Multi-Element Synthetic Transmit Aperture Method in Medical Ultrasound Imaging

Ihor Trots, Yuriy Tasinkevych, Andrzej Nowicki and Marcin Lewandowski

***Abstract*—**The paper presents the multi-element synthetic transmit aperture (MSTA) method with a small number of elements transmitting and all elements apertures in medical ultrasound imaging. As compared to the other methods MSTA allows to increase the system frame rate and provides the best compromise between penetration depth and lateral resolution.

In the experiments a 128-element linear transducer array with 0.3 mm pitch excited by a burst pulse of 125 ns duration were used. The comparison of 2D ultrasound images of tissue mimicking phantom obtained using the STA and the MSTA methods is presented to demonstrate the benefits of the second approach. The results were obtained using SA algorithm with transmit and receive signals correction based on a single element directivity function.

***Keywords*—**Beamforming, frame rate, synthetic aperture, ultrasound imaging

I. Introduction

THE ultrasound imaging has become much more prevalent than the other medical imaging techniques since it is more accessible, less expensive, safe, simpler to use and produces real-time images. However, to provide an accurate clinical interpretation the highest possible image quality is required. The most commonly used image quality measures are spatial resolution, image contrast and frame rate. The spatial resolution of the ultrasound image can be improved by using several transmit beams during the interrogation of each sector, each of which is focused at a different depth. It is done in modern ultrasound imaging systems at the cost of a decrease of the frame rate, proportionally to the number of transmit foci [1]. An alternative way to obtain an appropriate spatial resolution, without the decrease of the frame rate, is to use the synthetic aperture technique.

Synthetic aperture originates from the radars and sonars and has previously not been used in medical ultrasound imaging. The basic idea of SA is to gather information acquired simultaneously by small transmit-receive apertures placed in different positions and then to reconstruct the full image from the collected data. In the simplest case a single element transmits an unfocused wave and then it is switched to receive the backscattered signal which yields a low resolution image line. Combing the data obtained from a large number of emissions one is able to obtain a high resolution image.

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There are several methods to form a synthetic aperture for ultrasound imaging. Synthetic aperture focusing technique (SAFT) is the simplest method. It reduces the system complexity but is characterized by low signal-to-noise ratio and penetration depth. Multi-element synthetic aperture focusing (MSAF) is an alternative to SAFT. A group of elements transmits the unfocused wave-field and receives signals simultaneously. The acoustic power and the signal-to-noise ratio (SNR) are increased compared to the SAFT. Synthetic transmit aperture (STA), is an alternative to conventional phased array. At each time a single array element transmits an ultrasound pulse and all elements receive the echo signals [2]. The advantage of this approach is that a full dynamic focusing can be realized in both transmit and receive modes, giving the highest image quality.

Till now, in the SA methods it is assumed that the transmit and receive elements are the point-like sources and the dynamical focusing is realized by finding the geometric distance from the transmitting element to the imaging point and back to the receiving element. But when the element size is comparable to the wavelength the influence of the element directivity on the wave field generation and reception becomes significant and if ignored might be a source of errors and noise artifacts in the resulting image. In this work the STA algorithm [3], which takes into account the single element directivity to improve the quality of the resulting image, is applied to reconstruct ultrasound image.

The main objective of this work is to implement the MSTA method in ultrasound imaging where only a few elements transmit unfocused wave-field and all array elements receive the echo signals. This method allows to increase of the system frame rate and penetration depth. The latter is due to increase of the transmitted energy which improves the SNR and, as a result, the ultrasound image contrast.

The optimization was carried out using the *Field II* simulation program [4] in the MATLAB® environment. The number of elements used in transmit mode were optimized using the criteria of maximum penetration depth and maximum lateral resolution. The 128-element linear transducer array with 0.3 mm pitch excited by half cycle burst of the nominal frequency of 4 MHz and the sampling rate of 40 MHz was used in the experiments. The comparison of 2D ultrasound images of tissue mimicking phantom obtained using the STA and the MSTA methods are presented. The results show that the optimal aperture size allows to increase penetration depth maintaining lateral resolution.

