High frame-rate and high resolution medical imaging using adaptive beamforming

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Abstract—Recently, significant improvement in image quality has been demonstrated by applying the minimum variance (MV) beamformer to medical ultrasound imaging. In this paper we show that the low sidelobe level and narrow beamwidth of the MV beamformer can be utilized, not only to increase resolution, but to enhance image quality in several ways: Fewer and wider transmit beams combined with increased number of parallel receive beams may be used to increase frame rate. We demonstrate that the resolution obtained using an MV beamformer is equal to a conventional beamformed image of wire targets, using 1/4th of the number of transmit beams and four parallel receive beams, potentially increasing the frame-rate by a factor four. The enhanced resolution of the MV beamformer may also be utilized to decrease the number of focal zones required to form a high resolution image. We demonstrate better resolution using one focal zone with an MV beamformer, compared to full dynamic focus using DAS. Finally, we show that by lowering the frequency of the transmitted beam and beamforming the received data with the adaptive beamformer, increased depth of penetration is achieved without sacrificing lateral resolution.

I. INTRODUCTION

Several authors have applied the minimum variance (MV) adaptive beamformer to medical ultrasound imaging and shown significant improvement in image quality [1], [2], [3], [4], [5]. We have previously shown reduction in mainlobe width and decrease in sidelobe level and demonstrated increased resolution in medical images using the MV beamformer [4].

In this paper we show how the properties of the MV beamformer can be utilized to increase frame-rate and increase depth of penetration in medical imaging without sacrificing resolution compared to delay-and-sum (DAS). We demonstrate that higher frame-rate can be achieved in two ways: By using fewer and wider transmit beams combined with an increased number of parallel receive beams processed with the MV beamformer, increased frame-rate can be achieved without sacrificing image quality. Also, the high resolution of the MV beamformer allows fewer focal zones, giving a potential increase in frame-rate.

Due to the narrow beamwidth of the MV beamformer, the center frequency of the transmit beam can be lowered without reducing the lateral resolution. This gives increased depth of penetration in attenuating media without sacrificing image quality.

In the next section we present how we applied the MV beamformer to medical ultrasound imaging, and present three ways to utilize its properties to enhance image quality. In Section III we show results from each of the proposed enhancements, and draw conclusions from our findings in Section IV.

II. METHOD

A. Minimum variance beamformer

We consider a transducer consisting of $M$ channels, each recording a signal $x_m(t)$ per scan-line. We assume that each channel has been delayed to focus dynamically at points along the scan-line. The $M$ observations are ordered in a vector

$$X(t) = \begin{bmatrix} x_0(t) \\ x_1(t) \\ \vdots \\ x_{M-1}(t) \end{bmatrix}. \quad (1)$$

The output of the beamformer is a weighted sum of the delayed measurements,$$z(t) = \sum_{m=0}^{M-1} w_m(t)x_m(t) = w(t)^H X(t), \quad (2)$$

where $w_m(t)$ is the aperture weight for sensor $m$ at time $t$, and $w(t) = [w_0(t) \ w_1(t) \ \cdots \ w_{M-1}(t)]^H$. The MV beamformer minimizes the variance of the output of the beamformer [6], [7],

$$P(t) = E[|z(t)|^2], \quad (3)$$

while maintaining unit gain in the focal point. This gives the optimization problem

$$\min_{w(t)} w(t)^H R(t) w(t) \quad (4)$$

subject to $w(t)^H a = 1$, \quad (5)

where

$$R(t) = E \left[ X(t)X(t)^H \right] \quad (6)$$
is the spatial covariance matrix and $a$ is the equivalent of the steering vector in narrowband applications. Since the data already have been delayed to focus at the point of interest, $a$ is simply a vector of ones. The solution to (5) is [7]

$$w(t) = \frac{R(t)^{-1}a}{a^HR(t)^{-1}a}, \quad (7)$$

Applying the weights in (7) to (2) gives the MV amplitude estimate.

In practice the covariance matrix, $R(t)$, in (7) is replaced by the sample covariance matrix, $\hat{R}(t)$. To obtain a good estimate, we use spatial smoothing [8], where the array is divided into overlapping subarrays, and the covariance matrices for all subarrays are averaged. This technique is also used to avoid signal cancellation when signals are correlated. The estimated covariance matrix at time $t$ then becomes

$$\hat{R}(t) = \frac{1}{M-L+1} \sum_{i=0}^{M-L} \hat{X}_i(t)\hat{X}_i^H(t), \quad (8)$$

where

$$\hat{X}_i(t) = \begin{bmatrix} x_i(t) \\ x_{i+1}(t) \\ \vdots \\ x_{i+L-1}(t) \end{bmatrix}, \quad (9)$$

and $L$ is the subarray length. After computation of the optimal aperture weights using the sample covariance matrix, we obtain the amplitude estimate as

$$z(t) = \frac{1}{M-L+1} \sum_{i=0}^{M-L} w(t)^H\hat{X}_i(t). \quad (10)$$

The choice of $L$ affects the performance the MV beamformer. A smaller $L$ gives poorer resolution, but an increasingly robust amplitude estimate.

