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The Effect of the Imaging Parameters on the Performance of Coherence Factor in Plane-Wave Imaging

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***Abstract* -** Beamforming methods are usually presented and examined in the literature using specific imaging equipment and settings. However, the performance of any beamforming method is usually affected by imaging parameters such as the central frequency, transducer width and imaging depth. This paper shows how the weighting method of the Coherence Factor (CF) is affected by those three imaging parameters. CF is applied to DAS beamformer for Point Spread Function (PSF) imaging using Field II simulations. Results show that the amount of improvement added by CF to lateral resolution is higher at low central frequencies, transducer widths and at high penetration depths. Studies of such relations help to professionally selecting imaging equipment at various circumstances and limitations.

***Keywords*:** coherence factor, DAS, beamforming, lateral resolution, FWHM

1. Introduction

In order to improve imaging quality during beamforming operation that yields B-mode images from RF-data, many techniques are suggested in the literature. One of these techniques is the use of data-dependent weighting for the beamformer output. The most common weight is the Coherence Factor (CF), which is mainly used to highly improve imaging resolution and reducing cidelobes. CF is calculated by dividing the coherent sum of delayed RF-data by its incoherent sum. This yields high CF values (≈1) at points with high reflectivity, while points with low coherency will have low CF, resembling points at the sidelobe regions and background speckle which is usually inhomogeneous.

Coherence Factor was first invented by Hollman et al. in 1999 [1] as a measure of signal's coherency in ultrasound imaging. Since then, CF started to be widely used for enhancing ultrasound imaging quality by being combined with different beamforming methods in addition to DAS such as MV [2] and DMAS [3], [4]. In addition, various types of modifications were applied to CF, resulting in new coherence-based factors such as the Generalized CF (GCF) [5], Sign CF (SCF) [6], Scaled CF (scCF) [7], High Resolution CF (HRCF) [8] and other types. Those types however could add very little or no change to the quality improvement achieved using original CF, as confirmed by two studies that compared among various coherence-based factors for ultrasound imaging in 2017 [9] and 2020 [10].

A wide range of options for ultrasound imaging systems have become recently accessible. This makes it essential to specify the most important imaging feature so that a suitable imaging system is selected. Studies that clarify the level of improvement found from various system settings are helpful in making such decisions. The effect of a number of imaging system parameters on spatial resolution in PWI is studied in [11], using DAS beamformer, without considering the effect of CF. The effect of changing imaging depth on the performance of CF in terms of LR is presented in [3]. This study however did not give any information on the effect of other parameters on CF.

This work shows how the coherence factor affects imaging quality in form of spatial resolution at different central frequencies, different transducer widths and at a range of penetration depths. Section 2 provides a description of the background methodology behind DAS beamforming and Coherence Factor. Specifications used through simulations are described in section 3. In sections 4 and 5, results are given and discussed respectively, and finally the paper is concluded in section 6.

2. Methodology

Plane-Wave Imaging is performed by transmitting unfocused beams and performing beamforming on the received RF-data. Beamforming in this work is carried out using Delay-And-Sum (DAS) beamformer where the output of the beamformer is found, as the name indicates, by adding the delayed RF-data as in the following formula [12]:

$$P(x,z) = \sum_{j=1}^{N} T_j(t, \tau_j(x,z)) , \qquad \dots \ (1)$$

where $p(x,z)$ is the focal point, x and z are the axial and lateral distances of the point, respectively. s is the number of the transducer elements, $T_j(t)$ is the RF-data received by the j[th] element, delayed by the focusing delay (τ_j) according to the location of the point.

When a coherence-based factor is used, its value is multiplied by the beamformer output. This requires calculating a value for this factor for every focal point separately from the delayed RF-data found during beamforming, using [9]:

$$CF = \frac{\left|\sum_{m=0}^{N-1} x_m(n)\right|^2}{N\sum_{m=0}^{N-1} |xm(n)|^2} , \qquad \dots (2)$$

where x_m is a vector resembling the delayed RF-data of focal point.

3. Simulations and Measurements

In this work, the amount of improvement added by CF to lateral resolution (LR) at different central frequencies, imaging depths and number of elements is evaluated. This evaluation is based on the measurements of the Full Width at Half Maximum (FWHM) of PSFs. First, resolution is measured for a PSF at the 25 mm depth using a range of central frequencies from 1 MHz to 9 MHz. Then, measurements are repeated for the points from 15 mm to 40 mm depths with a step of 5 mm, using a central frequency of 5 MHz and a number of elements of 128 elements. The third type of resolution measurements are performed for the PSF at the 25 mm depth, with a central frequency of 5 MHz using various transducer widths, where width is changed by increasing the number of elements from 64 to 256 elements, while fixing element width to 0.3048e-3.

