Photoacoustic Study of Printed Samples

Markéta Držková, Lenka Otáhalová and Marie Kaplanová
Department of Graphic Arts and Photophysics, University of Pardubice
Pardubice, Czech Republic

Abstract

Photoacoustics and photoacoustic spectroscopy are presented as methods for the non-destructive study of the optical and thermal properties at different depths beneath the sample surface, together with physical principles of indirect photoacoustic effect and its applications in the field of graphic arts. Capabilities for photoacoustic evaluation of printed samples quality in terms of thickness and uniformity of individual ink layers, ink trapping and real tone value regardless of printed substrate characteristics are summarized. Recently the possibilities of photoacoustic investigation of ink trapping on two-colour overprinted solids were tested and compared with results obtained from optical density spectra and CIE L*C*h* coordinates.[1] In this paper a model for dot area determination was proposed and experimentally verified on sets of one-colour prints on paper and good correlation with densitometry results was found. This model was further used for evaluating halftone images printed over solids and photoacoustic approach was compared with another alternative method for dot area determination – image analysis.[2]

Introduction

The photoacoustic effect was discovered by A. G. Bell and first reported already in 1880.[3] But the photoacoustic experiments were difficult to perform and quantitate since they required investigator's ear to be the signal detector, so photoacoustic effect hadn't found practical application until the advent of microphone. In following decades it was mainly used in the study of optical absorption phenomena in gases; this technique was commonly referred to as optoacoustic spectroscopy. The photoacoustic effect in nongaseous matter was "rediscovered" in early 1970s and made its official debut in 1973 as photoacoustic spectroscopy.[4] The basic theory for the photoacoustic effect in condensed media was formulated by Rosencwaig and Gersho.[5,6]

In case of indirect photoacoustic effect utilised in experiment with gas-microphone configuration, the Rosencwaig-Gersho (or RG) theory shows that if the sample placed in sealed photoacoustic cell absorbs incident modulated light and only radiationless deexcitation processes occur, all the absorbed energy is converted into heat. The thermal wave travels to the sample surface and spreads into the surrounding boundary gas layer. Because of its periodic heating, this layer of gas expands and contracts periodically, producing an acoustic pressure signal. The amplitude of this pressure variation is proportional to the energy absorbed by the sample. As essentially it is only the thermal wave from the first thermal diffusion length μ, which contributes to photoacoustic signal, and μ is proportional to the reciprocal square root of modulation frequency, the lower is the frequency the deeper layers are studied.[4]

To eliminate changes of excitation light energy with modulation frequency and to avoid influence of photoacoustic cell construction parameters, measured photoacoustic signal is often normalized against totally absorbing material (e.g. "carbon black").

Photoacoustic Studies in Printing

The photoacoustics is understood as a measurement of the photoacoustic signal in frequency domain at constant wavelength of exciting radiation (depth profiling), while the photoacoustic spectroscopy in addition involves measuring at different wavelengths. Based on their possibilities, these methods can found many applications in the field of printing and printing technology. Recently were used for example in the study of thin ink layers on printed substrate.[7-9] UV curable inks and varnishes,[10,11] pigmented lacquer films,[12] pulps or papers[13-18] or process of paper yellowing.[19] Number of experiments was also performed with polymer or metal foils, packaging composite materials, adhesives etc.

The course of normalized photoacoustic signal versus reciprocal square root of modulation frequency is influenced by the nature of interface between sample and backing, i.e. in case of printed sample between ink and substrate. According to Rosencwaig-Gersho theory, for totally smooth interface the normalized photoacoustic signal grows linearly until the scanning depth reaches interface (for frequencies higher than the so-called characteristic frequency); when the scanning depth exceeds thickness of the sample, the normalized photoacoustic signal remains constant (for frequencies lower than characteristic frequency). The samples printed on the glossy substrate correspond closely to this model. In case the ink penetrates deep in the paper structure, the concentration of absorbing particles is not constant through the whole ink layer and one can observe gradual change from linear to constant part of the curve. This behaviour is typical for highly porous substrates. Described characteristics allow using photoacoustics to study the surface quality of papers and depth profiles of prints and to deal with mechanism of ink penetration into the printed substrate.

The photoacoustic signal of homogeneous optically transparent samples in low frequency region depends on optical absorption coefficient and sample thickness. Therefore, if optical properties are known, it is possible to determine thickness of the sample and vice versa.