B. Increasing frame-rate

We propose to utilize the high resolution of the MV beamformer to increase frame-rate without sacrificing resolution. Fewer and wider transmit beams combined with multiple parallel receive beams can be used to increase frame-rate in medical imaging. However, using conventional beamforming, there exists a trade-off between image quality and frame-rate, as wider transmit beams leads to lower resolution. We will show in Section III that by using an MV beamformer on reception, the resolution lost from the wide transmit beams can be compensated for.

A high-quality medical ultrasound image may be obtained using many focal zones. Using DAS beamforming we must trade off frame-rate for image quality, as increasing the number of focal zones leads to a reduction in frame-rate. In Section III we show that targets that are out of focus are may be equally well resolved using an MV beamformer, demonstrating that the number of focal zones can be decreased.

C. Increasing depth of penetration

We achieve increased depth of penetration in attenuating media if the frequency of the transmitted beam is reduced. This is because high frequencies are attenuated more than low. Lowering the transmit frequency will however affect resolution in the image, so by using a DAS beamformer penetration depth must be traded off for resolution. In the following section we show that the resolution lost by lowering the transmit frequency can be compensated for using an MV beamformer on reception. The axial resolution is however also affected, but is usually much better than the lateral resolution, so a reduction can be afforded.

III. Results

We have simulated a 96 element, 4MHz, 18.5 mm transducer, imaging wire targets using Field II [9]. All transmitter and receiver combinations were simulated, allowing dynamic focus on both transmission and reception. The depth of the wire targets ranged from 30 mm to 80 mm, and the wires were separated by 3 mm. The following results show simulations from the three proposed enhancements using the MV beamformer.

A. Parallel receive beams

Fig. 1 shows images of the wire targets obtained with DAS and MV beamforming. The MV image was formed with 1/4th of the number of transmission lines as the DAS image, using a wider transmit beam and four parallel receive beams. We chose the number of scan lines to be twice the number required from the Rayleigh criterion, to avoid potential amplitude loss if targets appear between scan lines. The wider transmit beam was achieved using only 1/4th of the available transducer elements. The loss in amplitude due to fewer transmit elements was compensated for. We see that the wires are resolved in both images, and that the mainlobe width is approximately the same. Fig. 2 shows the lateral resolution at depths 50 and 80 mm. We see that the resolution is approximately the same. The mainlobe is lower for the MV beamformer at 80 mm. The lateral resolution of DAS using four receive beams has been included for reference.

B. Decreasing the number of focal zones

Fig. 3 compares a DAS image using full dynamic focus to an MV image using one focal zone. The focal depth was 50 mm. We see that the resolution is better for the MV beamformer, even though only a single focal zone was used. Fig. 4 shows the lateral resolution at 50 and 70 mm. We see that the mainlobe is narrower and the sidelobes are lower for the MV beamformer at both depths. The amplitude is however lower, since the targets are out of focus of the transmission beam.
C. Depth of penetration

Fig. 5 compares the images obtained when we included attenuation in the simulations. The attenuation was 0.5 dB/cm/MHz. Figure (a) shows the image obtained using DAS with a 4 MHz transducer. Figure (b) shows the corresponding MV image using a 2 MHz transducer with the same size and number of elements. We see that the lateral resolution in the images is about the same. We also see that the reflections from the deeper targets are attenuated in the DAS image. From the steered responses in Fig. 6 we see that amplitude is about 10 dB lower using 4 MHz transmission at 70 mm, showing that increased depth of penetration is achieved without sacrificing lateral resolution using an MV beamformer.

IV. Conclusion

We have shown that the MV beamformer may be applied to medical ultrasound imaging to increase frame-rate or depth of penetration. On simulated images of wire targets we have demonstrated potential increase in frame-rate by a factor four without loss of resolution. We have also shown that the resolution achieved using one focal zone and the MV beamformer was better than DAS using full dynamic focus. This also shows potential for increased frame-rate. Finally, we have demonstrated increased depth of penetration by lowering the transmit frequency and applying the MV beamformer on reception. At half the transmit frequency, the lateral resolution was the same as for DAS, and about 10 dB gain was achieved for the deeper targets.

REFERENCES

Fig. 4. Steered responses of DAS and MV beamformers using an 18.5 mm, 96 element, 4 MHz transducer: DAS (solid) using full dynamic focus and MV (solid with diamonds) using one focal zone (focal depth 50 mm). The reduced amplitude in the MV response is due to targets being out of focus (a) 40 mm (b) 70 mm depth.

Fig. 5. Simulated wire targets using an 18.5 mm, 96 element transducer. (a) DAS (4 MHz) (b) MV (2 MHz).

Fig. 6. Steered responses of DAS and MV beamformers using an 18.5 mm, 96 element transducer. DAS (solid) used 4 MHz as transmit frequency, while MV (solid with diamonds) used 2 MHz (a) 50 mm (b) 80 mm depth.