II. Synthetic Aperture Method

A. Synthetic Transmit Aperture Method

As an alternative to the conventional phased array imaging technique the STA method can be used. It provides the full dynamic focusing, both in transmit and receive modes, yielding the highest imaging quality.

In the STA method at each time one array element transmits a pulse and all elements receive the echo signals (Fig. 1), where data are acquired simultaneously from all directions over a number of emissions, and the full image can be reconstructed from these data.

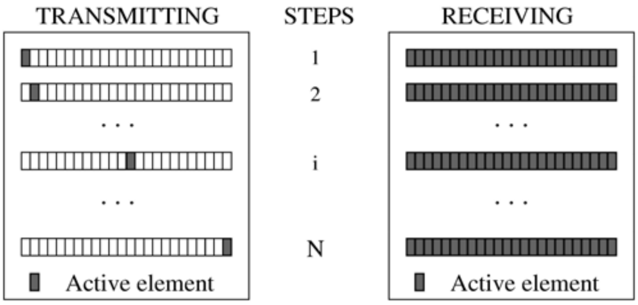

Fig. 1 Transmitting and receiving in the STA method

In the STA method focusing is performed by finding the geometric distance from the transmitting element to the imaging point and back to the receiving element. The structure of the synthetic aperture and geometric relation between the transmit and receive element combination and the focal point is shown in Fig. 2.

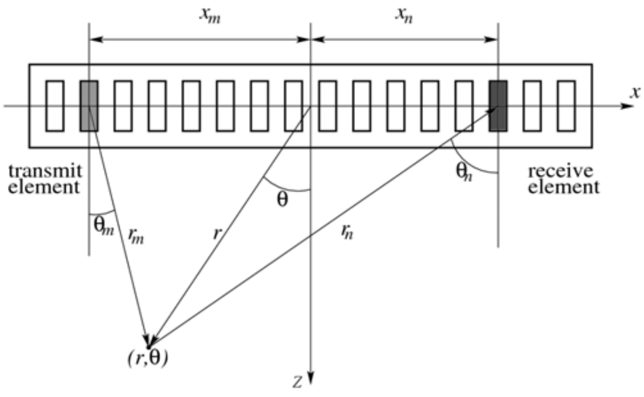

Fig. 2 Geometric relation between the transmit and receive element combination and the focal point in the STA method

When a short pulse is transmitted by element *m* and the echo signal is received by element *n*, as shown in Fig. 2, a round-trip delay is

$$\tau_{m,n} = \tau_m + \tau_n \,, \tag{1}$$

where (m, n) is a transmit and receive element combination, $0 \le m, n \le N-1$.

The delays for *m*'th element and *n*'th element are

$$\begin{aligned} \tau_m &= \frac{1}{c}\left(r - \sqrt{x_m^2 + r^2 - 2x_m r \sin\theta} \right) \\ \tau_n &= \frac{1}{c}\left(r - \sqrt{x_n^2 + r^2 - 2x_n r \sin\theta} \right) \end{aligned} , \tag{2}$$

where x_m, x_n are the positions of the *m*'th and *n*'th elements, respectively and r is a distance between the synthetic aperture center and the point (r,θ). For an N-element array for each point in an image, the A-scan signal can be expressed as

$$A(r,\theta) = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} y_{m,n}\left(\frac{2r}{c} - \tau_{m,n} \right), \tag{3}$$

where $y_{m,n}(t)$ is the echo signal and $\tau_{m,n}$ is the beamforming delay for the (m, n) receive and transmit element combination given in (1). The first and second summations correspond to transmit and receive beamforming.

B. Multi-element Synthetic Transmit Aperture

The MSTA imaging method represents the best solution in improving the lateral resolution and penetration depth. It is known that the lateral resolution can be improved by increasing array length. Only a small number of elements Ns is used to transmit a pulse but all array elements receive the echo signals. In practice, it is not very expensive to build a large transmit aperture, but it is very complex to form a large receive aperture. For a transmit pulse (from all transmit subaperture elements), the RF echoes for all receive elements are stored in memory. When all RF echo signals have been acquired, the total RF sum is formed by coherently adding them.