A Matlab function that calculates the values of the CF for all the points in the image grid is used. This function calculates a CF value for all image points in the same time (without for loops), using matrix operations property provided by Matlab.

Matlab with the help of Field II simulation program is used to perform simulations. Field II works under Matlab and includes all the required functions for simulating ultrasound imaging operations and mediums. The use of linear array transducer is assumed throughout simulations. The target imaging quality metric depending on which the performance of CF is evaluated is LR. Therefore, PSF imaging is used for quality evaluation using six points positioned at the centre of the transducer surface at depths from 15 mm to 40 mm with a step of 5 mm. LR is measured using Full Width at Half Maximum (FWHM), which resembles the main lobe width at the -6dB amplitude drop from the peak.

4. Results

LR measurements using various imaging parameters are given in this section, where LR curves are plotted with and without the use of CF when changing each of the three studied parameters separately. The amount of improvement added by CF to LR in each case is also plotted.

Figure 1 shows the amount of improvement in LR with increasing central frequency for the point lying at the 25mm depth. Those measurements are taken using a 128-element transducer. It is known that increasing central frequency improves LR, and the use of CF adds further improvement to it. This amount of improvement is higher at lower frequencies, where the use of CF with a central frequency of 3MHz provides nearly the same resolution when using 5MHz frequency with no CF.

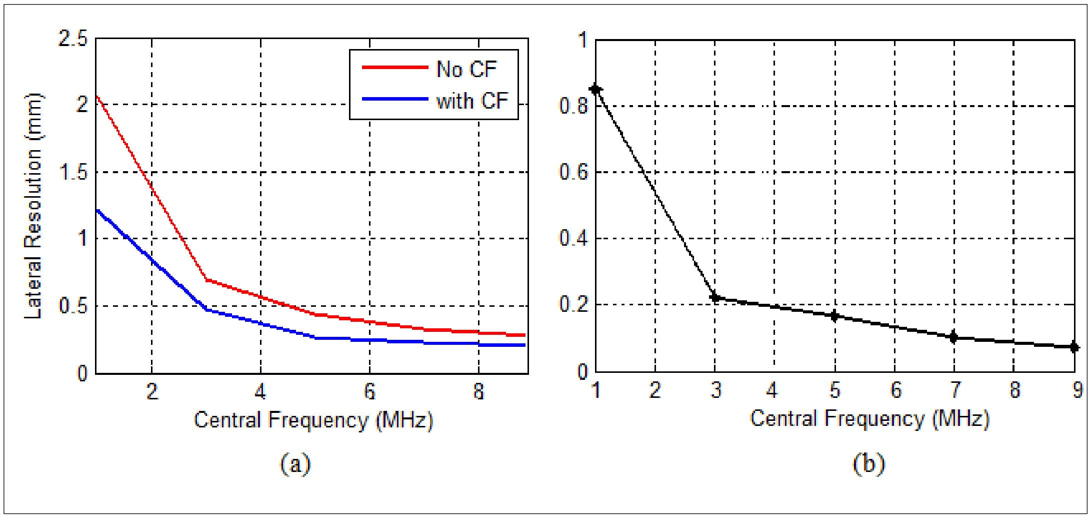

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Fig. 1: (a) Lateral resolution measured at the 25 mm depth vs. central frequency. (b) The amount of improvement added by CF to lateral resolution at the 25 mm depth vs. central frequency. The simulated transducer has 128 elements.

When going deeper, LR gets reduced as illustrated in figure 2a. This figure shows that FWHM is doubled when going from 15 mm to less than 40 mm depth (i.e. a reduction to the half for LR). Using CF adds a significant improvement to lateral resolution measurements, which at the 40mm depth gives the same resolution as that achieved at the 22 mm depth without CF. It can be interestingly noticed from figure 2b that when penetration depth increases, CF performance increases too, with a linear change from less than 0.1 mm at the 15 mm depth to 0.2 mm at the 40 mm depth. Figure 3 shows the simulated B-mode images of PSFs at a range of central frequency values using DAS-CF.

