Ultrasound Imaging: Beamforming Techniques

Soufiane Dangoury[1][a], Mohammed Sadik[1][b], Abdelhakim Alali[2] and Saad Abouzahir[1][c]
[1] *High School of Electrical and Mechanical Engineering (ENSEM) - Hassan II University of Casablanca, Morocco*
[2] *Ben M'Sik faculty of Science - Hassan II University of Casablanca, Morocco*

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Abstract: Ultrasound medical imaging continues to progress and allows practitioners to have a fundamental tool to make a good diagnosis and be able to take the best decisions for different medical fields and contributes to the improvement of the medical examination of different diseases. Researchers continue to develop approaches to improve the quality of the ultrasound image. Images generated by the ultrasound system requires high spatial resolutions for a better detection of the organs boundaries. However, images generated by the system suffers from artefacts (e.g. side lobs, grate lobs. etc) which negatively impact the quality of the ultrasound image. Several approaches have been proposed to enhance the spatial resolutions; however, their performances differ depending on the degree of artefacts. In this paper we present three methods of beamforming which has a serious role in the process of US image generation. The first one concern delay-and-sum (DAS) algorithm which is the most commonly used as beamformer , the second is an extension of DAS (DMAS: Delay Multiply and Sum) and the last one is MVB (Minimum Variance Beamforming) technic. the results show the difference between the three beamforming methods. We try in this work to identify thehiglights and limits of each of these methods.

1 INTRODUCTION

Ultrasound medical imaging is an imaging technique for exploring the inner structures of the human body. Up to date, several sophisticated imaging techniques has been developed to provide better quality images. Indeed, ultrasound is still used due to its simplicity and safety for practitioners and patients as it does not rely on ionizing radiation and has no negative impact on vital organs. However, the drawbacks of the ultrasound imaging reside in the quality of the signal which suffer from artefacts, and its accuracy depends on the skills of the practitioner. Several works have been carried out to improve the quality of the ultrasound image.

The delay and sum (DAS) technic is a part of non-adaptive beamformer, it improves the resolution easily around the focal point but with a greater depth, the method becomes ineffective, because of off-axis interference (Hoskins, 2010).

Authors in (Holfort, Gran & Jensen, 2009) propose an adaptive beamformer technic to overcome the depth issues as the minimum variance beamforming (MVB); their approach relies on the reduction of the interference, but it has also its limits, the SNR of the received signals decrease.

Authors in (Haji and al, 2018) take advantage of the promising results of MV for harmonic imaging.

The authors in (Nguyen and Prager, 2016) show that bidirectional pixel-based focusing (BiPBF) leads to improve the SNR of the image signals especially in the regions far from the focal points; this improves the contrast of the images.

Authors in (Asl and Deylami, 2018), propose a method based on dominant mode rejection (DMR), that approximate the covariance matrix using only some of the largest dominant modes in the dominant subspace; this method does not need a full matrix inversion which reduces the computation realized in normal case of the minimum variance beamforming (MVB) but with closed results. In (Matrone, and al, 2015) propose a non-adaptive method which slightly similar to DAS, the Delay-Multiply-And-Sum

[a] https://orcid.org/0000-0000-0000-0000
[b] https://orcid.org/0000-0000-0000-0000
[c] https://orcid.org/0000-0000-0000-0000

(DMAS) provides an interest point spread function than DAS.

Our contribution in this paper consists of a comparing of three mostly used methods in US imaging (DAS, DMAS and MV) and show their advantage and limits. We use, in this study, some metrics like FWHM end PSL to evaluate these methods graphically.

This paper is organized as follows: In section II, we explain the basic concept of beamforming by focusing on the DAS method. Section III will be dedicated to the presentation of the DMAS method. In section IV, a description of the Minimum Variance beamforming (MVB) method is given. The section V, will focus on a discussion of the three methods and their strengths and weaknesses and limits. And in last section, we conclude by dressing some issues for next exploration explore.

2 THE BASIC ASPECTS OF ULTRASOUND BEAMS

First, the lateral resolution is high when the width of the beam of ultrasound is narrow (Asl and Deylami, 2018).