The MSTA method is proposed to increase the system frame rate and the speed of the image acquisition which is determined by the number of transmissions M (Fig. 3). At each time a few elements are used to transmit an unfocused wave, and all the elements receive the backscattered signal independently. Thus, for N-element aperture, M×N data recordings are required for image reconstruction, where $M=N/Ns$ is the number of emissions, $M \ll N$.

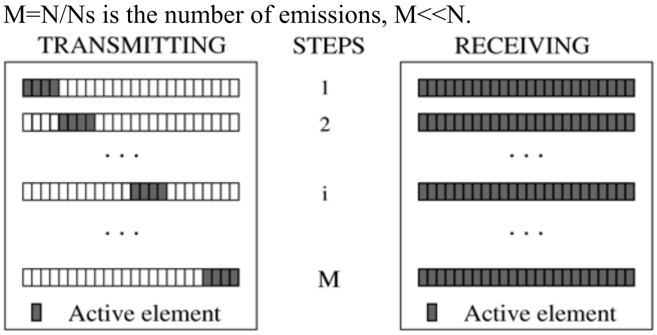

Fig. 3 Transmitting and receiving in the MSTA method

The geometrical locations of the transmit elements in a multi-element array system impact the radiation pattern of that system and as a result the lateral resolution of the image, whereas the number of active transmit elements directly influences the transmitted energy and the SNR. These parameters define the ultrasound image quality. Therefore, the optimization of a MSTA imaging system can be formulated as an optimization problem of the location and the number of transmit elements. The main optimization criterion in this method is the maximum penetration depth without decreasing the lateral resolution. This optimization leads to increasing image penetration depth and high lateral resolution.

Fig. 4 shows the geometry of the transmission and the reception for the MSTA system, where (r, θ) is the point of focus.

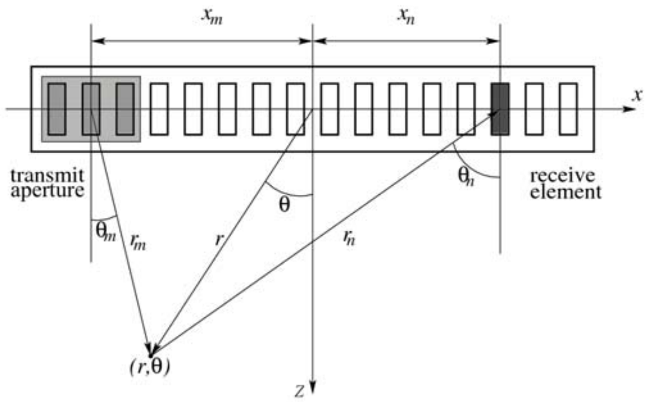

Fig. 4 Geometric relation between the transmit and receive element combination and the focal point in MSTA method

A round-trip delay $\tau_{m,n}$ can be obtained in a similar way as for the STA method and for every image point (r, θ) the A-scan signal is

$$A(r,\theta) = \sum_{m=1}^{M}\sum_{n=1}^{N} y_{m,n}\left(\frac{2r}{c} - \tau_{m,n}\right). \tag{4}$$

III. Element Directivity Diagram Influence

Generally, in the MSTA method it is assumed that for each point in the resulting image every combination of transmit-receive pairs contributes according to the round-trip propagation time only. The angular dependence is not taken into account in the applied point-like source model. Unfortunately, the element size of modern probes is often comparable to the wavelength of the emitted signal. This disqualifies the point-like source assumption making it inaccurate for the above operating conditions. The element directivity influences the partial contribution to the resulting signal $A(r, \theta)$ in (4) depending on the mutual position of the imaging point and transmit-receive pair, determined by the angles θ_m, θ_n (see Fig. 4). In [3] the STA algorithm which takes into account a single element directivity for RF echoes correction was discussed in the form of weighed summation of properly delayed RF echoes:

$$A(r,\theta) = \sum_{m=1}^{M}\sum_{n=1}^{N} f(\theta_m) f(\theta_n) y_{m,n}\left(\frac{2r}{c} - \tau_{m,n}\right), \tag{5}$$