Recently were also tested the possibilities of photoacoustic investigation of ink trapping on two-colour overprinted solids and compared with results obtained from optical density spectra and CIE L*C*h* coordinates.[1] Another field of interest in quality of print involves halftone images. Deformation of original halftone dots during printing process affects colour appearance of printed image. As illustrates Figure 1, dots are deformed not only in size (dot gain), but also in shape. In the following, the possibility to determine real dot area (tone value) by means of photoacoustics is examined.

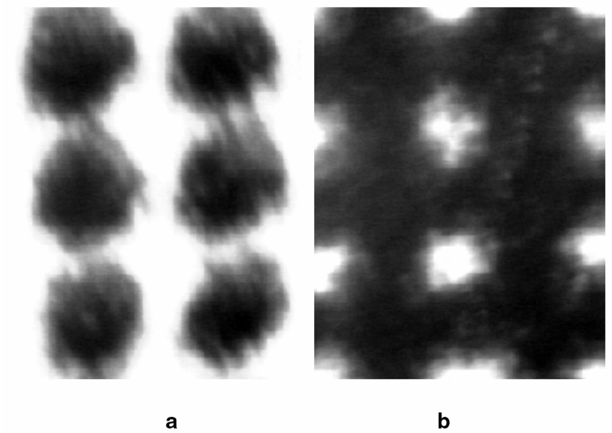

Figure 1. Captured images[2] of halftone prints with nominal tone values 40% (a) and 80% (b)

As to the photoacoustic signal contributes the total number of absorbing particles, on assumption of constant sample thickness and constant illuminated area, the photoacoustic signal of printed samples is affected only by area coverage. Based on this presumption a model for dot area (F) determination was proposed and compared with densitometry and image analysis.

The model, assuming linear combination of contributions of different areas on printed sample to photoacoustic signal, can be expressed by simple relation:

$$F_{PA} = 100\ (S_H - S_B) / (S_S - S_B) \quad [\%] \tag{1}$$

where S_H, S_S and S_B denote normalized photoacoustic signal of halftone print, solid print and backing (paper or bottom solid ink layer), respectively, and F_{PA} is photoacoustically determined dot area on halftone print.

Dot area is generally defined as:

$$F = 100\ \varphi \quad [\%] \tag{2}$$

where φ is area coverage.

Dot area can be determined by means of common densitometric measurement using Murray-Davies total dot area equation:

$$F_{MD} = 100\ (1 - 10^{-D_H}) / (1 - 10^{-D_S}) \quad [\%] \tag{3}$$

where D_H and D_S are densities of halftone and solid print, respectively.

Experimental

Amplitude modulated halftone scale samples (180 lpi) of cyan, magenta, and cyan printed over magenta solids were measured together with appropriate solids and blank paper. All samples (11 mm in diameter) were cut from the sheets printed with cyan and magenta inks (Huber, Cyan 43F 9000 and Magenta 42F 9000) on four-colour commercial sheet-fed offset press (Adast 856) on glossy coated paper (150 g/m^2). Samples were mounted on plexiglass backing using two-sided adhesive tape. As a reference, the “carbon black” was used.

In photoacoustic experimental setup two different light sources were used – 20 mW diode pumped solid-state laser (Suwtech, 532 nm) and 20 mW Flexpoint Minilaser (Laser Components GmbH, 655 nm), for magenta or cyan ink layers, respectively. Light beam (diameter ~ 1 mm) impinged on the surface of sample placed inside a cylindrical photoacoustic cell. Generated acoustic signal was detected by a capacitor microphone Brüel and Kjaer type 4166 and preamplified. Output signal was fed to a DSP lock-in amplifier Stanford Research Systems model SR830. The laser light was modulated using the internal oscillator of the lock-in amplifier. All measurements were controlled and processed by PC.

Optical density and spectra were measured by a reflection spectrophotometer Gretag SPM 50.

The scanning workplace for image analysis included a microscope (zoom 0.5–5) with a CCD area scan camera; all captured bitmaps were processed as described in Ref. [2].

Results

To evaluate validity of the above-mentioned model (see Eq. 1), area coverage determined from photoacoustic experiment (F_{PA}) and area coverage computed according Murray-Davies equation (F_{MD} see Eq. 3) from densitometric data was compared for each sample of one-colour print.

Figure 2 shows results for three sets of cyan samples (each set consisted of halftone scale of cyan printed on paper; samples were cut together with cyan solid and blank paper from the same sheet). Results for magenta samples are similar. Correlation between values determined via photoacoustics and densitometry was good for all sets (R^2 ~ 0,999) regardless the ink used.

