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Micro-Doppler Photoacoustic Effect and Sensing by Ultrasound Radar

Fei Gao, *Member, IEEE*, Xiaohua Feng, and Yuanjin Zheng*, *Member, IEEE*

Abstract—In recent years, photoacoustics has been studied for both anatomical and functional biomedical imaging. However, the physical interaction between photoacoustic generated endogenous waves and an exogenously applied ultrasound wave is a largely unexplored area. Here, we report the initial results about the interaction of photoacoustic and external ultrasound waves leading to a micro-Doppler photoacoustic (mDPA) effect, which is experimentally observed and consistently modelled. It is based on a simultaneous excitation on the target with a pulsed laser and continuous wave (CW) ultrasound. The thermoelastically induced expansion will modulate the CW ultrasound and lead to transient Doppler frequency shift. The reported mDPA effect can be described as frequency modulation of the intense CW ultrasound carrier through photoacoustic vibrations. This technique may open the possibility to sensitively detect the photoacoustic vibration in deep optically and acoustically scattering medium, avoiding acoustic distortion that exists in state-of-the-art pulsed photoacoustic imaging systems.

Index Terms—Photoacoustic effects, ultrasound radar, Doppler effect, signal-to-noise ratio.

I. INTRODUCTION

PHOTOACOUSTIC effect refers to the light-induced acoustic generation discovered by Alexander Bell in 1880 [1-2]. Based on photoacoustic effect, both photoacoustic microscopy (PAM) and photoacoustic tomography (PAT) have attracted increasing interest in recent years on multi-scale biomedical imaging research, ranging from molecular imaging of biomarkers to whole body imaging of small animals [3-11]. PAM and PAT circumvent the penetration depth limitation of conventional optical imaging modalities due to optical diffusion by listening to thermoelastically induced photoacoustic signals. In a typical photoacoustic imaging application, a nanosecond pulsed laser is employed to illuminate the biological tissue. Upon optical absorption and heating of endogenous chromophores (melanin, haemoglobin, etc.), transient acoustic waves are launched due to

Fig. 1. The mDPA effect and modelling. (a) Fundamentals of photoacoustics-ultrasound interaction when light absorber is illuminated by both pulsed laser and CW ultrasound simultaneously. mDPA effect occurs when the laser-induced thermoelastic vibration modulates the CW ultrasound in terms of micro-Doppler frequency shift. (b) Simplified round-shape model of the light absorber with diameter R . Laser illumination is from top side, and ultrasound excitation is from right side.

thermoelastic expansion. However, due to the low energy conversion efficiency ($10^{-12} \sim 10^{-8}$) from light illumination to acoustic pressure based on thermoelastic mechanism [2], acoustic attenuation, and scattering in heterogeneous biological tissues, the received acoustic signal is usually weak and severely distorted, limiting the endogenous contrast and resolution in photoacoustic imaging.

To enhance the signal-to-noise ratio (SNR), the pulse energy of laser may be increased, yet this is limited by the ANSI laser exposure standard for human safety ($< 20 \text{ mJ/cm}^2$ at 532 nm wavelength). The most commonly used approaches are pre-amplification of the signal and averaging after multiple data acquisitions. The signal enhancement in this way is still limited by long acquisition time, and the hardware's performance, e.g. limited gain, bandwidth and unavoidable instrumental noise. Contrast-enhanced photoacoustic imaging is studied extensively with the help of exogenous contrast agents, such as nanoparticles [12-13], carbon nanotubes [14], genetic reporter [15], and vaporized nanodroplets [16]. The problems encountered with these engineered contrast agents may include complexity of intervention, and possible adverse reactions such as allergy [17]. Besides increasing contrast,

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F. Gao and X. Feng are with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798. (email: fgao1@e.ntu.edu.sg, xfeng1@e.ntu.edu.sg).

Y. Zheng is with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798. (email: yjzheng@ntu.edu.sg).

acoustic distortion in heterogeneous tissues is mostly addressed through algorithm re-designs [18-20].