where $\theta_i(r,\theta)$, $i=m,n$ are the corresponding observation angles for the transmit-receive pair. Note, that the angles depend on the spatial location of the imaging point (r,θ). Since in the STA algorithm both the transmit and receive apertures are the single-element ones, in the proposed modification for the sake of simplicity the narrow strip transducer directivity function was used as the weight function $f(\theta_i)$, $i=m,n$. It can be calculated in the far-field approximation for a single element of the transducer array in an analogous manner as in [5]:

$$f(\theta) = \frac{\sin(\pi d/\lambda \sin\theta)}{\pi d/\lambda \sin\theta}\cos\theta, \tag{6}$$

where d is the element width, and λ is the wavelength. Some examples of the directivity function evaluated from (6) for different parameters d/λ are shown in Fig. 2.

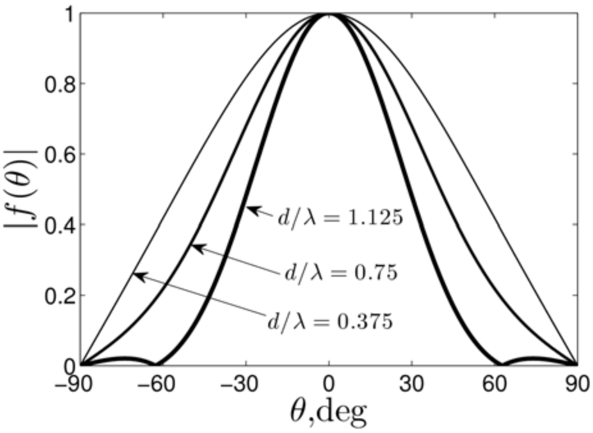

Fig. 5 Directivity function for different values of d/λ

The above result applies to a narrow strip transducer with a time harmonic uniform pressure distribution along its width. It is obtained by means of the Rayleigh-Sommerfeld formula in the far-field region. In the case of MSTA method which is discussed here, the analytic formula (6) cannot be used for evaluation of directivity function of the multi-element transmit aperture, although it can be applied to compute the weights for the single-element receive aperture. However, here the results of the solution of the mixed boundary-value problem for periodic system of baffles [6] will be used in order to evaluate the corresponding directivity functions.

IV. Ultrasound Imaging System

A simplified block diagram of the experimental setup used in this work is shown in Fig. 6.

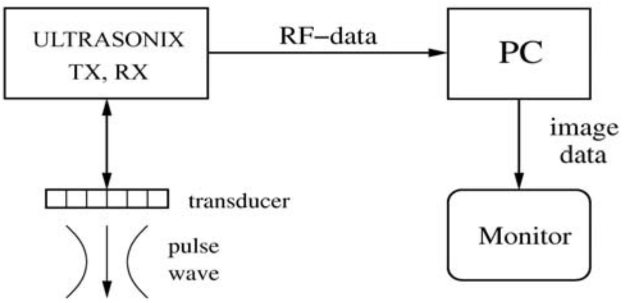

Fig. 6 Block diagram of the ultrasound imaging system

It's main part is an Ultrasonix - SonixTOUCH Research System (Ultrasonix Medical Corporation, Canada) equipped with a 128-element linear transducer array with 0.3 mm pitch. Ultrasonix enables a full control of transmission and reception parameters for all 128 elements of the transducer. Besides, a full access to raw RF data enables one to send it to the PC for further digital processing. Next, the processed data are displayed on the monitor. All post processing and display is done on PC using Matlab®. The processing creates 2D ultrasound image focused in every point.

In synthetic aperture imaging all scan lines (full image) are created in each and every firing, while in standard beamforming only a single line is created. The amount of raw RF data needed in the STA algorithm for an *N*-element ultrasound transducer for reconstruction of a single image is proportional to $D_{RF} * M * N$ and the number of delay-and-sum operations is $D_{RF} * M * N^2$, where D_{RF} is the number of samples in a single RF line. Thus, for the 128-element array, used in experiments, for 10 cm penetration (D_{RF} = 5500 at 40 MHz sampling frequency) storage requirements is $\approx$ 90*10^6 samples or $\approx$ 0.7 Gb of RAM (for 8 bytes per sample in Matlab® double precision format). And the total number of delay-and-sum operations in the STA image reconstruction algorithm is $\approx$11.5*10^9.

