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3D ultrasound imaging in frequency domain based on concepts of array beam and synthetic aperture

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ABSTRACT

The high frame rate (HFR) imaging method has the ability to achieve a high frame rate. In this method, only one transmission is required to construct a frame of image. In our previous work, using a moved one-dimensional (1D) array transducer, a three-dimensional (3D) ultrasound imaging method in frequency domain was developed. This imaging method was designed based on the concepts of array beam and synthetic aperture, which can simplify the two-dimensional (2D) array transducer. In this paper, based on array beam and synthetic aperture, the HFR imaging method is demonstrated from a novel view. From this view, the relationship between the HFR imaging method and synthetic aperture is established with the weighting function of array beam. Besides, the HFR imaging method, the imaging method with a moved 1D array transducer, and the synthetic aperture imaging method with a moved single element transducer are unified in the same analytical method with different weighting functions. The same frequency domain signal processing flow can be applied to these imaging methods. Comparisons to these imaging methods are implemented with simulations. Simulation results show that, in the imaging depth of 45 mm, the resolutions calculated as the total width of the −6 dB main lobe in x-direction are 1.099 mm, 1.056 mm and 0.596 mm for the methods with 1D transducer, 2D transducer and the single element transducer, respectively. The resolution in y-direction is 1.054 mm for the methods with 2D transducer, and 0.565 mm, 0.593 mm for the 1D and single element transducers, respectively. The resolutions in z-direction are 0.493 mm, 0.451 mm and 0.452 mm for the 2D, 1D and single element transducers, respectively. The resolution in the moved-direction is improved with a moved transducer, but the contrast of the image is decreased.

1. Introduction

B-mode ultrasound imaging has been widely used in clinical applications. However, it has certain limitations for clinical diagnosis. 3D ultrasound imaging has been developed for more than twenty years [1,2], and it has the ability to overcome the limitations of B-mode. Compared to B-mode imaging, it provides much more detailed information for medical diagnosis and clinical applications.

A moved 1D array transducer is commonly used to acquire 3D images [3]. In this method, a series of B-mode images are constructed when the 1D array transducer is moved to different locations and a 3D image can be reconstructed by combining these 2D images. The 1D array transducer can be moved using a mechanical device or manually. When the transducer is moved manually, motion tracking technology is required [4]. Various 3D reconstruction algorithms have been proposed [5–7]. While these 3D images exhibit satisfactory lateral and depth resolution, the elevation resolution is poor due to the sound field distribution of the transducer [8,9]. Synthetic aperture (SA) focusing technique improves the image resolution significantly [10,11]. In general, the SA technique in ultrasound imaging is performed with delay and sum (DAS) beamforming in the time domain, and the time of flight should be calculated point-by-point to perform the synthetic aperture focus [12]. Therefore, in these methods, the computational cost is high, especially in 3D imaging. A time domain beamforming method can be used to reduce the computational complexity [13].

Frequency domain imaging method is another approach to acquire a 3D image [14,15]. The frequency domain SA with a single element transducer may be a potential candidate. Recently, a new frequency domain implementation of SA focusing technique for 2D imaging has been reported [14]. With the similar analytical method, a 3D imaging model can be obtained. In this method, the transducer is moved in a rectangular region, and it transmits and receives the signals at each position. After scanning, all the

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received signals are processed in frequency domain to construct a 3D image. This method is a simple way to acquire 3D images. However, it needs a long time to scan the imaging area, which decreases of the frame rate.

A high frame rate (HFR) imaging method was proposed by Lu in 1997 [16,17]. As a frequency domain imaging method, a plane wave pulse or array beam is transmitted by a 2D array transducer, and the received signals are weighted with array beams of different parameters processed with Fourier transform. The spatial Fourier transform of the object function can be obtained from received signals, and then images are constructed with an inverse Fourier transform. Thus, the implementation of the method can be greatly simplified. Since only one transmission is required to construct a frame of image, this method can achieve a high frame rate for 3D imaging. Further, several array beams or plane wave pulses with different parameters can be used as transmitted signals, and the imaging quality can be improved by synthesizing the image spectrums related to different transmit events.

The extended HFR imaging method proposed by Lu is developed with limited diffraction beams. This method can also be obtained in the view of angular spectrum [18]. From this view, the weighting process with limited diffraction array beams in the HFR imaging method is replaced by Fourier transform.

Although the HFR imaging method can achieve a high frame rate and high imaging quality, it is limited by the complexity of the 2D array transducer. In our previous work, a 3D ultrasound imaging method in frequency domain with a moved one-dimensional (1D) array transducer was presented [9], which can simplify the 2D array transducer used in the HFR imaging method. This method is obtained based on the concepts of array beam and synthetic aperture. It has been found that the HFR imaging method can also be achieved with the same analytical method. This means that the HFR imaging method can also be viewed from the concepts of array beam and synthetic aperture.

