Square-Wave Aperture Weightings for Reception Beam Forming in High Frame Rate Imaging

Jian-yu Lu and Jing Wang, Department of Bioengineering, The University of Toledo, Toledo, OH 43606, USA, email: jilu@eng.utoledo.edu

Abstract – **Recently, the high frame rate (HFR) imaging method was extended to include multiple transmission beams such as steered plane waves and limited-diffraction array beams to improve image quality. In addition, limited-diffraction array beam transmissions have been approximated with square-wave aperture weightings so that only one or two transmitters are needed for three-dimensional imaging with a fully populated two-dimensional array transducer, simplifying the transmission subsystem of an imager. In this paper, the square-wave aperture weightings are applied to reception beamforming to simplify the limited-diffraction array beam aperture weightings proposed previously, which allows the production of all spatial frequency components of analog echo signals in realtime over a transducer aperture by direct summation and subtraction of these signals for image reconstructions. This approach reduces the need of some high-speed digital circuits and can also be used as a realtime spatial spectrum analyzer to produce both amplitude and phase of the waves impinging on the surface of a receiver with simple electronics as long as the spatial Nyquist sampling criterion is satisfied.**

Both *in vitro* (on an ATS539 phantom) and *in vivo* (on the hearts and a kidney of volunteers) experiments were performed with a broadband phased array transducer of 2.5MHz center frequency, 128 elements, and 0.15mm pitch using a home-made general-purpose HFR imaging system. A one-cycle, 2.5MHz sine wave pulse was used to excite the transducer with a pulse repetition period of about 187 microseconds. Results show that the quality of images reconstructed with the reception square-wave aperture weightings is very close to that of images reconstructed with the exact limited-diffraction array beam weightings or spatial Fourier transform on echo signals. The images reconstructed have over +/-45 degree field of view and an image frame rate of about 486/s is achieved for a depth of 120 mm.

Keywords - Square-wave aperture weighting; high frame rate; HFR; limited diffraction beams; medical imaging; beamforming; spatial spectrum analyzer

I. INTRODUCTION

Based on the limited-diffraction beam theory [1]-[4], a high-frame rate (HFR) imaging method was developed [5]-[9]. This method has a potential to achieve a high image frame rate (3750 frames or volumes per second for a depth of about 200 mm in biological soft tissues) with computationally efficient beamforming algorithm such as the fast Fourier transform (FFT) Recently, this method has been extended [10]-[15] to include multiple transmissions of limited-diffraction array beams [16]- [18] and steered plane waves [5], [19], [20] to increase image field of view and improve image quality, which is equivalent to having a dynamic focusing in both transmission and reception with a conventional delay-and-sum (D&S) method [21]. In addition, the extended HFR imaging method has been applied for HFR velocity vector imaging [22].

This work was supported in part by a grant, HL60301, from the National Institutes of Health of USA.

Although the extended HFR imaging method may reduce the number of transmitters needed as compared to the conventional D&S method, it may still need a large number of transmitters and a complicated switching network. To further reduce the number of transmitters required, a square-wave aperture weighting method was developed [10]. In this method, all the transducer elements are driven by only one or two transmitters to reconstruct high-quality images that are similar to those of the extended HFR imaging method, simplifying the transmitter subsystem of an imager.

In this paper, the square-wave aperture weighting method is applied to the reception beamforming to approximate the exact sine and cosine limited-diffraction array beam weightings [10]-[13]. This allows simpler analog summing and subtracting circuits to be used to produce all the spatial frequency components of echo signals simultaneously in realtime and may replace some high-speed digital circuits that are otherwise needed without significantly affecting the quality of images reconstructed.

In addition to the imaging applications, the square-wave aperture weighting method can also be used as a general-purpose realtime spatial spectrum analyzer for waves impinging on the transducer surface. This is similar to using an optical lens to obtain a realtime two-dimensiona (2D) spatial Fourier transform at either the focal distance or in the Fraunhofer region (far field) for thin objects placed against the lens aperture [23]. Unlike the Fourier optics where the phase information is usually ignored, the square-wave aperture weightings can naturally obtain both phase and amplitude of signals for applications such as ultrasound and microwaves.

II. METHOD

The theory of limited-diffraction array beam imaging with square-wave aperture weightings for transmission beams is given in Reference [10]. From Eqs. (6) and (7) of [10], it is clear that the ultrasound transmission and reception processes are exchangeable due to the reciprocal principle [24]. Therefore, the square-wave aperture weightings used in transmissions can also be applied to reception (see Eqs. (17) and (18) of [10]).