V. Computer Simulation

Simulation is a fundamental way of testing methods. This is done to confirm or reject an hypothesis in a controlled environment. Since it is possible to control all parameters in a simulation, one can set up a simple model and then gradually transform it into something more similar to reality. Once this is done one can continue with measurements and confirm or reject the simulations for a real setup, in vivo or on a phantom. All simulations in this work are carried out in a powerful software, *Field II*.

To simulate a measurement numerous parameters have to be set. The transducer used in the measurements described later is the linear transducer L14-5/38. The parameters used in the simulations are similar to those of the transducer. The medium in the simulations is homogenous and such parameters as the attenuation and the speed of sound were set to be the same as in experiments.

2D ultrasound image of phantom for 128-element linear transducer array with 0.3 mm inter-element spacing and half-cycle burst pulse at nominal frequency 4 MHz obtained by the computer simulation is shown in Fig. 7. The phantom medium attenuation is 0.5 dB/[MHz×cm] and consists of a collection of point targets spaced 32 pitches apart laterally and the collections themselves are spaced 5 mm apart axially.

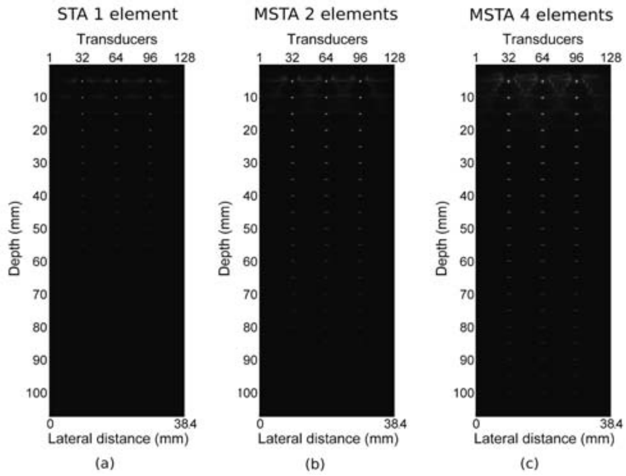

Fig. 7 Comparison of 2D ultrasound images obtained by computer simulation for 128-element linear transducer array using: (a) the STA method; (b) the MSTA method with 2-element transmit subaperture; (c) the MSTA method with 4-element transmit subaperture

It can be easily seen, that the penetration depth for the STA method in which 1 element transmits is equal to 4 cm (Fig. 7 (a)) while in the case of the MSTA method with 4-elements transmit subaperture (Fig. 7 (c)) the penetration depth increases up to 9 cm while maintaining resolution.

Fig. 8 shows the change of the amplitude of the echo obtained from the reflectors located at different depths depending on the size of the transmit subaperture. The medium attenuation is 0.5 dB/[MHz×cm] and consists of point targets spaced 10 mm axially.

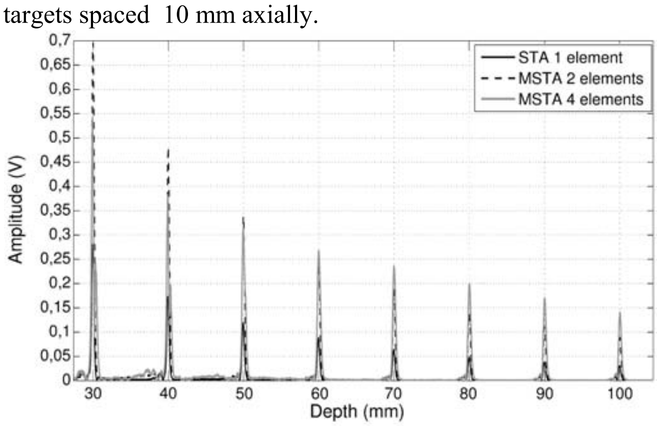

Fig. 8 Change of the amplitude of the echo signal depending on the size of the transmit subaperture. The normalization is performed with respect to the maximum values of each line

From Fig. 8 it can be seen, that to examine objects located up to 5 cm the optimal subaperture is 2-element wide, but for objects located deeper the optimal transmit subapeture is 4-element wide.

