Improvement of a system for 2-D optoacoustic imaging using a deconvolution filter

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Abstract—**The detection system for optoacoustic tomography (OAT) usually employs broadband piezoelectric sensors based on polymeric materials. Polyvinylidene fluoride (PVDF) and its copolymers are amongst the most popular ones. Within our knowledge, the existing reconstruction algorithms for OAT neglect the electrical and mechanical relaxation processes of the polymeric material. In a previous work, it was found that the ultimate limits of the polymeric sensor performance are given by the material properties. In this work a deconvolution filter, that minimizes the distortions introduced by the sensor, was developed based on a parametric model. This filter was used in a reconstruction algorithm based on the backprojection method with simulated signals from an 2-D OAT. The results show that it is possible to obtain a remarkable improvement in the resolution of the image.**

Resumen— **El sistema de detección para tomografía optoacústica (TOA) generalmente emplea sensores piezoeléctricos de banda ancha basados en materiales poliméricos. El fluoruro de polivinilideno (PVDF) y sus copolímeros se encuentran entre los más populares. Según nuestro conocimiento, los algoritmos de reconstrucción existentes para TOA no tienen en cuenta los procesos de relajación eléctrica y mecánica del material polimérico. En un trabajo previo, se encontró que los límites últimos del rendimiento del sensor están dados por las propiedades del material polimérico. En este trabajo se desarrolló un filtro de desconvolución, basado en un modelo paramétrico, que minimiza las distorsiones introducidas por el sensor. Este filtro se usó en un algoritmo de reconstrucción basado en el método de retroproyección con señales simuladas de un TOA 2-D. Los resultados muestran que es posible obtener una mejora notable en la resolución de la imagen.**

I. INTRODUCTION

A typical optoacoustic (OA) configuration consists of three essential elements: a light source, a system for detecting acoustic waves and another one for signal processing. For example, in the pulsed excitation mode, the tissue is illuminated by a laser with a typical duration of a few nanoseconds. The repetition rate of pulses is a few tens of Hertz, with energies in the range of microJoules per pulse. When this technique is used to perform OA tomography (OAT) the pressure profiles generated by the optical excitation are captured with sensors that surround the area of interest.

Generally, the detection system is an ultrasonic transducer. In OAT, it is possible to classify these devices into two categories: piezoelectric transducers, in which the measured electrical signal is directly proportional to the pressure; and optical detectors, which are sensitive to changes in the optical path length, induced by pressure waves [1]. Piezoelectric transducers are the most commonly used and are based on polymeric materials (broadband sensors) or ceramics (resonant sensors). From the geometric point of view, these sensors are of two types: small (point-like) or large (integrating) aperture. In the case of small detectors, the image reconstruction algorithms must compensate the diffraction effects. However, using point-like sensors allows making an arrangement with multiple elements. This way, a rapid acquisition of images with adequate resolution can be obtained. In the case of an integrating detector, an image of high angular resolution can be achieved and, if the detector has large bandwidth, it shows good distance discrimination [2]. The detection system for OAT usually relies on broadband piezoelectric sensors based on polymeric materials, being the polyvinylidene fluoride (PVDF) and its copolymers the most popular ones.

The third essential OAT element is devoted to obtain images from OA signals. This demands solving two inverse problems: one acoustic and the other optical [3]. In both cases, the ultrasonic signals are measured. In the acoustic inverse problem, the energy deposited in the sample is mapped, while the objective of the optical inverse problem is to obtain the image of the absorption coefficient. The OA effect applied to obtain images of living objects is the application that presents the greatest challenges in order to solve both inverse problems. Optically, large variations in the dispersion and absorption coefficients of living tissues lead to very complex, non-linear inverse problems. On the other hand, acoustically, the geometry of the detection system, as well as the heterogeneity and losses usually present in the sample, lead to distortions and artifacts in the obtained images [3].

