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Third order harmonic imaging for biological tissues using three phase-coded pulses ☆

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Abstract

Compared to the fundamental and the second harmonic imaging, the third harmonic imaging shows significant improvements in image quality due to the better resolution, but it is degraded by the lower sound pressure and signal-to-noise ratio (SNR). In this study, a phase-coded pulse technique is proposed to selectively enhance the sound pressure of the third harmonic by 9.5 dB whereas the fundamental and the second harmonic components are efficiently suppressed and SNR is also increased by 4.7 dB. Based on the solution of the KZK nonlinear equation, the axial and lateral beam profiles of harmonics radiated from a planar piston transducer were theoretically simulated and experimentally examined. Finally, the third harmonic images using this technique were performed for several biological tissues and compared with the images obtained by the fundamental and the second harmonic imaging. Results demonstrate that the phase-coded pulse technique yields a dramatically cleaner and sharper contrast image.

Keywords: Three phase-coded pulses; Third harmonic imaging; Biological tissues

1. Introduction

It is well known that the ultrasound wave propagates nonlinearly in biological tissue and harmonic components cumulate due to the nonlinearity. Recently, much attention has been focused on the study of the nonlinear propagation [1] and the nonlinear imaging techniques [2–4]. The application of the ultrasound contrast agent (UCA) motivated the development of the nonlinear imaging in clinical diagnosis [5]. To improve the resolution and specificity of harmonic imaging, a number of multi-pulse imaging techniques [6] have been developed. Pulse inversion technique [7] is the most common used method to successfully suppress the fundamental component while enhance the second harmonic by 6 dB. Amplitude modulation technique is also proposed to achieve a cancellation of the linear component and preserve the second harmonic. The second harmonic imaging is now evident in some commercial systems [8].

Compared to the second harmonic, the third harmonic has better spatial resolution and improved beam pattern performance, but lower sound pressure. High sensitivity and wide dynamic range are needed in the receiving system to achieve an acceptable amount of SNR. Therefore, how to get the desirable third harmonic component with favorable SNR and remove the other harmonics to reduce the confusion is the key topic. In this paper, a phase-coded pulse technique is put forward to selectively enhance the third harmonic component and suppress the fundamental or the second harmonic components to acquire more useful information of tissues. Combined with the theory of the finite amplitude wave, the principle and the advantage of this technique were theoretically discussed and experimentally examined. Improvements of the axial and lateral beam profiles, the signal amplitudes and SNR for the third harmonic are demonstrated both in numerical simulations and in experiments. Compared with the fundamental and the second harmonic imaging, the processed third

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harmonic imaging was performed for several biological tissues and results demonstrated that the improved performance dramatically improved image clarity and contrast.

2. Principle and method

A pulse signal with angular frequency ω and initial phase φ_0 is radiated in medium. The wave distortion and harmonic accumulation occur during the sound propagation due to the nonlinearity. From the Bessel–Fubini series solution of the Burgers' equation [9], the sound pressure at distance x is expressed as

$$p(x) = \sum_{m=1}^{\infty} \frac{2p_0}{m\sigma} J_m(m\sigma) \sin(m\omega\tau + m\varphi_0), \quad (1)$$

where p_0 is the sound pressure at the source, m is the order of the harmonics, $\sigma = x/x_k$ is the normalized axial distance, $x_k = (\beta M k)^{-1}$ is the shock formation distance, β is the nonlinearity coefficient, $k = \omega/c_0$ is the wave number, $M = v_0/c_0$ is the acoustic Mach number, v_0 and c_0 are the characteristic value of the velocity and isentropic sound speed, t is the transmitting time, $\tau = t - x/c_0$ is the retarded time.

