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# Improving quality of high-frame-rate imaging with coherent and incoherent processing

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***Abstract* – High-frame-rate (HFR) imaging methods using delay-and-sum (D&S), steered plane waves (SPW), and limited-diffraction beams (LDB) have been studied in 1990s. In the HFR imaging methods, multiple transmissions can be used to obtain sub-images that can be combined coherently or incoherently to form a final frame of image.**

**Coherent superposition of sub-images can obtain images of a high image contrast and resolution but has a low signal-to-noise (SNR) ratio on speckle. In opposite, incoherently-superposed images have low image contrast and resolution but have a high SNR.**

**To maintain high image contrast and resolution of the coherently-superposed images while also having the high SNR of the incoherently-superposed images, a new imaging method using coherent and incoherent processing is developed. In this method, a ratio image is first obtained by dividing the incoherently-superposed image with the coherently-superposed image. Then, the ratio image is used in a nonlinear process to obtain the final image that is a combination of the coherently- and incoherently-superposed images.**

**To verify the method, an experiment was performed with a home-made HFR imaging system and the results show that the new method can obtain high image contrast and resolution while having a high SNR. Due to its simplicity, the method has a potential to be incorporated into existing commercial imaging systems to obtain high contrast, high resolution, and low speckle images. The high SNR may also improve the accuracy of image segmentations for various applications.**

**Keywords -** ***High-Frame-Rate Imaging, Coherent Processing, Incoherent Processing, Steered Plane Wave, Limited-Diffraction Beams***

## I. INTRODUCTION

In 1990s, a high-frame-rate (HFR) two-dimensional (2D) and three-dimensional (3D) imaging method using single plane wave [1][2] or multiple plane waves steered at different angles (see Fig. 8 of [2]) in transmission was developed, where both the Delay-and-Sum (D&S) (see Fig. 5 of [2]) and Fourier-based (see Fig. 4 of [2]) methods were used to reconstruct images. The Fourier-based image reconstruction method was developed from the theory of limited-diffraction beam (LDB) [1]. One of the advantages of the Fourier-based image reconstructions is that the amount of computations can be reduced as compared to the D&S method, especially, in 3D imaging. In 2006, the HFR imaging method was further studied in terms of steered plane wave (SPW) in transmissions and extended to LDB in transmissions [3]-[6].

Because fewer transmissions can be used to reconstruct images, high image frame rate (or high time resolution) can be achieved with the HFR imaging method. Given the advancement in hardware and the development of new applications, recently, the HFR imaging method has gained a renewed interest. The applications of the HFR imaging method include: fast cardiac imaging [5][7]-[8], strain and strain rate imaging [8]-[9], blood flow velocity vector imaging [10]-[13], elasticity imaging [7][14]-[15], supersonic imaging [15], and functional imaging [16], etc.

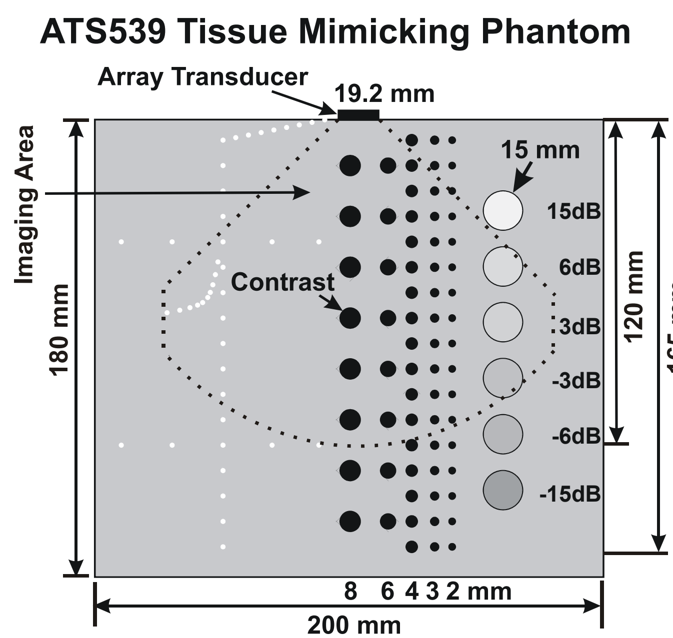


**Figure 1.** A cross-section of an ATS539 tissue-mimicking phantom showing the imaging areas of 120 mm depth with +/-45 degree field of view for the experiments. (Modified from Fig. 4 of [18].).

In the HFR imaging method where either SPW or LDB is used in transmissions, images can be reconstructed with either coherent (increasing image contrast and resolution but having high speckle noise) [3]-[6] or incoherent (reducing speckle noise but lowing image contrast and resolution) [1]-[2][17] superposition of sub-images obtained from different transmissions. In 2017, the incoherent superposition method was studied to reduce the speckle noise at the expenses of reduced image contrast and resolution [17].

In this paper, a nonlinear method that combines images reconstructed with the coherent and incoherent superposition is developed to obtain images of both low speckle noise and high image contrast and resolution.

## II. METHOD

In this method, two HFR images are first reconstructed with the coherent and incoherent superposition of sub-images obtained from different transmissions using the same radio-frequency (RF) echo data. Then, the incoherently-superposed image is divided by the coherently-superposed image to obtain a ratio image that is used to determine the portions of the incoherent image to be modified by the coherent image to obtain the final high-resolution and high-contrast image.