In the square-wave aperture weightings on echo signals received by the elements of an array transducer, the signals are directly summed and subtracted to produce a desired spatial frequency component according to the signs of the sine and cosine functions at the positions of the transducer elements. Such summations and subtractions can be done with analog circuits for realtime processing of the echo signals, eliminating some high-speed digital circuits. This process can naturally obtain both phase and amplitude of multiple frequency components of the waves impinging on the surface of the transducer, and thus can be used as a spatial spectrum analyzer not only for ultrasound, but also for electromagnetic waves such as microwaves, as long as the Nyquist criterion is satisfied by the spatial sampling frequency of the array.

III. RESULTS

A. In Vitro Experiments

To show the efficacy of the square-wave aperture weighting method on reception beamforming, we have performed *in vitro* experiments on an ATS539 tissue-mimicking phantom (ATS Laboratory, Inc.). The phantom consists of line, anechoic cylindrical, and grayscale cylindrical targets. In the experiment, a home-made HFR general-purpose medical imaging system [10], [25], [26] was used to drive an Acuson V2 phased array transducer (Siemens, Mountain View, California) of 128 elements, 0.15mm pitch, and 2.5MHz center frequency. In the experiment, a one-cycle sine wave at the center frequency was used. Radio frequency (RF) echo signals from each transducer element were digitized and stored in an SDRAM, and then transferred to a personal computer via a standard USB 2.0 port. The square-wave aperture weightings were applied to the received signals according to Eqs. (17) and (18) of [10]. Reconstructed images of the phantom are shown in Figs. 1 and 2, respectively, for limited-diffraction array beam [16]-[18] and steered plane wave [5], [19], [20] transmissions. In Fig. 1, square-wave aperture weightings were also applied to transmissions. In both figures, Panels (a) and (c) are results of the exact limited-diffraction aperture weightings of the received echo signals, while Panels (b) and (d) are those of the square-wave aperture weightings. From the figures, it is clear that the quality of images reconstructed with the square-wave aperture weightings of the echo signals is about the same as that of images reconstructed with the exact weightings. As demonstrated in the previous publications [11]-[13], as the number of transmissions is increased, the quality of images increases (compare Panels (c) and (d) with (a) and (b) respectively in both Figs. 1 and 2).

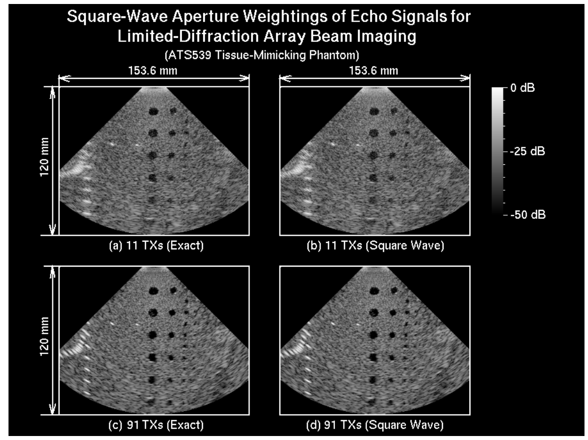

Figure 1. Reconstructed images of an ATS539 tissue-mimicking phantom with limited-diffraction array beam transmissions, where the transmission beams were produced with square-wave aperture weightings. A cross section of wire, anecho cylindrical, and grayscale cylindrical targets are shown at the left, middle, and right hand side of each image, respectively. A 128-element and 2.5MHz Acuson V2 phased array transducer of 0.15mm pitch was placed at the center top of each image and was in contact with the phantom surface. Images are log-compressed with a dynamic range of 50 dB. The speed of sound of the phantom is about 1450 m/s. The field of view of the images is larger than +/-45° over a 120mm depth. Images of the exact limited-diffraction array beam weightings on received echo signals ((a) and (c)) are compared with those of the square-wave weightings ((b) and (d)), respectively. Images on the top and bottom rows were reconstructed with 11 (up to 549 frames/s with 1450m/s speed of sound) and 91 (up to 66 frames/s) transmissions, respectively. (The images in (a) and (c) are the same as those in Figs. 3(a) and 3(d), respectively, of [14].)

