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New demodulation filter in digital phase rotation beamforming

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Abstract

In this paper, we present a new quadrature demodulation filter to reduce hardware complexity in digital phase rotation beamforming. Due to its low sensitivity to phase delay errors, digital quadrature demodulation is commonly used in ultrasound machines. However, since it requires two lowpass filters for each channel to remove harmonics, the direct use of conventional finite impulse response (FIR) filters in ultrasound machines is computationally expensive and burdensome. In our new method, an efficient multi-stage uniform coefficient (MSUC) filter is utilized to remove harmonic components in phase rotation beamforming. In comparison with the directly implemented FIR (DI-FIR) and the previously-proposed signed-power-of-two FIR (SPOT-FIR) lowpass filters, the proposed MSUC filter reduces the necessary hardware resources by 93.9% and 83.9%, respectively. In simulation, the MSUC filter shows a negligible degradation in image quality. The proposed method resulted in comparable spatial and contrast resolution to the DI-FIR approach in the phantom study. These preliminary results indicate that the proposed quadrature demodulation filtering method could significantly reduce the hardware complexity in phase rotation beamforming while maintaining comparable image quality.
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Keywords: Ultrasonic imaging; Beamforming; Phase rotation beamforming; Quadrature demodulation filter; Hardware complexity

1. Introduction

The adoption of digital receive beamforming (DRBF) techniques based on dynamic focusing has greatly improved the ultrasound image quality in the last few decades [1]. In the DRBF, the enhanced time delay accuracy in digital processing provides higher signal-to-noise ratios (SNR) and better spatial resolution. In addition, the DRBF's flexibility has enabled new imaging techniques (e.g., dynamic aperture and multi-beam) [2]. However, the DRBF significantly increases the computational complexity since it requires fast analog-to-digital converters (ADC) and front-end digital circuitries running at a high clock frequency. To alleviate the high-frequency requirement in ADCs and front-end circuitries, interpolation beamforming (IBF) and phase rotation beamforming (PRBF) methods have been developed [2–4] and are commonly used in ultrasound machines [5]. However, IBF and PRBF methods require many computationally-expensive interpolation and demodulation filters, respectively. Thus, this high computational requirement makes the development of ultrasound machines with large channel counts (e.g., for 3D ultrasound systems [6]) or very low-end machines (e.g., handheld [7]) challenging.

Various beamforming techniques, such as pipelined-sampled-delay-focusing (PSDF) [8], sigma-delta oversampled (SDO) [5] and direct I/Q [9], have been developed for further reducing the hardware burden in the DRBF. The PSDF technique relies on non-uniform sampling of the signals coming from the different receive channels to compensate for time delay differences in dynamic receive focusing [8]. While the PSDF succeeds in lowering the hardware complexity, the control of ADCs for non-uniform sampling

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Table 1
Acronyms used

ADC	Analog-to-digital converter
CR	Contrast resolution
DI-FIR	Directly implemented FIR
DRBF	Digital receive beamforming
FIR	Finite impulse response
IBF	Interpolation beamforming
LSB	Least significant bit
MSUC	Multi-stage uniform coefficient
PRBF	Phase rotation beamforming
PSDF	Pipelined-sampled-delay-focusing
SDO	Sigma-delta oversampled
SNR	Signal-to-noise ratio
SPOT-FIR	Signed-power-of-two FIR
TGC	Time-gain compensation

is challenging [10]. In the SDO beamforming, one-bit sigma-delta modulators running at a high clock frequency are utilized to eliminate the complicated digital delay circuitries (e.g., interpolation and phase rotation) [11]. On the other hand, it suffers from artifacts caused by synchronous errors between the sigma-delta modulator at each channel and the post-beamforming demodulator [5,12]. In addition, sigma-delta modulators running at the required clock frequency for the typical wideband signals in medical ultrasound imaging are difficult to implement. In the direct I/Q method, the complex baseband signals utilized in the PRBF are directly sampled from the receive signals. Thus, there is no need for lowpass filtering, which is a major computational task in the PRBF, during demodulation to remove harmonic components [9]. However, the direct I/Q approach assumes narrow-band signals and no depth-dependent attenuation, which is typically not satisfied in medical ultrasound imaging. Alternatively, the hardware complexity in the PRBF could be reduced by replacing the directly implemented finite impulse response (DI-FIR) filters with more efficient lowpass filters, such as signed-power-of-two (SPOT) FIR [13,14]. In the SPOT-FIR, filter coefficients are only represented by sums of a limited number of SPOT terms [15]. While the SPOT filter can substitute complex multipliers with adders and shifters, its computational complexity is still high.