II. METHODS AND MATERIALS

A. Theory of micro-Doppler Photoacoustic Effect

To potentially address the challenges of conventional photoacoustic imaging, here we report on a photoacoustic detection technique, which may increase the sensitivity without adding agents and avoid some of the acoustic distortions due to tissue heterogeneity. This is achieved by combining endogenous induced photoacoustic vibration and exogenously applied ultrasound exposure, abbreviated as photoacoustic-ultrasound interaction. More specifically, a pulsed laser illumination and CW ultrasound driving are utilized simultaneously. It is observed that the endogenous induced photoacoustic vibration can modulate the exogenously applied CW ultrasound wave in terms of Doppler frequency shift. The detailed working principle is discussed below.

Here we transmit the CW ultrasound and receive the backscattering ultrasound from an optical-absorbing object, which is excited with a pulsed laser to emit a photoacoustic pulse at the same time. Because the photoacoustic effect imparts a transient velocity change to the object due to thermoelastic expansion, the frequency of received CW ultrasound will be shifted due to Doppler effect. Being different from photoacoustic Doppler effect caused by bulk translation of the target at a constant velocity [21-24], the frequency shift induced by the mechanical vibration or rotation of the target is termed as micro-Doppler effect [25]. Interestingly, here we treat the photoacoustic effect as a thermoelastic mechanical vibration induced by pulsed laser illumination at the optical absorber site, instead of the conventional photoacoustic wave directly detected by ultrasound transducer, see Fig. 1(a). Therefore, photoacoustic induced thermoelastic vibrations will modulate the frequency of the received CW ultrasound wave, which we define as micro-Doppler photoacoustic (mDPA) effect. As shown in Fig. 1(b), the model of the mDPA effect is simplified to be a plane CW ultrasound wave with frequency f_0 hitting on a round-shape target with diameter R . The transient velocity vector $\vec{V}_{PA}$ of the photoacoustic vibration is proportional to the derivative of the photoacoustic pressure $p(t)$ expressed as:

$$V_{PA}(t) = \kappa_s R \frac{\partial p(t)}{\partial t} \quad (1)$$

where κ_s is the adiabatic compressibility. Then the transient micro-Doppler frequency shift can be expressed as:

$$f_{mDPA} = 2f_0 \frac{V_{PA}(t)}{c} \cos \theta = \frac{2f_0 \kappa_s R}{c} \frac{\partial p(t)}{\partial t} \cos \theta \quad (2)$$

where θ is the photoacoustic vibration angle annotated in Fig. 1(b). From Eq. (2) it is observed that the micro-Doppler

frequency shift f_{mDPA} is proportional to the derivative of the photoacoustic pressure $p(t)$, showing the feasibility of extracting the photoacoustic information from the micro-Doppler frequency shift of the ultrasound transmitter/receiver.

Fig. 2. Diagram of the experimental setup for the detection of conventional pulsed photoacoustic signal and CW ultrasound modulated by the micro-Doppler photoacoustic effect.

The proposed mDPA effect allows the weak and wideband pulsed photoacoustic signal to be carried by the intensive narrowband ultrasound wave, retaining much stronger immunity against acoustic attenuation and distortion in heterogeneous acoustic channel such as biological tissues.

B. Experimental Setup

Next we will experimentally test if this Doppler shift can be picked up (Fig. 2). The setup consists of a Q-switched Nd:YAG laser at 532 nm emitting single laser pulses with 7ns pulse width (Orion, New Wave, Inc). The collimated laser beam with 2 mm diameter spot size is guided onto a silicone tube immersed in water filled with diluted blue ink (Pelikan, $\mu_a \approx 100\text{cm}^{-1}$) pumped by a syringe pump. Two ultrasound transceiver systems are used. First a wideband ultrasound transducer (V323-SU, 2.25 MHz, 6 mm in diameter; Olympus) is adopted to receive the photoacoustic wave conventionally and acts as a reference. It is connected to a preamplifier (54 dB gain, model 5662; Olympus) and the signal is recorded with an oscilloscope (500 MHz sampling rate, WaveMaster 8000A; LeCroy). The data is 20 times averaged. The second transceiver system is running simultaneously using a dual-element ultrasound transducer (5 MHz, 6 mm in diameter, DHC711-RM; Olympus). It operates as CW ultrasound radar, transmitting and receiving CW ultrasound by its dual elements. A 5 MHz sine wave generated from a function generator is fed into a power amplifier (250 W; BT00200-AlphaSA-CW, Tomcorf) to drive the transmitting element. The receiving element is directly connected to the oscilloscope for data recording. Both the wideband and dual-element transducers are

placed near the testing tube at a distance of 4.5 cm. A synchronization signal from the pulsed laser is used to trigger the data acquisition of the oscilloscope.