For the objective comparison of the lateral resolution the cross sections at the depths of 3 cm and 10 cm (Fig. 7) are shown in Fig. 9.

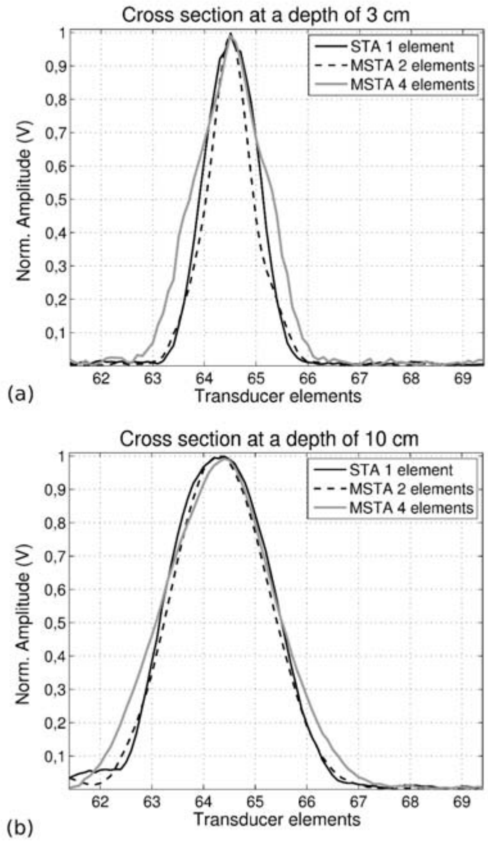

Fig. 9 Comparison of the main-lobe widths for different transmit subapertures at a depth of: (a) 3 cm; (b) 10 cm. The normalization is performed with respect to the maximum values of the corresponding cross sections at different depths

VI. Experimental Results and Discussion

The 128-element linear transducer array with 0.3 mm pitch and a burst pulse with time duration 125 ns (a half-cycle at nominal frequency 4 MHz) were used in the experiments. The pitch is about 0.8λ. All elements were used for both transmitting and receiving. The comparison of the STA and the MSTA methods was performed. In the case of the STA method a single element in the transducer transmitting aperture was used to generate an ultrasound wave covering the full image region. In the case of the MSTA method two and four element transmit subapertures were implemented. This gives a total of 64×128 RF-lines in the case of 2-element transmit subaperture, or 32×128 in the case of 4-element one (128×128 in the case of the STA method). The RF echo signals sampled independently at 40 MHz and processed by the corresponding MSTA and STA algorithms.

The tissue mimicking phantom model 525 Danish Phantom Design with attenuation of background material 0.5 dB/[MHz×cm] was used in the experiments. It consists of several nylon filaments twists 0.1 mm in diameter positioned every 1 cm axially. This phantom allows to examine the axial and lateral resolution at various depths in the ultrasound image.

The comparison of the 2D ultrasound images of the tissue phantom obtained by the conventional STA and the MSTA methods are shown in Fig. 10.

