Thermal and mechanical piston influence on photoacoustic signal

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Abstract - **In this work, the influence of the thermal and mechanical piston effects over the frequency at which the amplitudes of the components of the photoacoustic signal resulting from these two effects are equalized. The analysis was done in the measuring range 10 to 20kHz. An aluminum sample illuminated with modulated light, whose thickness varies from 10 to 1000 microns, was considered. It is important for development reliable inverse procedures and determination various properties of samples from experimental measurement.**

Key words - photoacoustics; aluminum; thermodiffusion; thermoelasticity;

I. INTRODUCTION

Photoacoustics (PA), which is based on the effect of converting light into sound, is used in the characterization of materials and devices. It is based on the measurement of a signal that depends on different physical processes that are affected by the optical, thermal, elastic, electronic and other physical properties of the material, as well as the geometric properties of the sample. The formation of theoretical simulation models based on the physics of the problem of the interaction of light and matter enables the analysis of physical processes from the experimentally measured PA response and the determination of the area of dominance in the analyzed frequency domain. Taking into account the theory of the composite piston [1-10] for the formation of the model in the frequency domain, the obtained PA signal corresponding to the experimentally measured response depends on the temperature-dependent thermodiffusion (TD) and thermoelastic (TE) effect and it is used for inverse PA problem solving, i.e. for measurement of thermal, elastic, electronic and other related properties of various samples.

The model of PA signal is mathematically very complex, nonlinear, ill posed and multi-parametrical. Besides, the measurement range is limited causing loss of information about properties and processes that is not dominant in this range. This can lead to an ambiguous mapping of the theoretical model into experimental results, causing a large error of the inverse solution, that is, a large error when determining thermal, elastic and other properties from the measured signals. Therefore, the area of dominance of the various components of the PA signal should be investigated firstly.

The analysis of the area of dominance of certain effects in the given frequency domain depends to a large extent on the properties of the material. Illumination of the sample, a tile of a certain radius and thickness, with monochromatic sinusoidally modulated light, leads to the absorption of exciting electromagnetic energy and its transformation into heat through de-excitation-relaxation processes. The heat thus generated leads to a change in the temperature distribution along the sample, which can be described by extended equations for determining the TD and TE components, because due to the negligible interaction of charge carriers and phonons, the appearance of heat due to the elastic expansion of the crystal lattice is also negligible [10-14].

Due to the occurrence of temperature variation on the back surface of the sample, a thin layer of air is formed, which represents a thermal piston that adiabatically moves the air to the microphone membrane. As the appearance of the thermal piston is a consequence of heat diffusion through the sample, the formed component of the PA signal is the TD component. The appearance of a temperature gradient along the sample leads to elastic bending, which, due to light modulation, forms a mechanical piston that forms a pressure disturbance that is detected by the microphone membrane. As the appearance of the mechanical piston is a consequence of the elastic properties of the sample, the measured signal is the TE component of the PA signal. The measured PA signals match the analyzed signals of the theoretical model containing these two components in the frequency range from 10 Hz to 20 kHz [15-25].

In the paper, the theoretical model was presented in the chapter II. After that, TD and TE components were analyzed for Al sample of thicknesses from 10 to 1000 μm in the experimentally accessible range 10Hz to 20 kHz, and frequency at which these two components is equal was calculated. The position of equating these two components TD and TE is important because of the development inverse procedure and high accuracy determination of the sample properties that manage these components. At the end, the most important conclusions are drawn.

II. THEORETICAL BACKGROUND

By illuminating the sample with modulated light $I=I_0(1+\cos\omega t)/2$, where $\omega=2\pi f$, with the frequency of modulation f, Fig. 1, there is a periodic change in the temperature distribution along the sample and the appearance of a sound $\delta p_{total}(f)$, which, based on the Model of composite piston [1-10,15-25], appears in two pistons, thermal and mechanical. The component of the thermal piston is determined by TD effects in the sample and can be labeled $\delta p_{TD}(f)$, just as the component of the mechanical piston is determined by TE effects and can be labeled $\delta p_{TE}(f)$.