III. RESULTS

A. System Evaluation and Data Extraction

To extract the micro-Doppler frequency shift from the received ultrasound signal, band-pass filtering and down-conversion technique are employed, which multiplies the

located 4.5 cm away with a delay of about 30 μs with good agreement.

B. Signal Evaluation

The extracted mDPA signal amplitude is proportional to the derivative of the photoacoustic pressure according to Eq. (3), so it is also expected to reveal the optical absorption coefficient as

Fig. 3. The mDPA and pulsed photoacoustic system. (a) micro-Doppler photoacoustic system, and (b) conventional pulsed photoacoustic system. (c) Received CW ultrasound signal with frequency modulation by micro-Doppler photoacoustic system. (d) Received CW ultrasound signal with frequency modulation by conventional pulsed photoacoustic system. (e) mDPA signal. (f) PA signal.

received ultrasound wave (Fig. 3(c-d)) $US(t) = A_{US} \sin[2\pi(f_0 + f_{mDPA})t]$ with a reference signal $R(t) = A_R \cos[2\pi f_0 t]$. Here A_{US} and A_R are the respective amplitudes. Then we apply low-pass filtering:

$$\begin{aligned}
 mDPA(t) &= US(t)R(t) = A_{US}A_R \sin[2\pi(f_0 + f_{mDPA})t] \cos[2\pi f_0 t] \\
 &= \frac{1}{2}A_{US}A_R \sin[2\pi(2f_0 + f_{mDPA})t] + \frac{1}{2}A_{US}A_R \sin[2\pi f_{mDPA}t] \\
 &\xrightarrow{\text{Low-pass filtering}} \frac{1}{2}A_{US}A_R \sin[2\pi f_{mDPA}t] \\
 &\xrightarrow{\text{Small-angle approximation}} A_{US}A_R \pi f_{mDPA} t \\
 &= \frac{2\pi f_0 \kappa_s R A_{US} A_R}{c} \cos \theta \frac{\partial p(t)}{\partial t} \Big|_{t=K} \frac{\partial p(t)}{\partial t} t
 \end{aligned}
 \tag{3}$$

where small-angle approximation is applicable due to the much shorter duration of photoacoustic wave than mDPA period, and $K = 2\pi f_0 \kappa_s R A_{US} A_R \cos \theta / c$ is assumed to be the mDPA conversion constant. Both photoacoustic (PA) wave (Fig. 3(f)) detected by conventional pulsed photoacoustic system (Fig. 3(b)) and mDPA wave (Fig. 3(e)) detected by the proposed mDPA system (Fig. 3(a)) indicate the photoacoustic source

Fig. 4. Normalized amplitude comparison of micro-Doppler photoacoustic (mDPA) signal and pulsed photoacoustic (PA) signal by varying the laser pulse energy.

the conventional photoacoustic signal does. In the measurement, the data of both pulsed PA measurement and mDPA measurement of CW ultrasound are averaged by 20

Fig. 5. SNR analysis of mDPA versus pulsed photoacoustic signals. (a) Signal and noise levels of micro-Doppler photoacoustic and pulsed photoacoustic signals before and after acoustic channel. (b) Waveform of received pulsed photoacoustic signal, and (c) recovered mDPA signal. The mDPA signal detection retains higher SNR than conventional pulsed photoacoustic detection.

times, with 5 times repetition of the experiments. The laser pulse energy is varied from 20 μJ to 90 μJ well within laser exposure safety limit (20 mJ/cm^2 for green light of 532 nm wavelength). The repetition-averaged results with negligible standard deviation of ~ 0.01 in this controlled experiment show that the normalized amplitude to the maximum amplitude of the mDPA wave has a good agreement with the normalized amplitude of conventional photoacoustic wave for optical absorption measurement as shown in Fig. 4. More quantitative analysis under different measurement conditions (e.g. bulk movement) will be performed to evaluate its measurement reliability in more realistic environment in the future work, which will further validate its potential application in clinical environment. This experiment was repeated to get the similar results using ex vivo vessel-mimicking phantom, which is made of silicone tube filled with real porcine blood and covered by a sheet of breast chicken tissue. More complex heterogeneous phantom and in vivo experiments will be conducted to push the proposed method towards real applications.