So, there is a trade-off between the lateral resolution and the width of the beam. The shape of the ultrasound beam is important for detecting more details along all the image depths, but unfortunately, it is difficult to control easily the beams' shape because the diverges rapidly after being transmit.

2.1 Focusing

This technique makes it possible to focus the beam on one point at a given scan line chosen by the operator and making the beam very narrow and concentrate more power on the corresponding points, this is more likely to increase the lateral resolution considerably in the chosen region. However, this negatively impact the frame rate as it is computationally intensive. This issue can be resolved by shifting the active group of elements by cancelling one element from one side end and enabling a new one to the other.

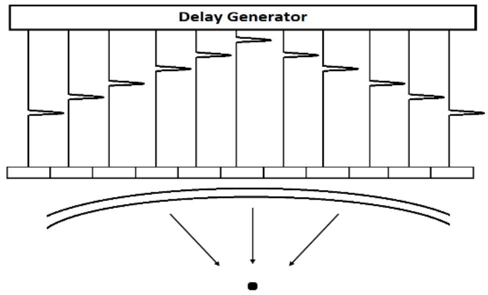

Figure 1: Beam technic principle.

As we can see in Figure 1, all the transmitted pulses from the active aperture must arrive simultaneously at one point. This is achieved by controlling the excitation delay between different element.

According to (Hoskins, 2010) Among the most used beamforming methods in commercialized ultrasound the delay and sum (DAS) beamformer due the simplicity it presents when setting up which is simply based on obtaining the radio frequency signal from different channel by summing them after applying an appropriate delay.

2.2 Delay and Sum Beamforming Method

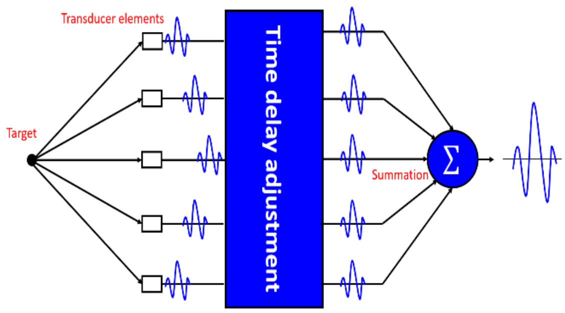

Figure 2: Simplified schematic of DAS.

When we are receiving echo signals from a point all the receives signals form the active aperture must be summed together to produce the final signal to the considered scan line in this same time and we can achieve that by controlling delay between different element consist the aperture.

DAS technic beamformer is easy to apply and robust in noisy environments, meanwhile, it performs well in real-time ultrasound imaging (Hoskins, 2010). Although, the resulting signal suffers from trade-off between the main lobe level and the side lobe width (Haji and al, 2018). Improving the image quality of ultrasound system has become the focus of many researchers in this field (Mohades and al, 2018).

The DAS-beamformed formula is obtained as:

$$y_{DAS}(t) = \sum_{j=0}^{N} S_i(\mathrm{t} - \Delta t_j) \qquad (1)$$

Where y_{DAS} is the received signal at the j'th scan; N is the number of active elements, and Δtj is the delay time applied to the received signal of the j'th scan (Jongin and al, 2016).

2.3 Apodization

Apodization is a process of beam forming, it can be used in both transmit and receive beamforming. This process consists of giving different weightings to transmit or received signals from different elements constituting the active part of the probe (aperture). In transmitting, an element is excited more than other, and in receiving one signal is more amplified than the other. It leads to improve CNR by reducing side-lobe and clutter but we lose in fitness of the focal zone and therefore it reduced the lateral resolution, however several methods has been proposed to solve this problem like constrained least squares (CLS), dual-apodization with cross-correlation (DAX) methods (Jin and Jong, 2014).

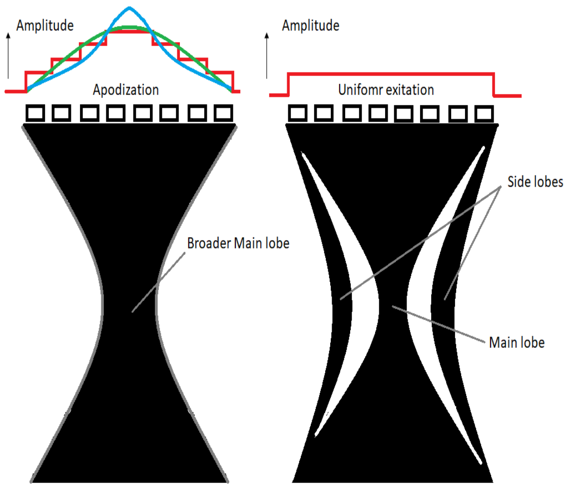

Figure 3: A uniform excitation and non-uniform excitation (Apodization).