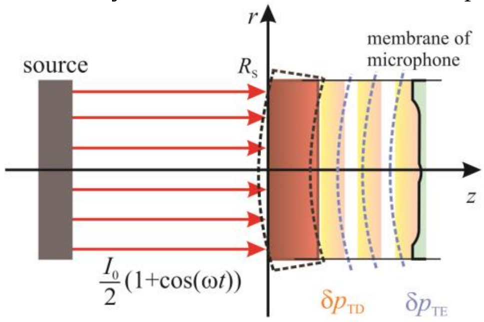

Fig. 1. Composite piston model: thermal piston $\delta p_{TD}(f)$ and mechanical piston $\delta p_{TE}(f)$.

$$\delta p_{TD}(f)=\frac{\gamma p_0}{l_c T_0}\frac{\sqrt{D_g D_T}}{k}\frac{1}{2\pi i f}\frac{\sqrt{1+2\pi i f\tau_s}}{\sqrt{1+2\pi i f\tau_g}}\frac{1}{\mathrm{sh}(y)}. \tag{1}$$

$$\delta p_{TE}(f)=\alpha_T\frac{\gamma p_0}{V_0}\frac{3\pi R_s^4 I_0}{l^3}\frac{1}{y}\left[\mathrm{th}\left(\frac{y}{2}\right)-\left(\frac{y}{2}\right)\right]. \tag{2}$$

where D_T and D_g are thermal diffusivities of the sample and air, τ_s and τ_g are relaxation times of the sample and air, l is the thickness of the metal, l_c is length for cell, $V_0=2\pi R^2 l_c$ is the volume of cell, R_s is the radius of the sample, γ is the adiabatic ratio, T_0 is the ambient temperature and p_0 is pressure, and $y=l(2\pi i f(1+2\pi i f\tau_s)/D_T)^{1/2}$ is nondimensional variable.

The basic idea of determining these components is to be able to analyze and interpret the overall PA signal:

$$\delta p_{total}(f)=\delta p_{TD}(f)+\delta p_{TE}(f). \tag{3}$$

as well as the experimentally measured PA signal obtained by measure with an open photoacoustic cell in the wide frequency range 10 Hz to 20 kHz. Therefore, the formed theoretical model for determining the PA signal represented by the amplitude and phase characteristics fits with the experimentally measured signal with the application of the instrument influence model obtained by additional modeling of the acoustic influence of the microphone as a filler [18,22-25].

The total PA signal $\delta p_{total}(f)$, eqs. 1-3, directly depends on various parameters diffusivity D_T, conductivity k, expansion α_T relaxation time τ_s, sample radius R_s, sample thickness l, and others. The characteristic shape of the amplitude and phase of the PA signal of aluminum, Fig. 2, is shown with an increase in thickness from 10 to 1000 μm. A change in the shape of the total PA signal is observed with the appearance of a saddle shape that moves towards lower frequencies with an increase in the thickness of the sample, Fig. 2, where the signal changes its slope.

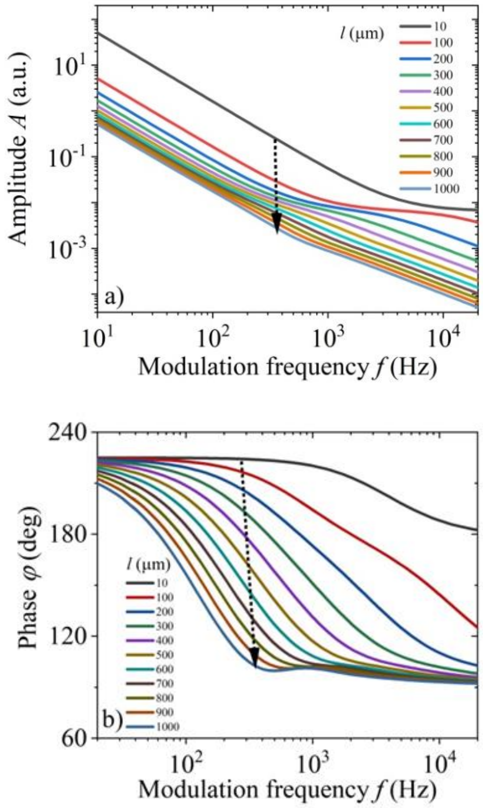

Fig. 2. PA signals: a) amplitude and b) phase , of aluminum obtained in the thickness range from 10 to 1000μm.