There are a lot of techniques for obtaining images in OAT systems. The approach that has had the best experimental results is the backprojection technique, time domain algorithm very simple to implement. For this reason, we focus on this approach. Algorithms in the time domain are based on projecting each one of the one-dimensional OA time signals into the three-dimensional space in a way that is consistent with the flight time principle [3]. There are many implementations of this approach, being the most complete

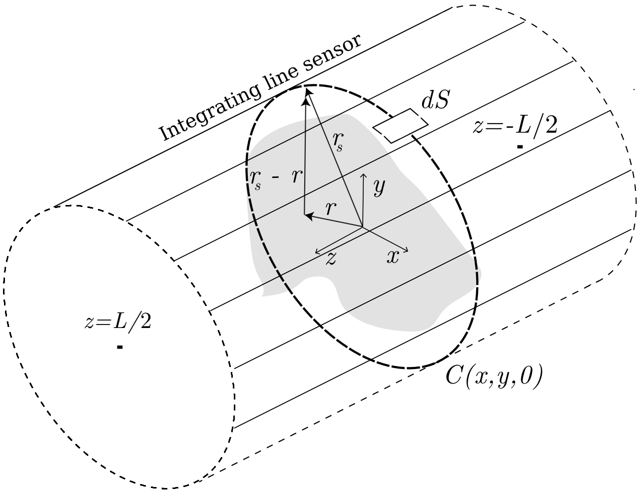

Fig. 1. Schematic of the OAT system for obtaining 2-D images used in this work

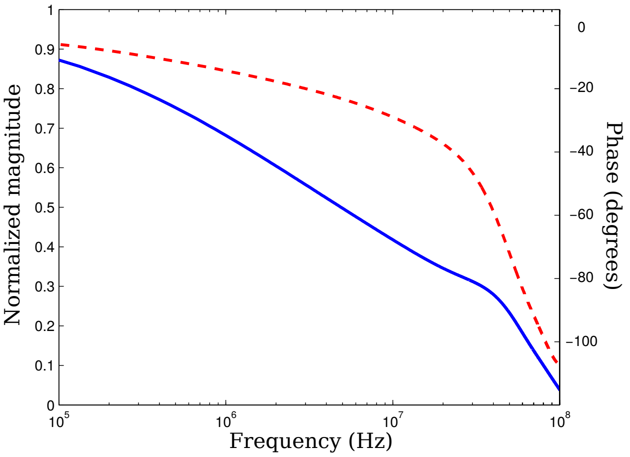

Fig. 2. Magnitude (solid blue curve) and phase (dashed red curve) of the simulated transfer function of a PVDF point sensor using the parameters detailed in [5].

the universal backprojection algorithm developed by M. Xu and coauthors [4] that provides an exact solution for the most common detection surfaces: spherical, cylindrical and plane. To the best of our knowledge, the existing reconstruction algorithms for OAT neglect the electrical and mechanical relaxation processes of the polymeric material used in the ultrasonic sensors. In a previous paper [5], we studied how the backprojection algorithm is affected by the use of polymeric piezoelectric sensors and it was found that the image resolution is reduced due to the relaxation processes that strongly attenuate and distort the high frequency components of the OA signals.

In this work, a deconvolution filter, that minimizes the distortions introduced by the sensor, was developed based on a parametric model [6]. This model uses FFT and numerical integration techniques in an explicit, semi-analytical approach. The filter was used in a reconstruction algorithm based on the backprojection method with simulated signals from shape line detectors of a 2-D OAT. The results show that it is possible to obtain a remarkable improvement in the resolution of the image.

II. DECONVOLUTION FILTER

The chosen OAT scheme for the simulations is known as OA projection imaging. The detection of the ultrasonic waves is carried out with an array of integrating line detectors [7], [8]. Fig. 1 shows the individual line sensors, arranged in parallel on a cylindrical surface S over a circumference C. This array obtains images that represent the projection of the three-dimensional spatial OA sources onto a plane perpendicular to the line detector. If several images of the sample from different projections angles (over the z-axis) are obtained, a three-dimensional image by inverse Radon transformation can be composed [7], [8].