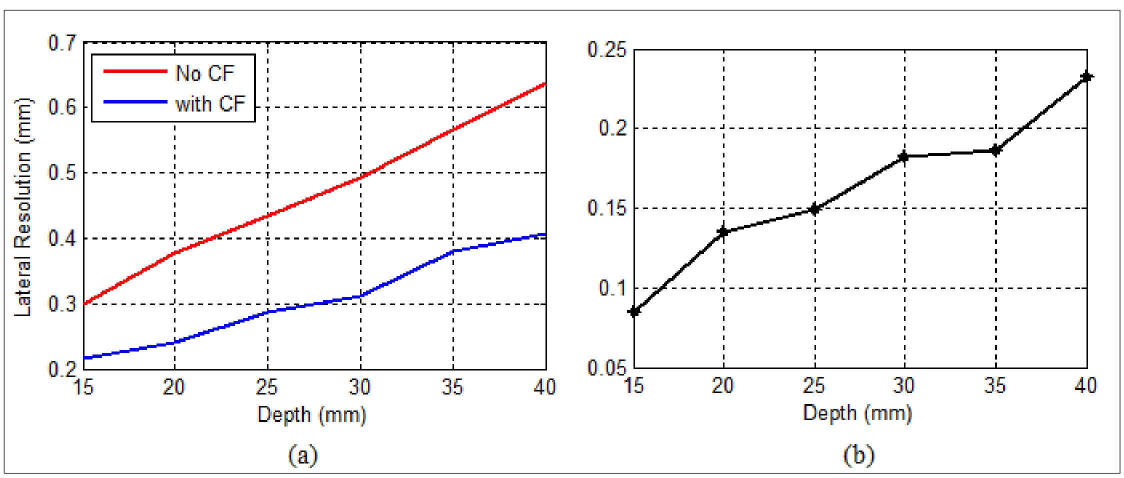

Fig. 2: (a) Lateral resolution measured using a 5 MHz central frequency vs. imaging depth. (b) The amount of improvement added by CF to lateral resolution at a range of imaging depths. The simulated transducer has 128 elements.

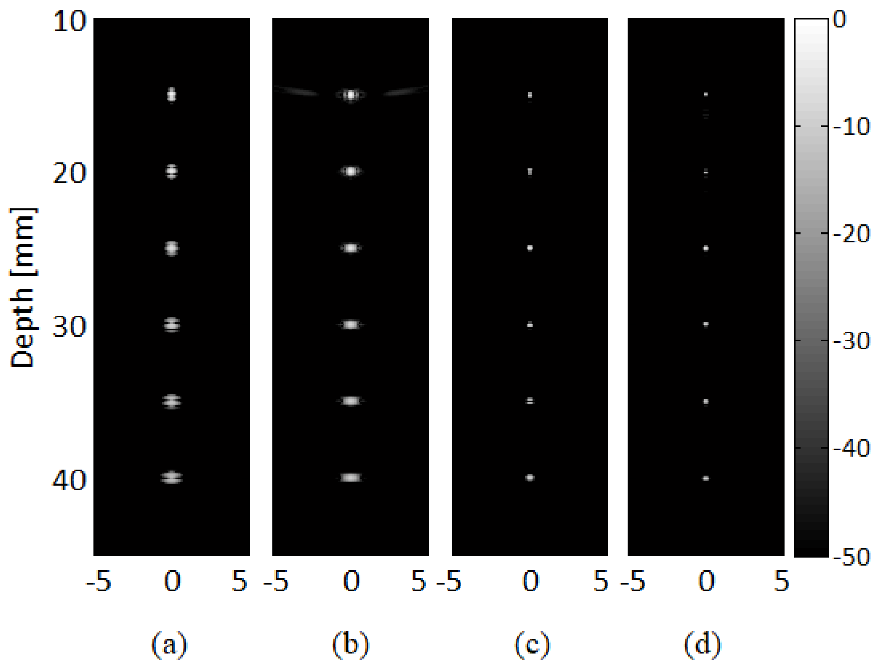

Fig. 3: Simulated B-mode images of PSFs using: (a) 3MHz (b) 5MHz (c) 7MHz and (d) 9MHz central frequency. All images have a dynamic range of 60dB.

It is illustrated in figure 4 that increasing the width of the used transducer by increasing the total number of elements results in improved resolution, and with the presence of CF resolution is further improved. A 0.5mm LR achieved using 256-element transducer can be also achieved using a transducer with only 128 elements when CF is used.