In this paper, we propose a new quadrature demodulation filtering technique based on an efficient multi-stage uniform coefficient (MSUC) filter. The necessary hardware resources of the developed MSUC filter is compared with the conventional DI-FIR and the previously-proposed SPOT-FIR. Since the developed MSUC filter may degrade image quality, its effect on image quality is also analyzed. The acronyms used in this paper are listed in Table 1.

2. Methods

2.1. Digital phase rotation beamforming with digital quadrature demodulation

Fig. 1 shows the block diagram of a digital phase rotation beamformer with quadrature demodulation. The receive ultrasound signals are amplified in proportion to depth in order to compensate for signal attenuation (i.e., time-gain compensation, TGC). After TGC, the RF signals are digitized by ADCs whose sampling frequency is typically $4f_0$ where f_0 is the transducer center frequency. The digitized RF signal can be represented by

$$x[n] = A_{\mathrm{I}}[n] \cdot \cos[2\pi f_0 n] - A_{\mathrm{Q}}[n] \cdot \sin[2\pi f_0 n] \tag{1}$$

where $A_{\mathrm{I}}[n]$ and $A_{\mathrm{Q}}[n]$ are the baseband in-phase and quadrature signal, respectively. The baseband signal can be extracted by removing the carrier frequency through quadrature demodulation, which consists of mixing and lowpass filtering. The digitized RF signal (i.e., $x[n]$), which is originally centered around $\pm f_0$, is first multiplied with cosine ($\cos[2\pi f_0 n]$) and sine ($\sin[2\pi f_0 n]$) values. These multiplications generate not only the signals centered at 0, but also signal harmonics centered at $\pm 2f_0$ in the in-phase and quadrature components of the mixed signal ($M_{\mathrm{I}}[n]$ and $M_{\mathrm{Q}}[n]$). To remove these harmonics shown in Fig. 1, lowpass demodulation filtering after mixing is required. Afterwards, the receive beamforming based on dynamic focusing is performed on the extracted baseband signals (i.e., $A_{\mathrm{I}}[n]$ and $A_{\mathrm{Q}}[n]$) for coherent summation consisting of delay, phase compensation and summation to improve SNR and spatial resolution.

Table 2 lists the computational load of each processing function (in terms of multiplications and additions) in the

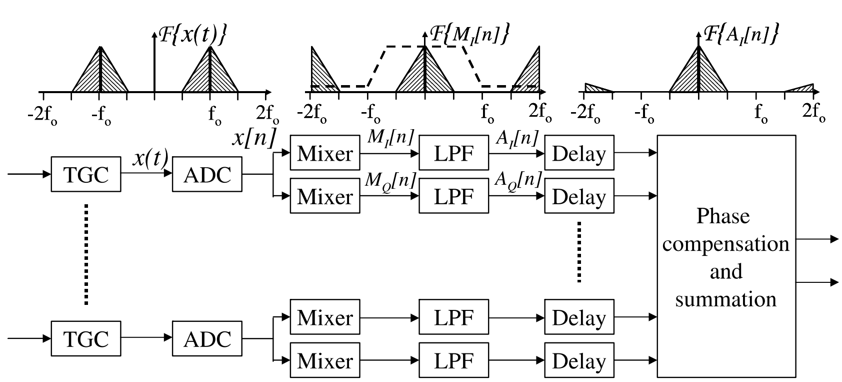

Fig. 1. Block diagram of a phase rotation beamformer with quadrature demodulation. $\mathscr{F}\{\cdot\}$ represents the Fourier transform.

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