Supposing that the initial phases of the three pulse signals are φ_0, $\varphi_0 + 2\pi/3$ and $\varphi_0 + 4\pi/3$, the sound pressure at distance x of the nth ($n = 0$ to 2) pulse is

$$p_n(x) = \sum_{m=1}^{\infty} \frac{2p_0}{m\sigma} J_m(m\sigma) \sin[m\omega\tau + m(\varphi_0 + 2\pi n/3)]. \quad (2)$$

Summing up the received three echo signals and substituting $n = 0$ to 2 into Eq. (3), the pressure amplitude of the processed mth harmonic is obtained as

$$p_{sm}(x) = \begin{cases} 3\frac{2p_0}{m\sigma} J_m(m\sigma) \sin[m(\omega\tau + \varphi_0)], & m = 3, 6, 9, \\ 0, & \text{otherwise}. \end{cases} \quad (3)$$

Compared with the single pulse transmission mode, the processed amplitude of the third harmonic is increased by 9.5 dB, whereas the fundamental and the second harmonic components are fully suppressed.

3. Simulation and experiments

3.1. Experimental setup

The schematic block diagram of the experimental system is shown in Fig. 1. A planar transducer (diameter 8 mm, center frequency 2 MHz) and a broadband needle hydrophone (NP1000, 20 MHz) are used as transmitter and receiver. A sound permeable sample container with a thickness of 20 mm is placed between the transmitter and the hydrophone close to the hydrophone to minimize the influence of sound diffraction. A function generator (Agilent 33250A) transmits three phase-coded pulses (sine wave frequency 2 MHz, repetition frequency 1 kHz, eight cycles) with initial phases of 0, $2\pi/3$ and $4\pi/3$ in turn. The transmitted pulses are amplified by a broadband power amplifier (ENI A150, 55 dB) and then excite the transducer. The transmission signals are received by the hydrophone and recorded by the computer through a digital oscilloscope (Agilent 54810) via GPIB interface. Processed in the computer off line, the amplitudes harmonics are obtained.

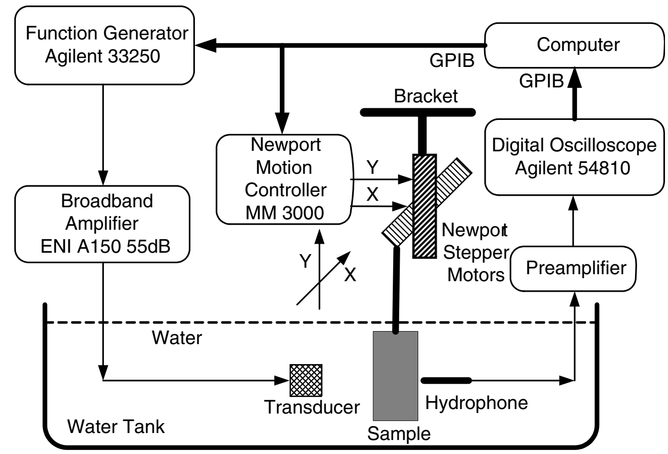

Fig. 1. Schematic block diagram of the experimental system.

3.2. Third order harmonic enhancement

The spectra of the received signals with a sample of porcine liver tissue obtained before and after the use of the phase-coded pulse technique are shown in Fig. 2, which are normalized by the maximum amplitude of the fundamental frequency. In comparison with the case of the single pulse transmission mode in Fig. 2(A), only the third as well as the sixth harmonics are evidently prominent in the processed signal in Fig. 2(B). The amplitudes of the fundamental frequency and the second harmonic are effectively suppressed by 26.5 dB and 33.3 dB, whereas the third harmonic is enhanced by 9.8 dB, which is close to the theoretical prediction of 9.5 dB.

3.3. Improvement of axial and lateral beam profiles

The nonlinear propagation of finite amplitude ultrasound beam can be simulated exactly by the Khokhlov–Zabolotskaya–Kuznetsov (KZK) nonlinear wave equation [10] and it is solved using backward implicit finite differences approximation in frequency domain [11]. The simulated axial and lateral beam profiles of the fundamental up to third harmonics at $p_0 = 0.5$ MPa are displayed in Figs. 3 and 4. The solid lines are obtained by the numerical calculation and the dashed lines represent the experimental results. The experimental axial and lateral beam profiles coincide quite well with the corresponding theoretical simulations. By using the three phase-coded pulse technique, the energy of the processed third harmonic is three times that of the single pulse mode and it is also higher than that