III. RESULTS AND DISCUSSION

The individual TD and TE components of the total PA signal are the result of illuminating the sample with modulated light, due to which the temperature variation on the back surface of the sample leads to the appearance of the TD component, and the temperature gradient of the front and back sides of the sample leads to elastic bending and the appearance of the TE component. The dominance of these components in the frequency domain, Fig. 3, shows that TD dominates in the low-frequency domain (red line) and TE in the high-frequency domain (green line) of the total PAS (black line). By increasing the thickness of the sample from l_1=100 μm to l_2=900 μm, it is observed that the area of dominance of TD decreases and the area of dominance of TE increases.

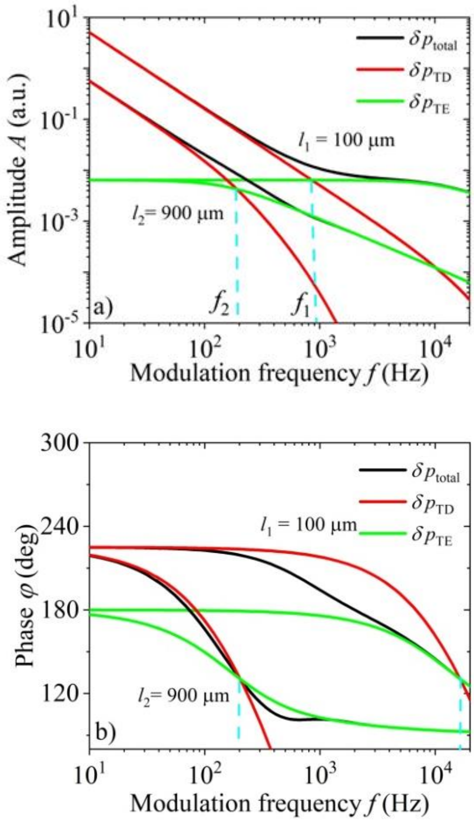

Fig. 3.a) Amplitude $A(f)$ and b) phase $\varphi(f)$ of the total PA signal $\delta p_{total}(f)$ with thermodiffusion $\delta p_{TD}(f)$ and thermoelastic $\delta p_{TE}(f)$ components for samples of thickness l_1=100μm and l_2=900μm.

Based on this consideration of the dominance of the influence of individual components, the point of equalization of the value (or geometrically the point of intersection) of these two components TD and TE of a certain frequency point can be observed f_1 and f_2 where the influence of TD is lost and the influence of TE of a sample of a certain thickness and is strengthened l_1 and l_2, respectively. It is noted that $f_2 < f_1$ for samples where $l_2 > l_1$.

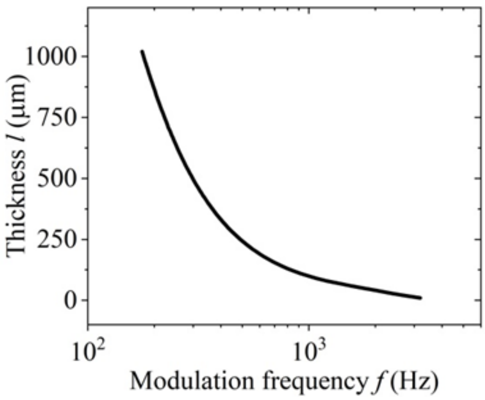

Fig. 4. Tendency of the displacement of the intersection point of the two components $\delta p_{TD}(f)$ and $\delta p_{TE}(f)$ for the aluminum sample with a change in thickness from 10 to1000μm.

This is confirmed by the tendency of the behavior of the equalization point of the components $\delta p_{TD}(f)$ and $\delta p_{TE}(f)$ with an increase in thickness from 10 to 1000μm, which is given in Fig. 4. For the sample thickness l=10μm , the equalization point $\delta p_{TD}(f)$ and $\delta p_{TE}(f)$ is at f ~ 4kHz which indicates the dominance of TD in thin samples in the low-frequency part f < 4 kHz influence of thermoelasticity in the high-frequency part f > 4 kHz. With increasing thickness, the equalization point moves towards lower frequencies. For a sample of thickness l = 1000 μm, the point of equalization of these two components is f ~ 200 Hz what indicates that for samples of greater thickness, the TD influence is lost, and thermoelasticity becomes dominant.