3 DELAY MULTIPLY AND SUM METHOD

The Delay Multiply AND Sum (DMAS) method can be defined as a non-linear beamformer, which consist of computing the received aperture spatial autocorrelation. The method was proposed to be used in ultrasound B-mode imaging as in (Matrone and al, 2016), (Nguyen and Prager, 2016). The method is also called F-DMAS, because of its role to enhance the clutter rejection and contrast resolution by decreasing the pulse-echo beam side lobes and make narrow the main lobe.

According to (Matrone and al, 2016), its operation is close to the computation of the aperture spatial resolution function. DMAS beamforming relies on the measure of the backscattered signal coherence and provides enhanced noise rejection and contrast/lateral resolution compared to the conventional DAS (Jin and Jong, 2014), (Matrone and al, 2016).

This is an improved version of DAS; it relies on the same principle to apply delays on the signals received by different element according to their geometrical position in the probe to make signals in phase. In the basic form of DMAS the signals are multiplied by each other before the summation which is considered mathematically like an autocorrelation function. That means, at each time, the spatial cross-correlation of the received signals acquired by the active transducers. Which make DMAS beamforming algorithm a nonlinear method (Matrone and al, 2016).

The DMAS-beamformed formula is obtained as follow:

$$\boldsymbol{y_{DMAS}(t) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} S_i(t) S_j(t)}$$

The number of multiplications that they must be realized is: $\frac{N^2-N}{2}$

Where Si represent the RF delayed voltage signal received by the ith transducer and yDAS is the DMAS-beamformed output. This formula presents a problem related to the presence of a squared in dimension signals [Volt] 2.

3.1 Improved Version of (DMAS) Beamformer

In (Matrone and al, 2016) authors propose to insert more processing steps into the original DMAS. They introduce the "equivalent RF-signal" which apply "signed" square root to each couple in the summation, then scale the amplitude of each multiplication term to similar dimensionality of the RF signal, while preserving the sign.

$$y^*_{DMAS} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{s}_{ij}(t)$$

$$= sign(s_i(t)s_j(t)).\sqrt{|s_i(t)s_j(t)|}$$

$$= \sum_{n=1}^{\frac{N^2-N}{2}} \hat{s}_n(t)$$

3.2 Filtered-delay Multiply and Sum Beamforming

$$\boldsymbol{y_{F-DMAS}(t) = h_{BP}(t) * y_{DMAS}(t)}$$

The hBP denotes the bandpass (BP) filter it includes to operation addition and subtraction of frequency in the result of the multiplication. Then, after the multiplication between RF data Si(xi) and Sj(xi), the frequency bands f0 + f0 = 2f0 and f0- f0 = 0 are formed. The BP filter reduces the second band while maintains the first high-frequency band for the resulting signal of the F-DMAS algorithm (Park and al, 2016).

4 MINIMUM VARIANCE BEAMFORMER METHODE

All the carried worked in this field aim to eliminate the interference and noise components from received signals by applying the beamforming. The pre-computed weights in the DAS approach are not capable the reach the goal. The MV beamformer can delete insignificant signals as it is minimizing the variance of the beamformer output (Matrone, 2018).

Supposing that y (k) is the delayed signal from a specific point of the image located at k, which is recorded by i-th element of an M-element array, in this case the beamformer output can be written as:

$$y(t) = w^H(t)x_d(t) = \sum_{i=1}^{M} w_i^*(t)x_i(t-\Delta_i)$$

we denote by w(t) = [w1(t);…..;wi(t)]T $\in C^{M\times 1}$ is the complex vector of beamformer weights, (.)T is the transpose, (.)H is conjugate transpose, and Δi is the delay time on the i_{th} transducer to focus at a specific point in the image.