C. Sensitivity Evaluation

To compare the sensitivity of the proposed mDPA system with a conventional pulsed photoacoustic system, pre-amplification and averaging are removed from both the

mDPA system and the conventional pulsed photoacoustic system. At the source site as shown on the left side of Fig. 5(a), both the mDPA signal and the pulsed photoacoustic signal are detectable above the noise floor. However, after acoustic attenuation and distortion during the propagation, the amplitude of the pulsed photoacoustic signal is below the input referred noise of ultrasound receiver, which is equivalently to the base-line noise floor of the oscilloscope used in the experiment as shown on the right of Fig. 5(a). Therefore, the pulsed photoacoustic wave can be hardly detected in presence of the background noise (Fig. 5(b)). On the other hand, the mDPA system is still capable of recovering the photoacoustic information (Fig. 5(c)), for the reason that photoacoustic vibrations modulate the intense CW ultrasound wave in terms of the micro-Doppler frequency shift. The modulated CW ultrasound wave reserves the high intensity and the narrow bandwidth, which allows band-pass filtering with high quality factor (Q) to significantly suppress the noise. The experimental result shows higher signal SNR (14dB) and fidelity than pulsed photoacoustic signal SNR (2.5dB) during its propagation in acoustic channel.

IV. DISCUSSION AND CONCLUSION

We would clarify that the micro-Doppler photoacoustic effect in this paper follows the static Doppler effect and Eq. (2)

holds, because the period of CW ultrasound (200 ns) is much smaller than the transient photoacoustic vibration period ($>1 \mu\text{s}$) in time-domain demodulation analysis. Moreover, no matter static or quasi-static Doppler analysis [26-27], the amplitude of the Doppler shift frequency is proportional to the amplitude of the vibration, which still guarantees the validity of the proposed method for photoacoustic detection. Finally, the quasi-static Doppler effect may be applicable to the case of CW laser induced photoacoustic vibration, which will be further studied in the future work.

To further elaborate the feature and advantage of the proposed mDPA system, it is interesting to make an analogy between the photoacoustic detection system and the well-established telecommunication system. More specifically, conventional pulsed photoacoustic detection is similar with amplitude modulation (AM) communication system, where information is carried in terms of signal's amplitude. On the other hand, the proposed mDPA detection can be related to a frequency modulation (FM) communication system, where information is carried in terms of signal's frequency shift. According to communication theory, FM systems are far better at rejecting noise as compared to AM system: the noise is distributed uniformly in frequency and varies randomly in amplitude. Therefore, the FM system is inherently immune to the random noise due to its narrowband characteristics and high Q band-pass filtering, guaranteeing the superior advantages of the FM mDPA system over conventional AM pulsed photoacoustic system. On the other hand, it should be noted that potential limitations may also exist, such as the sensitivity to bulk movement. To overcome this, the experimental setup is required to keep stable during the measurement, which could minimize the unwanted environmental variations. In most cases and if necessary, a motion sensor (e.g. 3D accelerometer and/or gyroscope) can be used to record exactly the bulk movements and then calibrate them out from the experiment. Lastly, an ultrasound transmitting module is required for the mDPA measurement, which increases the complexity and cost of the system compared with conventional PA measurement way.

The current photoacoustic imaging techniques majorly include pulsed light induced PA generation and frequency-modulated CW light induced PA generation. Due to much higher peak power, pulsed light induced PA retains good SNR in time domain [3]. On the other hand, CW light induced PA has much lower SNR due to low peak power of CW laser, which however, could be overcome by "matched filter" cross-correlation processing to significantly suppress the noise [28]. The mDPA technique proposed in this paper is clearly different from the existing pulse and CW PA generation. Specifically, the mDPA technique fuses merits of both existing pulsed and CW PA techniques. It employs pulse laser to induce high SNR PA vibration, and CW ultrasound Doppler frequency modulation to significantly suppress the noise outside the narrow bandwidth. Overall, the mDPA technique is potentially developed as another general PA imaging technique, may be better than existing pulse or CW PA imaging in terms of signal SNR and sensitivity.