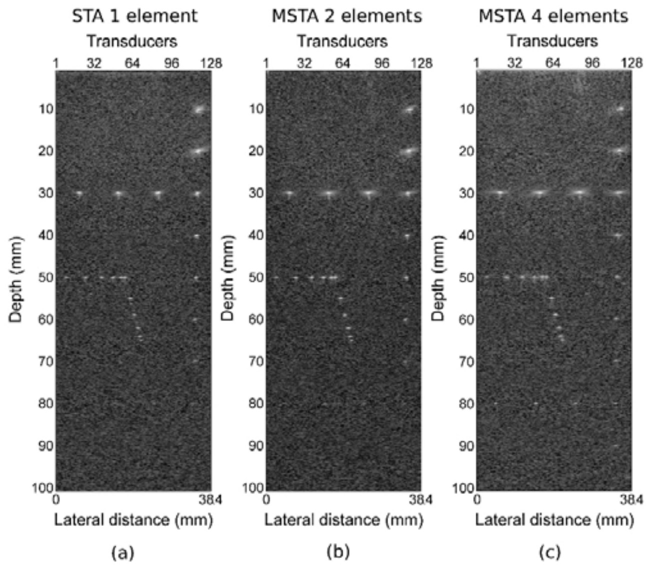

Fig. 10 2D ultrasound images of tissue mimicking phantom using: (a) the STA method; (b) the MSTA method with 2-element transmit subaperture; (c) the MSTA method with 4-element transmit subaperture

The obtained 2D ultrasound images clearly demonstrate the advantage of the MSTA method. With the enlargement of the transmit subaperture the acoustical power increases yielding higher SNR, that leads to an increase in the penetration depth maintaining both axial and lateral resolution. The latter strongly depends on the transducer acoustic field and is discussed in [7].

The results in Fig. 10 confirm the ones obtained in the computer simulations that to examine the objects located not deep, in given case up to 4 cm, the 2-element transmit subaperture (Fig. 10 (b)) is optimal, because the image resolution is the same as for the STA method (Fig. 10 (a)) but the time needed to reconstruct the image decreases twice. To examine objects located deeper, in considered case from 4 cm up to 10 cm, the 4-element transmit subaperture (Fig. 10 (c)) is optimal. In this case, the penetration depth increases maintaining image resolution. It is to be noted, that the frame rate increases four times increases in comparison to the STA method.

In order to compare quantitatively the SNR gain the 116th line from 128 RF-lines of the 2D ultrasound images shown in Fig. 10 are depicted in Fig. 11 and the SNR is calculated. For this purpose the noise level which appeared straight after the signal was chosen.

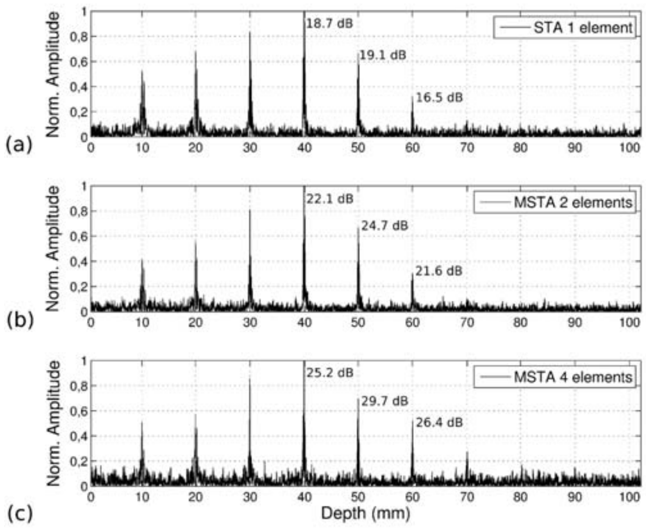

Fig. 11 The RF-lines of the tissue mimicking phantom using: a) the STA method; b) the MSTA method with 2-element transmit subaperture; c) the MSTA method with 4-element transmit subaperture

Fig. 11 shows that two times elongated transmit subaperture improves the SNR by about 5 dB that in its turn leads to improvement of the penetration depth and the contrast of the synthesized image.

VII. Conclusion

The work presents the investigation of the multi-element transmit aperture algorithm for ultrasound imaging. The main concern of the paper is the optimal choice of transmit aperture size providing the best compromise between the lateral resolution and penetration depth of the resulting 2D ultrasound image. This approach allows to increase the system frame rate that is very important in clinical examination of dynamically organs moving, e.g. heart.

In this work it has been shown, that two times elongated transmit aperture can improve the SNR by approximately 5 dB maintaining the same imaging resolution as compared to the conventional STA. This, in its turn, makes the ultrasound image more contrast.

The MSTA method can be applied in a standard ultrasound scanner. Introduction of this method in medical ultrasound would increase the efficiency and quality of the ultrasound diagnostic.

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