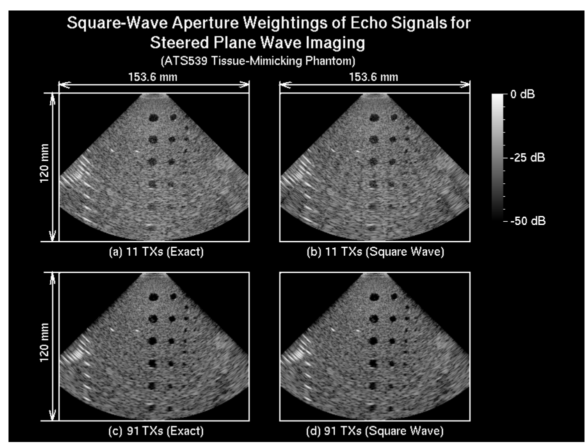

Figure 2. This figure is the same as Fig. 1, except that steered plane waves, instread of limited-diffraction array beams, were used in transmissions. (The images in (a) and (c) are the same as those in Figs. 4(a) and 4(d), respectively, of [14].)

B. In Vivo Experiments

In vivo experiments on human hearts and kidney of volunteers were also conducted with the home-made general-purpose HFR medical imaging system [10], [25], [26]. The experiment conditions are the same as those of the *in vitro* experiments above. These conditions are also the same as those of Fig. 14 of [10] (for Figs. 3 and 4), and Figs. 13 and 14 of [13] (for Figs. 5 and 6), except that the square-wave aperture weightings were applied to the received echo signals. From the *in vivo* experiments, it is also clear that the quality of images reconstructed with the square-aperture weightings of echo signals is similar to that with the exact weightings for various transmission schemes.

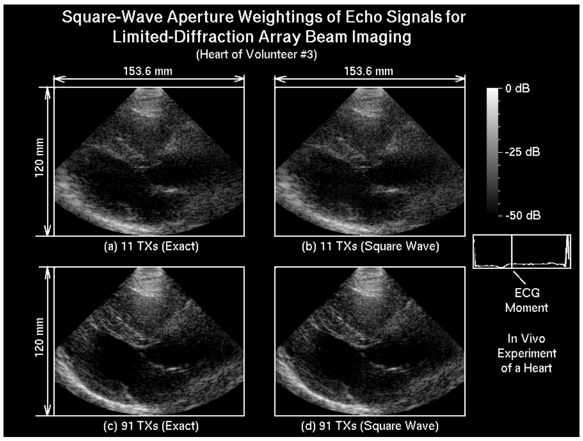

Figure 3. *In vivo* images of the heart of a volunteer obtained with limited-diffraction array beam transmissions, where the transmission beams were produced with square-wave aperture weightings. The experiment conditions and image layout are the same as those of Fig. 1, except that the speed of sound is assumed 1540 m/s. The images were obtained near the moment when the mitral valve was pushed open rapidly (see the vertical bar in the box of the ECG curve on the right hand side of the figure). The time between adjacent transmissions was 187 µs, which was the shortest allowed by the home-made HFR imaging system at the depth. Images of the exact limited-diffraction array beam weightings on received echo signals ((a) and (c)) are compared with those of the square-wave weightings ((b) and (d)), respectively. Images on the top and bottom rows were reconstructed with 11 (up to 486 frames/s) and 91 (up to 59 frames/s) transmissions, respectively. (The images in (a) and (c) are the same as those in Figs. 14(c) and 14(a), respectively, of [10].)

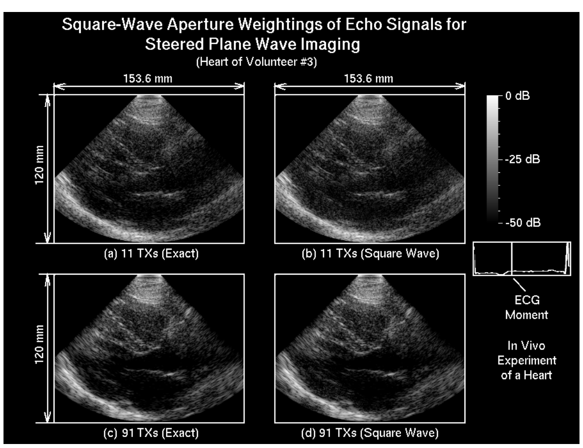

Figure 4. This figure is the same as Fig. 3, except that steered plane waves, instread of limited-diffraction array beams, were used in transmissions. (The images in (a) and (c) are the same as those in Figs. 14(f) and 14(d), respectively, of [10].)