By introducing the equalization point of the two pistons determined by the components $\delta p_{TD}(f)$ and $\delta p_{TE}(f)$, of the PA signal curve, Fig. 4 shows that in the low-frequency domain the curves have a certain slope that changes in the frequency area of the equalization point. The dominant effects of physical processes in the low-frequency part, for the range of frequencies lower than the equalization frequency, are TD, and in the high-frequency part, for frequencies higher than the equalization frequency, they are TE effects.

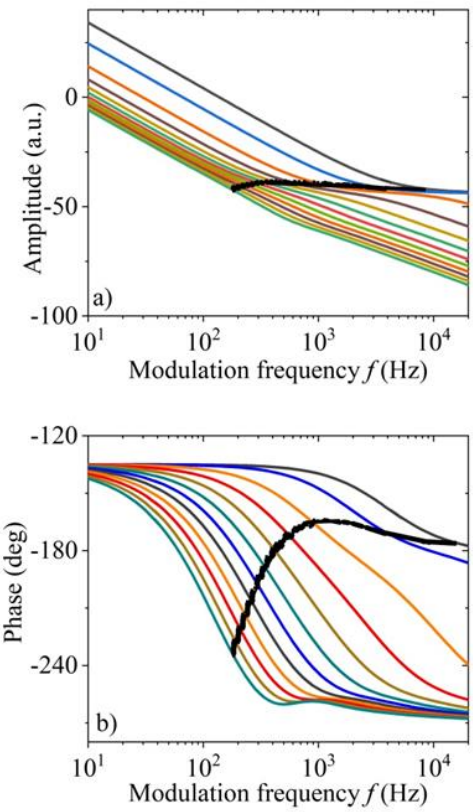

Fig. 4. Equalization of the influence of thermal and mechanical piston on the PA signal of aluminum samples of different thicknesses.

The dominance of certain effects allows to analyze and determine the properties of individual components in certain frequency ranges. The TD component, $\delta p_{TD}(f)$ eq.1, allows the thermal diffusion coefficient D_T, conductivity k, relaxation time τ_s and the TE component $\delta p_{TE}(f)$, eq.2, allows to determine the coefficient of thermal expansion α_T, sample radius R_s, sample thickness l, and others to be determined more precisely from the experimentally measured PA signal.

. There is also a possibility that with a change of some parameter (eg thickness) the equalization point is outside the observed measurement frequency range from 10 to 20 kHz, which tells us that in the sample there are dominant either TD (if the equalization point is >20 kHz) or TE effects (if equalization point <10 Hz) that result in the formation of only thermal or only mechanical piston. For experimental measurements, it is important to determine the transition area in the environment of the equalization point and determine its width, in which there is an influence of both thermodiffusion and thermoelastic effects.

Conclusion

The influence of the thermal and mechanical piston on the PA signal in the wide frequency range is different. In the low-frequency range, the influence of the thermal piston dominates, and in the high-frequency range, the influence of the mechanical piston dominates. The transitional range between these two ranges, where there is an influence of both thermal and mechanical pistons, is in the range where their equalization occurs. Analysis and determination of the equalization position of these influences in the measurement frequency range from 10 to 20kHz allows to determine the frequency range with the dominance of individual influences. Based on the model of the thermal piston, which is a consequence of the effect of thermal diffusion in the sample, and the model of the mechanical piston, which is a consequence of the thermoelastic properties of the sample, by knowing the point of equalization of these two effects, the properties of the material, such as thermal diffusion and conductivity in the low-frequency range and thermal expansion in the high-frequency range, can be determined more precisely.

Analyzing aluminum in the measuring range from 10 to 20kHz, with an increase in sample thickness from 10 to 1000 microns, the equalization point decreases from 4kHz to 200Hz, which indicates a decrease in the area of thermodiffusion dominance and an increase in the frequency area where thermoelasticity dominates.

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