Minimum variance beamformer optimizes the power of the output signal while keeping a distortion less response to the desired signal originating from the focal point of the receiver.

$$\min_w w^H R\, w$$

$$\min_w \boldsymbol{w^H R\, w} \quad \text{subject} \quad \text{to} \quad \boldsymbol{w^H a} = 1$$

where R = E[x_d x_{dH}] is the M×M array covariance matrix and a is the desired signal steering vector.

The solution is given by

$$w_{MV} = \frac{R^{-1}a}{a^H R^{-1} a}$$

In It should be noted here that in practice, R is unavailable, hence, the sample covariance matrix (SCM) is used:

$$\hat{R} = \frac{1}{N}\sum_{n=1}^{N} x_d(n)x_d(n)^H$$

Resulting from N recently received samples is used in instead of the true covariance matrix (Asl and Deylami, 2018).

4.1 Additional Factors

In adaptive beamforming techniques, an accurate estimation of the covariance matrix R and an enhancement in the contrast is highly standing, then some common steps are adding to the treatment process.

4.1.1 Diagonal Loading

Diagonal loading (DL) consists of adding a noise signal into the sample covariance matrix $\hat{R}$ precisely it adds a constant to the diagonal values of the estimated covariance matrix. thereby improves the stability and to provide robustness to the algorithm. In this technique $\hat{R}$ replaced with $\boldsymbol{\hat{R} = \hat{R} + \varepsilon I}$ where ε is the loading factor Commonly, the equations for ε are:

$$\varepsilon = \frac{1}{\Delta * \mathrm{L}} tr\{\boldsymbol{\hat{R}}\}$$

where $tr\{.\}$ is the trace of the sample covariance matrix, and the Δ is a fixed number.

4.1.2 Time Smoothing

In order to enhance the stability of the sample covariance matrix $\hat{R}$, with the use of the echo data, that is represented by k, will also add the echo data around k to calculate $\hat{R}$. Thus, the sample covariance matrix $\hat{R}$ is defined by as follow:

$$\hat{R} = \frac{1}{2\mathrm{K}+1}\Sigma_{\mathrm{k}=-\mathrm{K}}^{\mathrm{K}} X(\mathrm{k})X(\mathrm{k})^{\mathrm{H}}$$

where 2K+1 is the echo data number used to build the sample covariance matrix $\hat{R}$. For adaptive beamforming, the 2K+1 is usually less than the width of the transmitted ultrasound pulse.

Time smoothing algorithm is equivalent to entire image smoothing, which will reduce the lateral resolution. And increased matrix calculations will greatly improve the computational demand of $\hat{R}$, thus, improving the computing complexity of algorithm.

4.1.3 Coherence Factor Weighting

To attenuate the side-lobe level and improve the robustness of the beamformer the coherence factor (CF) weighting considered as useful parameter. CF technique is an adaptive weighting method. It is defined as the ratio between the coherent and incoherent sums obtains in a DAS beamformer.

$$\mathrm{CF}(k) = \frac{\left|\sum_{m=1}^{M} \mathrm{x_d}(m,k)\right|^2}{M\sum_{m=1}^{M}\left|\mathrm{x_d}(m,k)\right|^2}$$

where k represent the time index, $\mathrm{x}d(m,\ k)$ is the received signal at channel m after applying a proper delays. Thus, the CF is the ratio of main lobe energy to the total energy, and it is used as an index of focusing quality (Jensen, 1996).

The value added by using the coherence factor are between 0 and 1.

The implemented beamforming equation using the above factors leads to the following equation of our signal:

$$y(k) = \frac{\mathrm{CF}(k)}{M-L+1}\sum_{l=1}^{M-L+1} W^H(k)X_d^l(k)$$

5 EVALUATION RESULTS

In the simulation, height rang of targets were located at 3.5 mm to 7.5 mm, 0.5 mm between them in the axial direction. The simulation parameters are described in Table 1. The input signal was a sinusoidal wave with 2 cycles. A 96 element 40 MHz linear array transducer was designed as shown in Table 1.

The dynamic receiving will be used to keep the f-number constant (depth of focus in tissue divided by width of aperture) and that is achieved by expanding the aperture while the receive focus is advanced and by this way we keep the lateral resolution constant along all the foci.

