the problem of optoacoustic tomography. When a linear approximation cannot be applied, the formulation and solution of the inverse problem become drastically complicated [3, 9].

Consider an object in which a laser source (located at the origin of coordinates) induces an optoacoustic response, which is detected with an external microphone. Because the transverse dimensions of a laser beam can be quite small, we can consider in fact a one-dimensional problem of tomography. Let us introduce the following notation: $f(x)$ is the normalised spatial distribution of the acoustic response; $T(t)$ is the time profile of the laser pulse; v_s is the sound speed in the object under study; $\alpha(x)$ is the differential absorption coefficient of laser radiation; $\alpha_0 = \ln(I/I_0)$ is the total absorption coefficient; I_0 is the total intensity of the initiating pulse; I is the intensity of a pulse transmitted through the object.

Note that because the acoustic signal is excited due to absorption of laser radiation, we can assume that the distributions $\alpha(x)$ and $f(x)$ will be identical, i. e., $\alpha(x) = \alpha_0 f(x)$. Then, the detected acoustic response $P(t)$ will have the form

$$P(t) = \int_{-r}^{r} Cf_1(x)T[t + (r - x)v_s]\mathrm{d}x, \quad (1)$$

where

$$Cf_1(x) = f(x)\exp\left[-\alpha_0\int_0^x f(x)\mathrm{d}x\right], \quad (2)$$

if both the laser and detector of the acoustic response are located at the point $x = 0$, or

$$Cf_1(x) = f(x)\exp\left[-\alpha_0\int_{l-x}^{l} f(x)\mathrm{d}x\right], \quad (3)$$

if the laser is located at the point $x = l$ and the detector of the acoustic response is located at the point $x = 0$. Here, C is a constant that normalises the functions $f(x)$ and $f_1(x)$ to unity. Below, we will consider only the first case and assume that the function $f_1(x)$ is described by expression (2).

Equation (1) is the Fredholm integral equation of the first kind, which can be solved by a standard method. If the laser pulse duration $\Delta t \ll l/v_s$, then, independently of the pulse shape, the function $T(t - x/v_s)$ virtually becomes the delta function, and the equality $f_1(x) = AP[(t - t_0)/v_s]$ is satisfied, where A is a constant and t_0 is the time at which the function $T(t)$ has a maximum.

3. Consideration of absorption of initiating radiation

Let us assume that the function $Cf_1(x)$ is known with an accuracy to a constant factor C and the functions $f_1(x)$ and $f(x)$ are normalised to unity. Then, the function $f(x)$ can be found by solving equation (2), where $f_1(x)$ and α_0 are known and C is unknown. Let us introduce functions

$$F(x) = \int_0^x f(x)\mathrm{d}x, \quad F_1(x) = \int_0^x f_1(x)\mathrm{d}x$$

assuming that $\alpha_0 \neq 0$ [otherwise, equation (2) transforms to an identity]. Then, it follows from (2) that

$$Cf_1(x) = \frac{\mathrm{d}F}{\mathrm{d}x}\exp[-\alpha_0 F(x)]. \tag{4}$$

As was shown in [6, 7], equation (4) has the solution

$$f(x) = \frac{Cf_1(x)}{1 - C\alpha_0 F_1(x)}, \tag{5}$$

where

$$C = \frac{1}{\alpha_0}[1 - \exp(-\alpha_0)]. \tag{6}$$

Expressions (5) and (6) give the function $f(x)$ if the function $f_1(x)$ is known for any $\alpha_0 \neq 0$. For $\alpha_0 = 0$, the function $f_1(x)$ coincides with the function $f(x)$ within an accuracy to a constant factor.

Consider now the case when, along with absorption related to the optoacoustic effect, another absorption component is present, which has a different spatial distribution. Let the corresponding differential absorption coefficient is $\alpha'_0 f'(x)$, where $\alpha'_0 = \mathrm{const}$ and $f'(x)$ is a known normalised function. Then,

$$Cf_1(x) = f(x)\exp\left[-\alpha_0\int_0^x f(x)\mathrm{d}x - \alpha'_0\int_0^x f'(x)\mathrm{d}x\right]. \tag{7}$$

Let us introduce the functions

$$F'(x) = \int_0^x f'(x)\mathrm{d}x, \; f'_1 = f_1\exp\left[\alpha'_0 F'(x)\right],$$

$$F'_1(x) = \int_0^x f_1(x)\exp\left[\alpha'_0 F'(x)\right]\mathrm{d}x.$$

Then, by solving equation (7), we obtain

$$f(x) = \frac{Cf'_1(x)}{1 - C\alpha_0 F'_1(x)}. \tag{8}$$

If we assume now that α'_0 and $f'(x)$ are known and normalise the function $f'_1(x)$, a constant C can be calculated from expression (6). The functions $f'_1(x)$ and $F'_1(x)$ are assumed known in this case because they can be calculated from the experimental function $f_1(x)$ and functions α'_0 and $f'(x)$, which are treated as known functions. Therefore, expression (8) is the solution of the problem formulated.

