Optik 160 (2018) 402–414

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Denoising signals for photoacoustic imaging in frequency domain based on empirical mode decomposition

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ARTICLE INFO

Article history:
Received 14 January 2018
Accepted 5 February 2018

Keywords:
Photoacoustic imaging (PAI)
Empirical mode decomposition (EMD)
Threshold value
Signal processing

ABSTRACT

As a newly developed biomedical imaging technology, photoacoustic imaging (PAI) has attracted great attention worldwide. Traditional frequency domain PAI modality requires tremendous calculations by involving back-projection algorithm in time domain. A pure frequency domain method referred as model-based frequency domain PAI modality based on amplitude and phase analysis was introduced recently. However, the noises in signals may distort the reconstruction images severely. Since noises are normally un-stationary and non-linear, the degree of difficulty increases for restraining the impact of noises by Fourier transform. Also, impacts of different types of noise vary hugely. Moreover, inappropriate sifting process may even aggravate image distortion. In this study, a frequency domain PAI system based on chirp modulation signals has been introduced, in which the influence introduced by two main types of noise have been analyzed by simulation to show how different types of noises may damage reconstructed image in practical and to what extent. White Gaussian noise acts as an additive noise and distort the image gradually while the stochastic noise distort the image very rapidly as the fluctuation increase. Then a new method based on the empirical mode decomposition (EMD) for signal-sifting is demonstrated. By carefully choosing the thresholds and iterative steps, the reconstructed image quality has been promoted, the relative intensity of the target and noises has increased a lot. Further discussion about this method is also made, which certifies the availability of the proposed method.

1. Introduction

Photoacoustic Imaging (PAI) is a new type of imaging technology based on photoacoustic effect. It has developed so rapidly lately and has shown a promising future in many applications, such as biomedical imaging, nondestructive inspection, clinical diagnosis, etc. Photoacoustic effect is a conversion from light to acoustic waves due to optical energy absorption and thermal elastic expansion of certain structures [1,2]. The discovery of photoacoustic effect could be dated back to the year 1880 [3]. PAI has several advantages over pre-existing biological imaging technologies, such as safer operation, low-cost and higher resolution [4–8]. As a non-invasive imaging technology that brings no harm to human body [9], PAI combines the merits of both optical imaging and ultrasonic imaging and has been applied in other area for nearly half a century [10]. PAI has showed its tremendous development potential and broad application prospect in biological imaging area [11,12].

According to the difference in excitation sources, PAI can be roughly divided into two main types: time domain PAI which employs pulse laser as excitation source and frequency domain PAI employing continuous wave (CW) laser [13,14]

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https://doi.org/10.1016/j.ijleo.2018.02.023
0030-4026/

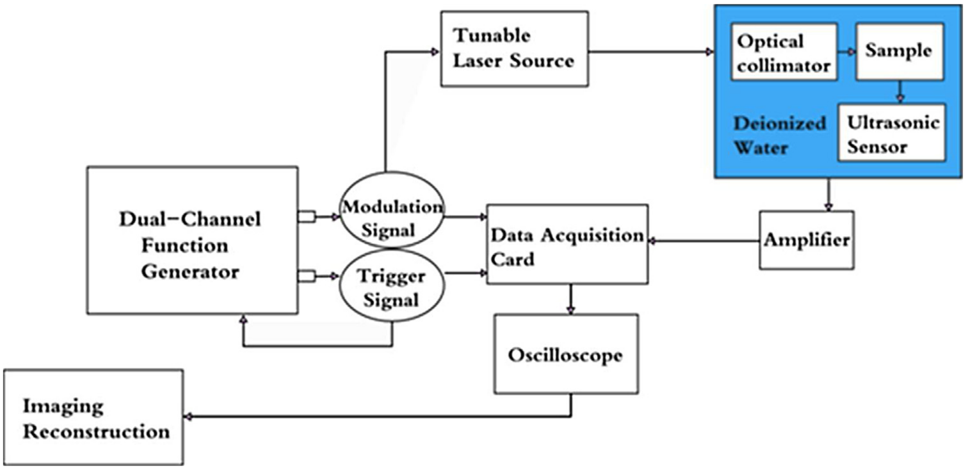

Fig. 1. Schematic view of the experiment setup.

(In the last few years, phase domain PAI debuted in this area which also uses the CW laser [15]). Lihong V. Wang's group from University of Washington not only done abundant works in applications and promotions of time domain biomedical imaging, but also carried out works with nanometer sensors [16–18]. However, the time-consumption in reconstruction is one of the major problems. Michael Jaeger also made great contributions in this field. They improved the resolution, and meanwhile attempted to standardize PAI for the first time [19,20].

The research team from University of Toronto lays the foundation for frequency domain PAI both theoretically and practically [21,22]. Many following up studies have been carried out and demonstrated that comparing with time domain PAI, frequency domain PAI is more economic, more portable and has prior imaging depth. The B. Lashkari's group from University of Toronto reported their work in verifying the principle of frequency domain experimentally in 2006. Pouyan Mohajerani from Helmholtz Zentrum München Munich invented a brilliant model-based algorithm into this field in 2014 [23] which brought more effectiveness in frequency domain PAI.

Nevertheless, due to the fact that excitation source for frequency domain PAI always has lower power than that of time domain, the signal to noise ratio value is small. Therefore, how to reduce the influences of the noises in PAI signal becomes very critical [24] and has turned out to be significant issue all researchers confronted.

In this study, we are mainly focusing on the preprocessing of PAI signals with the empirical mode decomposition (EMD) method and choosing the appropriate threshold to attain good effects of noise reduction. By applying this mechanism, the reconstructed image quality is successfully improved because the EMD method can distinguish different frequency components and minimize the frequency mixture. Unlike other direct sifting methods, this iterative method is self-adaptive and can find the least-contaminated frequency components. This method can reinforce the robustness of frequency domain PAI, and enhance the feasibility of the technique to be applied into industrial application.

2. Experiment

Fig. 1 shows the setup for the experiment. In this experiment, a near infrared CW laser is employed as the excitation source. And its output amplitude is modulated to excite PAI signals periodically. Instead of choosing discrete frequency modulation mode laser as the excitation source since it could be more time efficient, the more time-consuming modulation mode laser source is taken into consideration based on two reasons. On one hand, linear frequency-sweep is the simplest frequency modulation pattern and has been applied widely in radar and sonar systems in the last century. It is fully capable to satisfy the requirement of high resolution under limited transmitting power. On the other hand, without any pre-knowledge of the target's physics characteristic (absorptivity for instance), CW modulation could leave more information for post-processing. The procedure is as follows: A modulation waveform (chip signal, wavelength centered at 808 nm with 200 mW peak power) is generated by one channel from a dual channel function generator and modulates the chirp periodically. Meanwhile, the modulation signal is also input into the data acquisition card as a reference signal during the image processing step. The other channel generates a pulse to trigger itself as well as the data acquisition card at the same time to realize synchronization of the system. The CW laser outputs the modulated laser beam and collimated by a single mode fiber collimator, and be irradiated to the sample surface eventually. Almost simultaneously, a beam of ultrasonic wave is produced due to the sample's thermal elastic expansion after the absorption of laser energy. The PAI signals are captured and detected by the ultrasonic sensor (frequency center is 3.5 MHz and focusing radius is 3.81 cm) and converted into electrical signals. The signals from the ultrasonic sensor are very weak, generally only a few hundred micro volts. Therefore, amplified signals by the amplifier are transported into the computer. Then the corresponding reconstruction algorithm is executed automatically according to our pre-compiled program.