When the duration of the pulse is much shorter than the thermal and mechanical relaxation times involved in the OA process, the pressure in a position $\mathbf{r} = (x, y, z)$ follows the wave equation [7],

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right) p(\mathbf{r}, t) = 0 \qquad (1)$$

with the following initial conditions,

$$p(\mathbf{r}, 0) = p_0(\mathbf{r}) \qquad \left(\frac{\partial p(\mathbf{r}, 0)}{\partial t}\right) = 0 \quad \mathbf{r} \,\epsilon\, \mathbb{R}^3$$

where c is the speed of sound in the medium and $p_0(\mathbf{r})$ is the spatial profile of the initial pressure generated by the sample. The key to the inverse problem is to reconstruct the initial pressure $p_0(\mathbf{r})$ from the data measured by each of the sensors surrounding the sample $p_d(\mathbf{r_s}, t)$. However, the OA signal is the convolution of the pressure pulses that reach the detector $p_{d0}(\mathbf{r_s}, t)$ and its transfer function $h(t)$:

$$p_d(\mathbf{r_s}, t) = p_{d0}(\mathbf{r_s}, t) \circledast h(t) \qquad (2)$$

If $h(t)$ is a positive constant and assuming that the speed of sound c is constant and homogeneous, the projection of the initial pressure distribution in the sample into the xy plane can be obtained using the backprojection algorithm described in [7]. Finally, this distribution is directly proportional to the absorbed energy density which is the goal to achieve by the 2-D OAT.

In a previous work [5] we found that the transfer function $h(t)$ of a polymeric piezoelectric sensor is far from being a constant function. Both its magnitude and phase vary noticeably with frequency. Fig. 2 presents the module and phase of the Fourier transform of h for a point detector, according to the parametric model of Fernandez Vidal, et al. [6].

A way to reduce the effects that h produces on p_d is the deconvolution of the recorded pressure signals by the transducer impulse response, prior to backprojection into de reconstructed image [9]. In this work, we used the Fourier division deconvolution because is the simplest method and the operation can be written as

$$p_{d0}(\mathbf{r_s}, t) = \mathcal{F}^{-1}\left\{\frac{\mathcal{F}\left\{p_d(\mathbf{r_s}, t)\right\} V(f)}{\mathcal{F}\left\{h(t)\right\}}\right\} \qquad (3)$$

where the operators $\mathcal{F}$ and $\mathcal{F}^{-1}$ represent the direct and

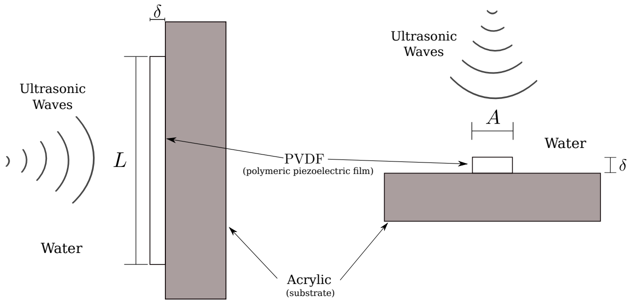

Fig. 3. Schematic out-of-scale of a line shape sensor. Side view (left) and top (right).

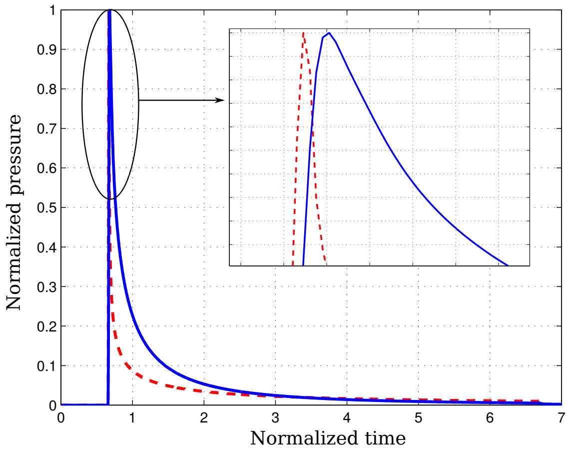

Fig. 4. Simulated sensor impulse response to a point source. Solid blue curve: PVDF based sensor. Red dashed curve: ideal sensor.

inverse Fourier transforms, respectively. $V(f)$ is a window function that limits the bandwidth of the recorded OA signal in order to prevent unwanted high frequency amplification by the division by $\mathcal{F}\{h(t)\}$.