Interferometric measurement based on light detection is a

similar approach with the proposed mDPA technique to measure the surface displacement, such as Michelson interferometer [29]. However, these light-based interferometer can only measure the displacement after the PA signal has propagated to the surface, which still suffers acoustic distortion. On the contrary, the proposed mDPA can directly measure the PA vibration at the original vibrator site due to CW ultrasound's deep penetration, which allows better signal fidelity and less distortion, although the sensitivity and resolution may be poorer than light-based interferometric measurement.

In summary, the photoacoustics-ultrasound interaction is studied to experimentally observe the mDPA effect. Simultaneous illuminating the object by pulsed laser and CW ultrasound leads to the micro-Doppler frequency modulation of CW ultrasound induced by transient thermoelastic expansion and vibration. Secondly, based on the mDPA effect, a new photoacoustic detection system, termed micro-Doppler photoacoustic system, is proposed to extract the photoacoustic information from the received modulated CW ultrasound signal through down-conversion technique. Due to the mDPA effect, the weak and wideband photoacoustic signal is modulated onto the CW ultrasound carrier in terms of micro-Doppler frequency shift. Taking advantage of CW ultrasound's high intensity and narrowband spectrum, it retains much stronger immunity than the pulsed photoacoustic signal against the acoustic attenuation and distortion suffered during its propagation in the heterogeneous acoustic channel. Comparison studies demonstrate that mDPA signal could achieve much higher signal-to-noise (SNR) ratio and fidelity than conventional pulsed photoacoustic system. It is expected that an imaging system based on mDPA effect may outperform the conventional pulsed photoacoustic imaging in some aspects such as distortion and sensitivity. The resolution is determined by the bandwidth of the ultrasound transducer. The trade-off exists that to achieve a good sensitivity using narrowband transducer for CW ultrasound, it will compromise with lower spatial resolution due to narrower bandwidth. More detailed optimization will be studied in the future work.

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Fei Gao received his B.S. degree in electrical engineering from Xi'an Jiaotong University, Xi'an, China in 2009. He received the PhD degree in electrical and electronic engineering at Nanyang Technological University, in 2015. He was a postdoctoral visiting scholar at Stanford University in 2015. After that, he joined NTU again working as a research fellow and electromagnetic-ultrasound group leader under the supervision of Prof. Yuanjin Zheng. His research interests include fundamental study and system development of thermoacoustic and photoacoustic imaging modalities, circuit and system for biomedical applications. He has authored and co-authored over 40 journal and conference papers, one book chapter, and one patent filed.

Xiaohua Feng obtained his B.S. degree in electrical engineering from Xidian University, Xi'an, China in 2011. He is currently a PhD candidate in School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His research interest includes microwave induced thermoacoustic imaging, photoacoustic imaging, pulsed radio frequency pain relief therapy, and biomedical circuits and system design.

Yuanjin Zheng (M'02) received the B.Eng. and M.Eng. degrees from Xi'an Jiaotong University, Xi'an, China, in 1993 and 1996, respectively, and the Ph.D. degree from the Nanyang Technological University, Singapore, in 2001. From July 1996 to April 1998, he was with the National Key Laboratory of Optical Communication Technology, University of Electronic Science and Technology of China. In 2001, he joined the Institute of Microelectronics (IME), Agency for Science, Technology and Research (A*STAR), and had been a principle Investigator and group leader. With the IME, he has led and developed various projects on CMOS RF transceivers, ultra-wideband (UWB), and low-power biomedical ICs etc. In July 2009, he joined the Nanyang Technological University, as an assistant professor and program director for Bio-imaging program. His research interests are biomedical sensors and imaging, thermoacoustic and photoacoustic imaging, and SAW/BAW/MEMS sensors. He has authored or coauthored over 100 international journal and conference papers, 16 patents filed, and several book chapters.