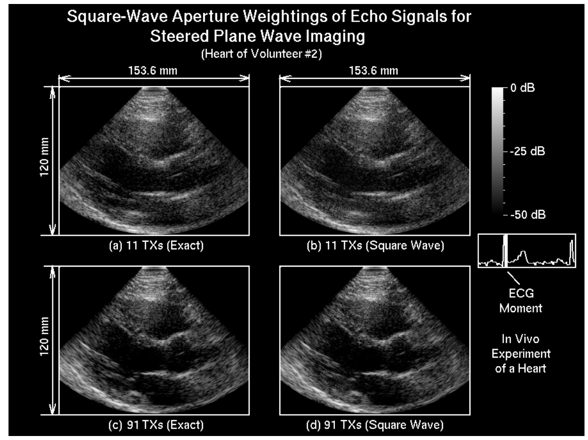

Figure 5. *In vivo* images of the heart of a volunteer obtained with steered plane wave transmissions. The experiment conditions and image layout are the same as those of Fig. 3. The images were obtained at a moment shortly after the "R wave" peak (see the vertical bar in the box of the ECG curve on the right hand side of the figure). Images of the exact limited-diffraction array beam weightings on received echo signals ((a) and (c)) are compared with those of the square-wave weightings ((b) and (d)), respectively. Images on the top and bottom rows were reconstructed with 11 (up to 486 frames/s) and 91 (up to 59 framess) transmissions, respectively. (The images in (a) and (c) are the same as those in Figs. 14(a) and 14(c), respectively, of [13].)

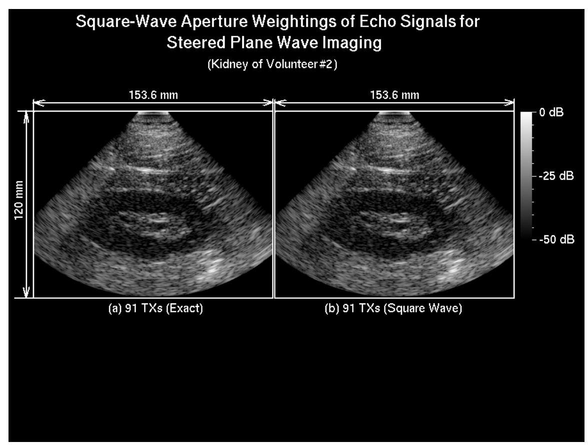

Figure 6. *In vivo* images of a kidney of a volunteer obtained with steered plane wave transmissions. The experiment conditions and image layout are the same as those of Fig. 3. The image of the exact limited-diffraction array beam weightings on received echo signals (a) is compared with that of the square-wave weightings (b). The images were reconstructed with 91 transmissions, with the time between adjacent transmissions of 187 µs. The images in (a) is the same as that in Fig. 13(a) of [13].

IV. CONCLUSION

It has been shown in the previous studies that the high frame rate (HFR) imaging method [5]-[9] and its extension [10]-[15] can be implemented with limited-diffraction array beam aperture weightings or 2D spatial Fourier transform over the transducer aperture [10]. The limited-diffraction array beam aperture weightings can be approximated with square-wave aperture weightings to simplify the transmitter subsystem of an imager to allow only one or two transmitters to drive a fully populated array transducer [10]. In this paper, the limited-diffraction array beam aperture weightings on received echo signals are approximated with the square-wave aperture weightings [10] to simplify electronic circuits for image reconstructions.

Both *in vitro* and *in vivo* experiments have been conducted with the home-made general-purpose HFR medical imaging system [10], [25], [26]. The results show that the square-wave aperture weightings on received echo signals are capable of reconstructing high-quality images as compared to those reconstructed with the exact limited-diffraction array beam aperture weightings.

Besides the imaging applications, the square-wave aperture weighting method has a potential to be used as a general-purpose realtime spatial spectrum analyzer for waves impinging on a receiver surface using simple analog addition and subtraction circuits as long as the spatial Nyquist sampling criterion [23] is satisfied, producing both amplitude and phase of signals in applications such as ultrasound and microwaves.

ACKNOWLEDGMENTS

This work was supported in part by a grant HL 60301 from the National Institutes of Health.

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