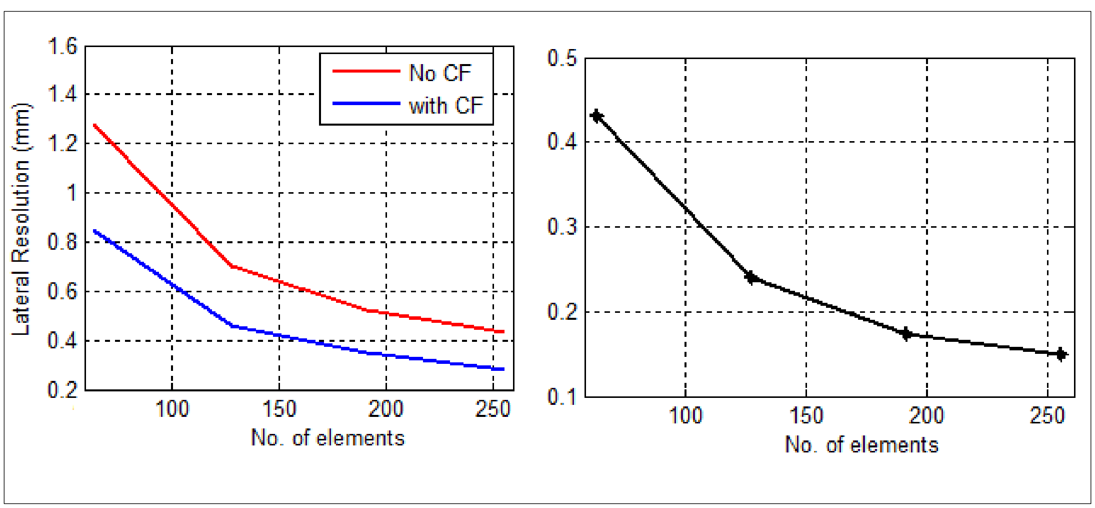

Fig. 4: (a) Lateral resolution measurements at the 25mm depth vs. number of elements. (b) The amount of improvement added by CF to lateral resolution at the 25mm depth vs. number of elements. The used central frequency is 5MHz.

5. Discussion

The use of CF for improving LR in medical ultrasound imaging is usually accompanied with producing dark spots at the sidelobe and background speckle areas, which is known as Black Box Regions (BBR). It is important thus to evaluate the amount of improvement added by CF at different circumstances to avoid unnecessary degrade in imaging quality and possibly apply CF to only specific parts of the image. Central frequency of the transmitted signal is one of the parameters that remarkably affect imaging quality. As in figure 1a, increasing central frequency results in a dramatic improvement in LR, and when CF is added, LR is further improved. However, as in figure 1b, the amount of improvement added by CF becomes less as central frequency increases. This is because LR is already remarkably improved so that values of less than 0.5 mm are achieved at frequencies of larger than 5MHz.

The reduced amount of intensity reaching deep imaging areas results in wider mainlobes and thus lowers LR. This is where the presence of CF becomes more effective as in figure 2a, where it is shown that LR is improved by more than the third at the depth of 40mm using CF. This is because in contrast to DAS that depends on the intensity level of the received RF-data to specify amplitudes, CF is able to distinguish coherent signals even when low intensity levels are achieved, by depending mainly on the ratio between coherent and incoherent sums of the received RF-data, as in eq. (2).

As the number of elements in the transducer increases, LR becomes higher. This is due to the increased amount of beamformed data. The value of the CF is also improved with this factor as the number of delayed values increases. This improves LR and in the same time reduces the effect of off-axis signals during the calculation of CF according to equation (2), resulting in reduced dark spots and reduced BBRs.

Optimizing ultrasound imaging quality is a combination of the selection of suitable equipment, imaging technique and beamforming, in addition to being done by a professional sonographer. In specific imaging circumstances, the use of narrow transducers is necessary to provide a complete contact between transducer surface and the body and prevent air gabs in between. This can be compensated for during beamforming, through the use of CF which can provide a similar imaging resolution to that achievable with wider transducers.

6. Conclusions

CF adds a noticeable difference to the quality of ultrasound images measured with LR at the circumstances where low central frequencies, high penetration depths or narrow transducers are used. This is because at these cases, LR is highly degraded and the use of data dependent weighting methods such as CF during beamforming makes an obvious difference. Otherwise when LR is high, the use of coherence-based factors becomes negligible because of adding very little or no change to quality.

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