5.1 Description of the Phantom

In the simulation, height rang of targets were located at 3.5 mm to 7.5 mm, 0.5 mm between them in the axial direction. The simulation parameters are described in Table 1. The input signal was a sinusoidal wave with 2 cycles. A 96 element 40 MHz linear array transducer was designed as shown in Table 1

Table 1: Simulation Parameters.

Parameters	Value
Total Number of Elements	96
Number of Elements	96
Number of Scanlines	204
Center Frequency [MHz]	40
Element Pitch [µm]	40
Speed of Sound [m/s] 1	1500

5.2 B-mode Image

After applying each method onto the received radio frequency data. The images are then normalized by itself, after that the envelope of the signal will be extracted. A log compression is used with a dynamic range of 60 dB. After passing through this process the final image of each from the studied methods will be show,

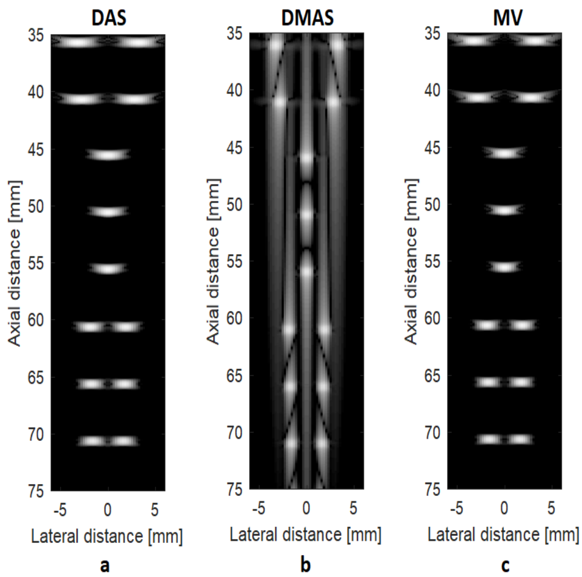

Figure 4: F-DMAS beamformer block-diagram.

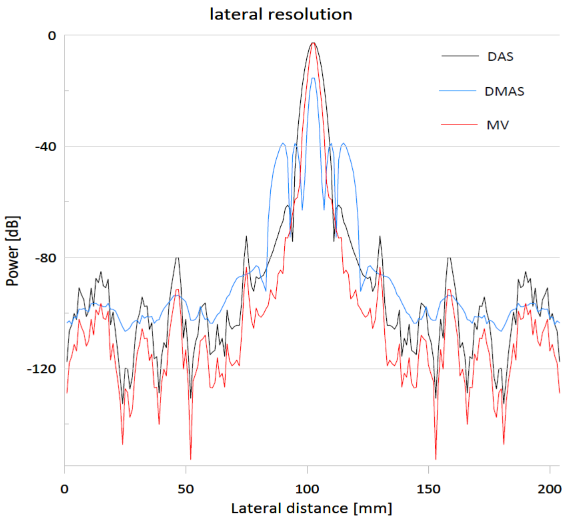

Figure 5: Lateral variation of DAS, DAMS and MV

The performance of the aforementioned techniques is estimated using the Peak-Side-Lob and Full-Width at Half Maximum (FWHM) values (PSL), we choice randomly the depth of 57 mm for the evaluation in this paper,

Table 2: FWHM and PSL od the different used techniques.

Parameters	FWHM (mm)	PSL
DAS	1.53	-2.82
DMAS	0.98	-15.53
MV	1.23	-2.88

6 CONCLUSION

From the lateral resolution we notice clearly that the minimum variance beamforming shows the good performance the main-lobe becomes very narrow as long as the amplitude stays high however DAS beamforming provides a good amplitude but the main-lobe is still wide which gives a poor resolution as we have already described

unfortunately, the DMAS technique shows a poor performance given the time it takes to give the result. although the main lobe is very narrow but note to the huge loss in contrast due to the degradation in terms of signal amplitude as well as the sidelobes which are not well attenuated like the case of MV and DAS.

for this paper, the study was limited to the basic aspect of its methods which can be improved as well as the use of metrics like FWHM and PSL which judges very well the different techniques possible in this field.

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