The transfer function $h(t)$ was obtained from the inverse Fourier transform of the division of the simulated response of a polymeric piezoelectric sensor excited by point-like acoustic source to that of an ideal sensor. The simulation of the responses were implemented with the parametric model detailed in [6], adapted for an integrating line detector. The main assumptions of the model are i) each point of the sensor surface behaves like a point detector that can be modeled as a linear, time invariant system (LTI); ii) all of the points on the sensor surface are described by the same LTI model; iii) the main characteristics of the sensors are modeled through transfer functions and/or filters applied to the LTI systems; iv) the otput signal of the sensor is obtained from the integration of the responses of the LTI systems over the sensor surface.

In the simulations, we considered a line shape sensor (L = 20 cm $>>$ A) based on a PVDF film (δ = 25 μm) attached to an acrylic block used as a substrate (see Fig. 3). Also, the acoustic coupling between the sample and the sensor is through water. The characteristic values of the polymer (piezoelectric coefficient, relaxation time and acoustic attenuation) and the reflectance coefficients of the water-polymer and polymer-substrate interfaces are the same used in [5]. In Fig. 4 shows the impulse responses to a point source of a PVDF sensor (solid blue curve) and an ideal sensor (red dashed curve) where it can been see the distortion introduced by a real detector.

For $V(t)$ we use a fifth order Butterworth filter with a cutoff frequency of 50 MHz which is a value similar to the mechanical resonance frequency of the piezoelectric film.

III. RESULTS

In order to investigate the performance of the deconvolution filter, we carried out numerical simulations of three different phantoms with a program developed in GNU/octave. In this work we assume that the characteristic time of the laser pulse is much smaller than any of the other times involved in the OA process. We simulated an OAT with 256 integrating line sensors on the cylindrical detection surface S with a diameter of 10 mm and setting the origin of coordinates at the middle of the axis of the cylindrical volume delimited by S. In the simulations we considered that the water that surrounds the sample is at 300 K. Fig. 5 shows the three sets of simulations comparing the reconstructed images using non-filtered (middle column) and filtered (right column) OA signals. The projections of the initial pressure distributions into the xy plane were obtained using the backprojection algorithm described in [7]. In the first column it is shown the initial pressure distribution p_0 used in each simulation: a sphere with a radius of 25 μm at the origin (first row); two spheres with different radii, 75 μm and 100 μm, (second row); and four spheres with different radii (15 μm, 20 μm, 25 μm and 30 μm) that are superimposed (third row).

The three studied cases show that, when the OA signals are not filtered, the reconstructed images have a loss of resolution due to the attenuation and distortion in the high frequency components ($>$ 1 MHz) introduced by the piezoelectric sensor. When the OA signals do not have an important spectral content at high frequencies, (the pressure signal generated by the sphere of 100 μm), there is no appreciable difference between filtered and non-filtered signals. On the other hand, in cases like the third one (four small spheres), the use of the filter clearly improves the resolution of the image.

IV. CONCLUSIONS

In this study, we implemented a method to minimize the distortions introduced by polymeric piezoelectric sensors used in the OAT detection system. The method consists of deconvolving the pressure data before using the universal reconstruction algorithm. The filter design was based on a parametric model and in measured characteristic values of a PVDF transducer. In order to test the filter we carried out a set of simulations with different phantoms. The results suggest that it is possible to obtain an significant improvement in the resolution of the image.

In future work, we aim to investigate the performance of the deconvolution filter with measured OA signals. In this direction we are developing a 2-D OAT based on PVDF integrating line sensors. Moreover, we plan to examine the robustness to noise of the method.