In this paper, the HFR imaging method is obtained from a novel view based on the concepts of array beam and synthetic aperture. Three frequency domain imaging methods, including the HFR imaging method, 1D array imaging method, and the synthetic aperture imaging method with a moved single element transducer, are unified with different weighting functions in the same analytical method. The same signal processing flow is applied to these imaging methods. In the signal processing flow, the received signals are processed with three-dimension Fourier transform in the temporal domain and spatial domain. Then, the spatial spectrum of the 3D image is obtained with conversion functions, which is the only difference between these methods. Finally, the 3D image is constructed with 3D inverse spatial Fourier transform. Comparisons to the three imaging methods are implemented with simulations.

2. Theory

In this section, a 3D frequency domain SA with a single element transducer is first obtained. Then, the HFR imaging method using a 2D transducer is derived with the concepts of array beam and synthetic aperture. Finally, the imaging method with a moved 1D array transducer that proposed in our previous work is concisely introduced. Meanwhile, the three imaging methods in frequency domain are unified with different weighting functions in the same analytical method.

Assume that the 3D object is composed of randomly positioned point scatters embedded in a uniform background supporting a constant speed of sound c [15], and the transducer is located at the plane z = 0. The elements used as transmitter and receiver are located at $(x_t, y_t, 0)$ and $(x_r, y_r, 0)$ respectively (Fig. 1).

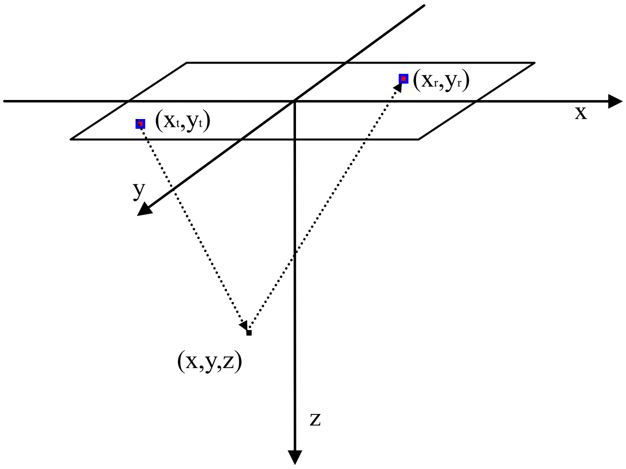

Fig. 1. The relationship between the scatter and the elements of transmitter and receiver.

When $p(t)$ is used as the excited signal, the received signal scattered from a point located at (x, y, z) is expressed as:

$$r_{one}(x_t, y_t, x_r, y_r, x, y, z, t) = f(x,y,z)p \times \left(t - \frac{\sqrt{(x_s-x)^2+(y_s-y)^2+z^2}}{c} - \frac{\sqrt{(x_r-x)^2+(y_r-y)^2+z^2}}{c}\right), \tag{1}$$

where $f(x, y, z)$ is the object function (reflection coefficient).

As the imaging system is linear, the received signal scattered from the object can be regarded as the linear superposition of all the echo signals from individual point scatters as below:

$$r_{object}(x_t, y_t, x_r, y_r, t) = \iiint r_{one}(x_t, y_t, x_r, y_r, x, y, z, t)dxdydz, \tag{2}$$

with (1), (2) becomes

$$r_{object}(x_t, y_t, x_r, y_r, t) = \iiint f(x,y,z)p \times \left(t - \frac{\sqrt{(x_s-x)^2+(y_s-y)^2+z^2}}{c} - \frac{\sqrt{(x_r-x)^2+(y_r-y)^2+z^2}}{c}\right) dxdydz. \tag{3}$$

Applying the temporal Fourier transform of $r_{object}(x_t, y_t, x_r, y_r, t)$, (3) becomes

$$R_{object}(x_t, y_t, x_r, y_r, k) = \iiint f(x,y,z)A(k) \times e^{-jk\sqrt{(x_t-x)^2+(y_t-y)^2+z^2}} e^{-jk\sqrt{(x_r-x)^2+(y_r-y)^2+z^2}} dxdydz, \tag{4}$$

where $A(k)$ is the temporal Fourier transform of $p(t)$, k is the wave number, and $k = \omega/c = 2\pi f/c$.

(4) describes the received signal in spectrum domain when only one element is used for transmitting. Assuming that the geometry of the array transducer located at the plane z = 0 is described by $W_g(x_t, y_t)$, and the transmitted signal is weighted with $W_t(x_t, y_t, k)$. When an array transducer is adopted and all elements of the array transducer are considered as transmitter independently with the linearity assumption of the imaging system, the received signal is a linear superposition of all echo signals from each individual transmitter as below