Photoacoustic and densitometric data for overprint samples were treated in the same manner and found correlation was again good (R^2 ~ 0,999). Results for three sets of overprint samples are shown in Figure 3 (each set consisted of halftone scale of cyan printed over magenta solids; samples were cut together with cyan solid printed over magenta solid and magenta solid alone from the same sheet).

Comparison of dot area values resulting from image analysis (F_{IA}) and densitometry (F_{MD}) – see Figures 4 and 5 – shows for all samples deviation growing uniformly with area coverage, thus probably indicating some systematic error in image analysis method used; more pronounced deviation is observed for overprint samples with high area coverage. Correlation between area coverage values determined via image analysis and computed according Murray-Davies equation from densitometric data is somewhat worse (R^2 ~ 0,990) than in case of photoacoustics.

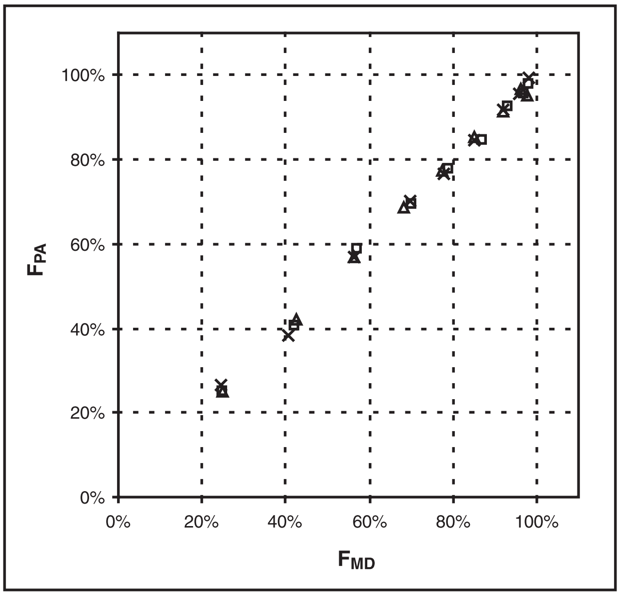

Figure 2. Relationship between dot area determined from photoacoustic experiment (F_{PA}) and dot area according Murray-Davies equation (F_{MD}) for halftone scales of cyan printed on paper (squares, triangles and crosses represent three sets of samples)

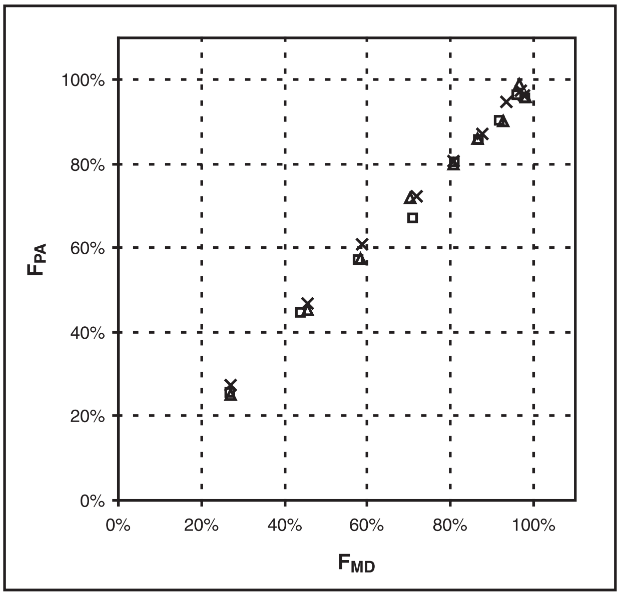

Figure 3. Relationship between dot area determined from photoacoustic experiment (F_{PA}) and dot area according Murray-Davies equation (F_{MD}) for halftone scales of cyan printed over magenta solids (squares, triangles and crosses represent three sets of samples)