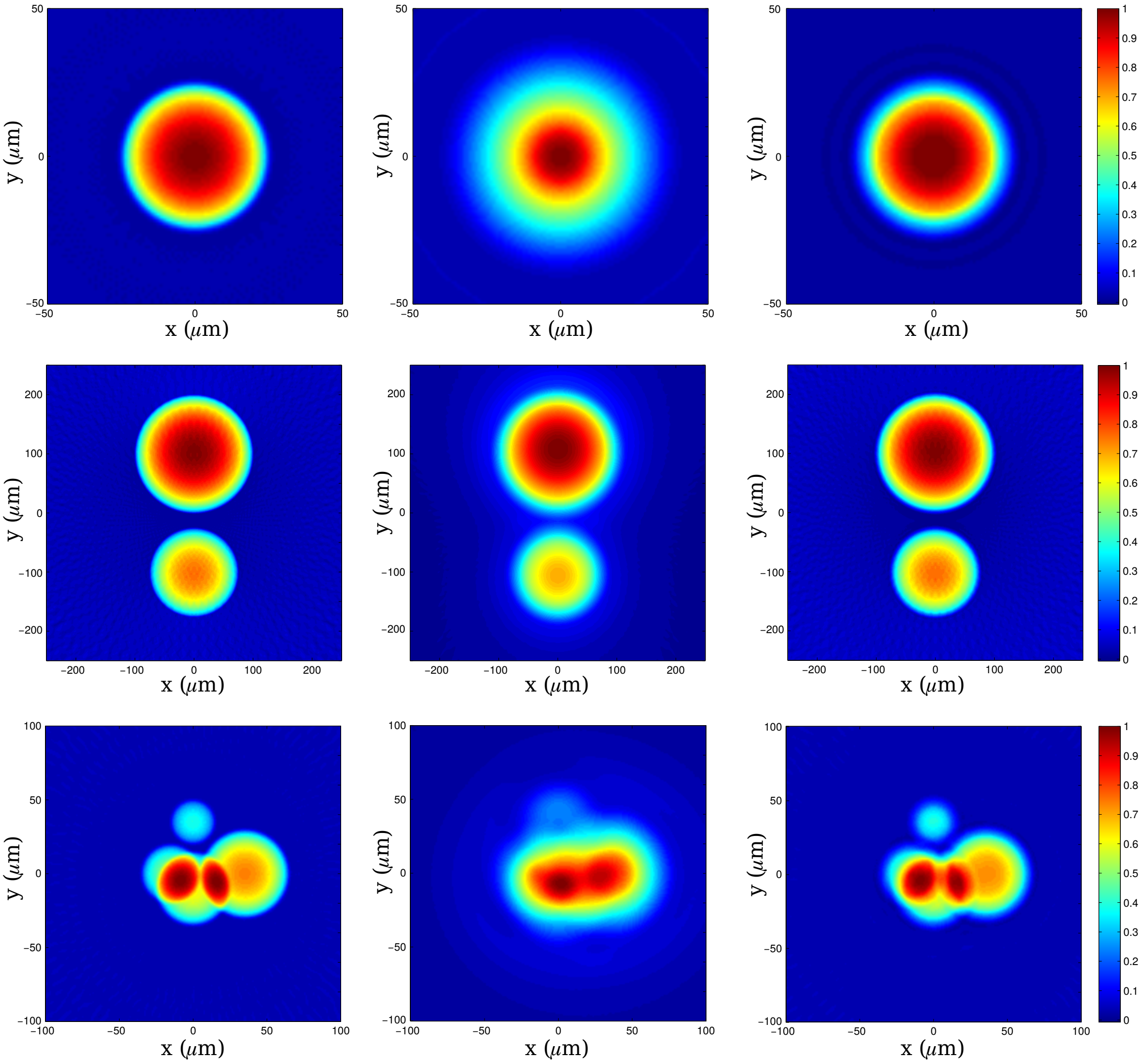

Fig. 5. Comparison of reconstructed images using non-filtered (middle column) and filtered (right column) OA signals. In the left column are shown the initial pressure distribution p_0 used in each simulation. Top: one sphere in the center of the OAT. Middle: two spheres of different sizes displaced from the center. Bottom: four spheres superimposed in different positions

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