Consider now the question of determining α'_0 and $f'(x)$. The coefficient α'_0 can be found from the absolute value of the total energy of the detected acoustic signal (so far this energy was levelled by the normalisation). For this purpose, each particular setup should be calibrated with the help of reference samples with different relations between α_0 and α'_0. The function $f'(x)$ cannot be known in the general case. However, in some cases, it can be characteristic for the object under study. In particular, if the additional absorption is independent of the coordinate, this function can be equal to a constant l^{-1}.

Note that because a sound signal is produced only by the excited region of the object under study, we can scan a laser beam along another spatial coordinate y. In this case, the coefficients α_0 and α'_0, which depend on the coordinate y, are described by the expressions

$$\alpha_0(y) = \langle\alpha_0\rangle\frac{1}{l}\int_0^l f(x,y)\mathrm{d}x, \; \alpha'_0(y) = \langle\alpha'_0\rangle\frac{1}{l}\int_0^l f'(x,y)\mathrm{d}x,$$

where angle brackets mean averaging.

4. Model experiments

We performed numerical simulations of two-dimensional internal cross sections using the method described above. Typical results are presented in Fig. 1. We assumed that the speed v_s of a sound wave was 10^3 m s^{-1}, the laser pulse duration was 10^{-7} s, the dimensions of the object under study was 0.1×0.1 m, and $\langle\alpha_0\rangle = \langle\alpha'_0\rangle = 3$. For generality, the initial distribution functions for the optoacoustic (Fig. 1a) and non-optoacoustic (Fig. 1b) components were chosen different. The required distribution of the optoacoustic absorption component was simulated by three Gaussians, while the distribution of the non-optoacoustic component was simulated by a step function. Note that these model functions are conventionally used in numerical experiments.

Simulations were performed for the conditions that were as close as possible to the real experiment. At the first stage, the model functions were represented in the form of matrices.

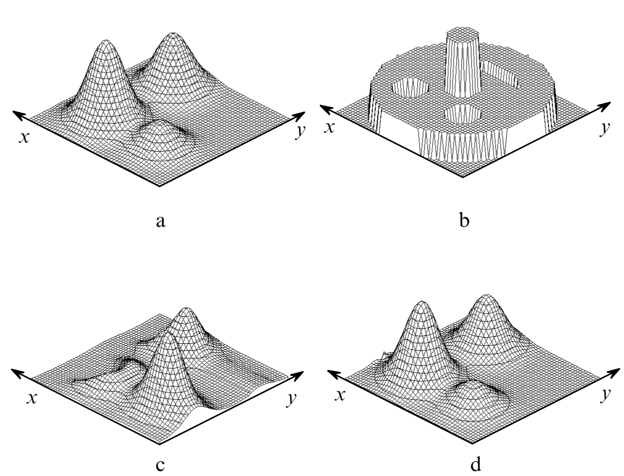

Figure 1. Simulation of the optoacoustic reconstruction for different absorption of initiating laser radiation. The initial distribution function of the optoacoustic source (a); the initial distribution function of non-optoacoustic absorption (b); the simulated optoacoustic response (c); and the result of processing of the optoacoustic response (d)

The models could be specified mathematically or by introducing digitized images. Then, we simulated the optoacoustic response along the x axis during scanning along the y axis. A weak stochastic noise was superimposed on the optoacoustic response. Fig. 1c shows the simulated optoacoustic response.

Thus, despite a schematic representation of a phantom object, which was chosen in this particular case exclusively for clarity, the above method can be used in nondestructive studies of the internal structure of a variety of physical objects, from composite materials [10] to medical and biological media and plasmas.

At the next stage, we run a program based on formula (8), with scanning along the coordinate y (see [4]). The relevant result is demonstrated in Fig. 1d. By comparing Figs. 1a and 1d, one can see that the performed reconstruction is correct.

Note in conclusion that the solutions obtained in this paper enhance the possibilities of optoacoustic tomography, providing its application to the case of two-component absorption.

Acknowledgements. The authors thank N B Podymova and A A Karabutov for useful comments. A A Aliverdiev thanks the staff of the FNTiS laboratory and A B Batdalov for help in this study. The authors also thank a late Prof. N N Koroteev for his attention to this work at its earlier stage. This work was partially supported by the INTAS grant No. 96-0457 within the framework of the research program of ITs FFM.

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