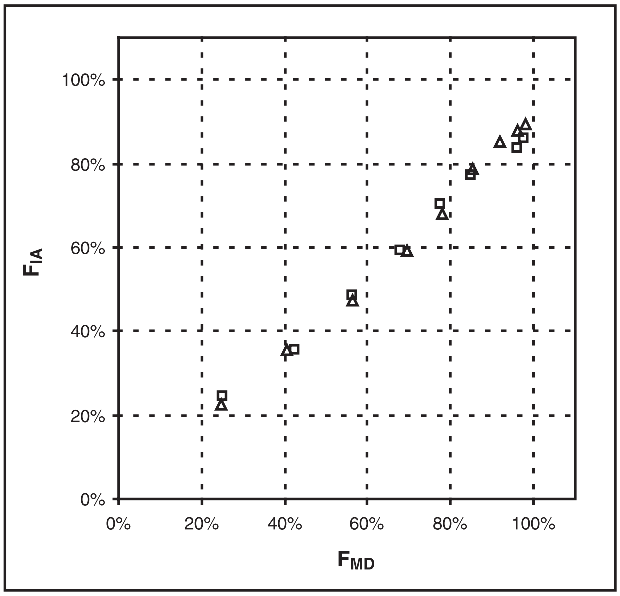

Figure 4. Relationship between dot area determined via image analysis (F_{IA}) and dot area according Murray-Davies equation (F_{MD}) for halftone scales of cyan printed on paper (squares and triangles represent two sets of samples)

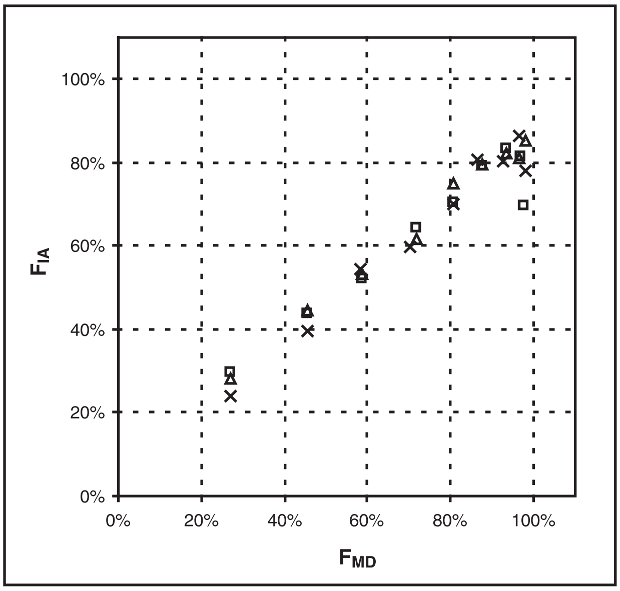

Figure 5. Relationship between dot area determined via image analysis (F_{IA}) and dot area according Murray-Davies equation (F_{MD}) for halftone scales of cyan printed over magenta solids (squares, triangles and crosses represent three sets of samples)

Conclusion

The suggested model for dot area determination was experimentally verified on set of one-colour prints (magenta and cyan) on paper and good correlation with densitometry and image analysis data was found. Based on this results further application of described technique in evaluating halftone images printed on coloured substrate with low absorption at given wavelength was successfully tested on cyan halftone images printed over magenta solids.

In comparison with image analysis,[2,20,21] photoacoustic measurement seems to be more suitable for the determination of area coverage, since results of photoacoustic model are closer to densitometric values and image analysis procedure employed takes more time and is more influenced by deformation of dot shape than photoacoustic approach. Further, dot area resulting from image analysis is affected by quality of captured image, and in case of overprints also by improper colour separation.

As one of the important benefits provided by photoacoustic measurements suggests itself photoacoustic evaluation of dot area of spot inks (enabled by choosing appropriate wavelength of the light source), which could be complicated with commonly used methods. The next research will be also focused on ink trapping of more complex halftone prints.

In conclusion, it can be said that in comparison with commercially used optical reflection methods the sample preparation and data processing of photoacoustic measurement is more time consuming, but in return, photoacoustics provides broad range of additional information. As there is no other method available for study of subsurface structure of prints, non-destructive photoacoustic depth-profiling provides unique capabilities for evaluation of printed samples quality in terms of thickness and uniformity of individual ink layers, ink trapping and real tone value regardless of printed substrate characteristics.

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Biography

Markéta Broklová Drzková, graduated from University of Pardubice in 1999 with thesis entitled Photoacoustic Study of Offset Inks Properties. At present continues in postgraduate studies in Technology of Macromolecular Materials together with working at Department of Graphic Arts and Photophysics as assistant lecturer. Since 1999 her research concerns in various applications of photoacoustics in printing. Current work is focused on investigation of halftone overprints. Pedagogical profile: mainly supervision of semestral projects and diploma. works of undergraduate students, teaching 3D modelling.