There are many ways that the ratio image can be used to obtain the final images. The first is to set a threshold for the ratio. If the ratio is larger than the threshold, the corresponding value of the pixel of the coherently-superposed image is used to replace that of the incoherently-superposed image. If the threshold is 1.0, the final image will be the same as the coherently-superposed image. If the threshold is infinity, the final image will be the same as that of incoherently-superposed image, i.e., the incoherently-superposed image will not be modified. The results in this paper are from this method due to its simplicity and thus could be easily implemented in existing commercial imaging systems where the D&S and other methods are used for image reconstructions. The threshold may be set to a different value for a different number of transmissions. For example, the threshold was set to 2.5 for 11 transmissions (11 TX), and 3.16 for 91 transmissions (91 TX).

Other ways to use the ratio image have been investigated to obtain the final images, such as, using a block of pixels in the ratio image to determine if the corresponding block of the coherently-superposed image should be used to replace or combine with the pixels of the incoherently-superposed image. Due to a 4-page limit of this paper, the results with these approaches are not shown.

## III. EXPERIMENT

To verify the efficacy of the new method, an experiment was performed with a home-made HFR imaging system [5][6]. In the experiment, a linear phased array transducer of 128 elements, 2.5-MHz center frequency, and about 58% two-way pulse-echo bandwidth was used. The dimensions of the transducer aperture were 19.2-mm (width) and 14-mm (height). An ATS539 tissue-mimicking phantom was used (**Fig. 1**). Images were reconstructed with the Fourier method [1][2]. The dimensions of the reconstructed images of the phantom were 153.6 mm in width and 120 mm in depth. Images were log-compressed at 50 dB dynamic range.

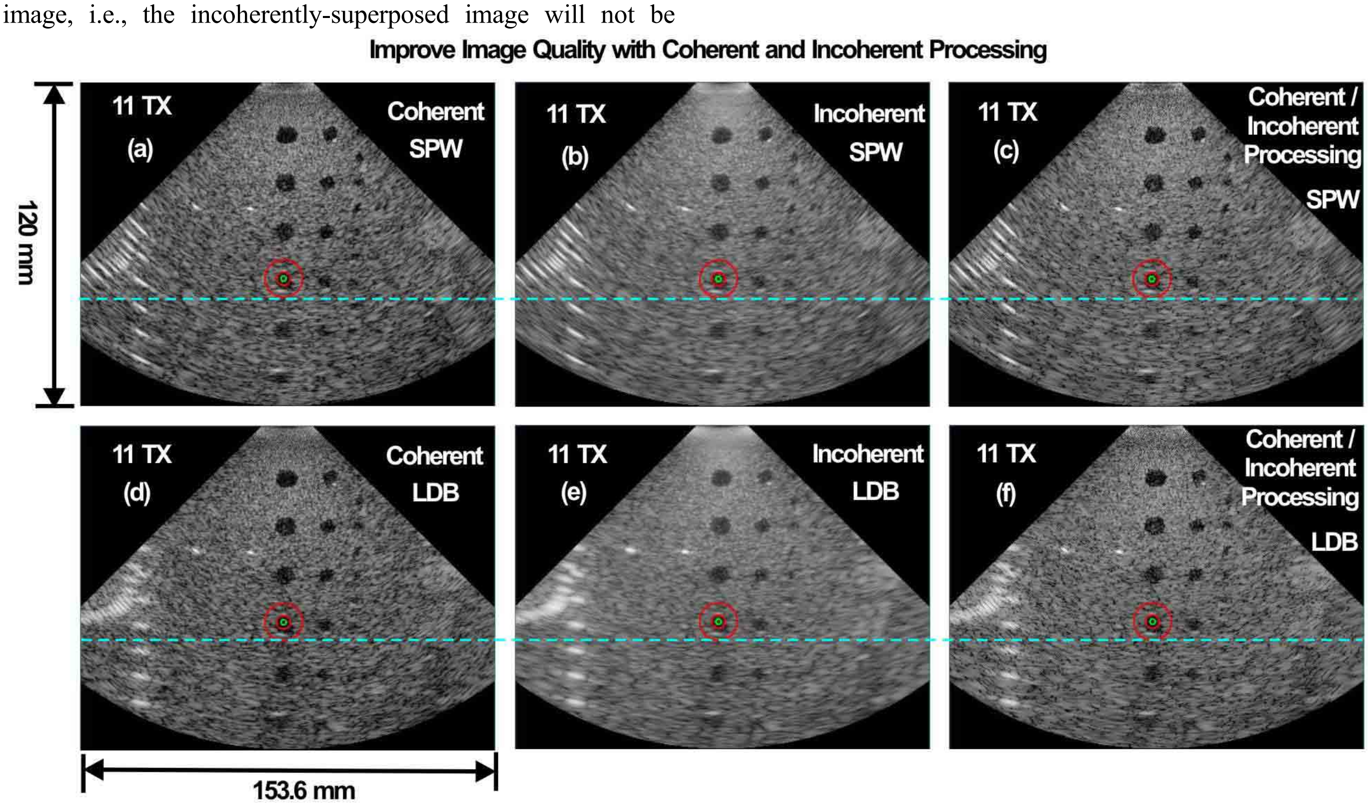


**Figure 2.** Images obtained with the coherent superposition ((a) and (d)), incoheren superposition ((b) and (e)), and the new coherent and incoherent processing ((c) and (f)) using 11 sub-images (corresponding to 11 transmissions or 11 TX) recontructed with the steered plane wave (SPW) ((a), (b), and (c)) and limited-

diffraction-beam (LDB) ((d), (e), and (f)) methods. The threshold for (c) and (f) is 2.5 for the ratio image. The Fourier-based method were used to reconstruct all images [1][2][4][5]. (The results of coherent and incoherent superposition are similar to those of [17].)

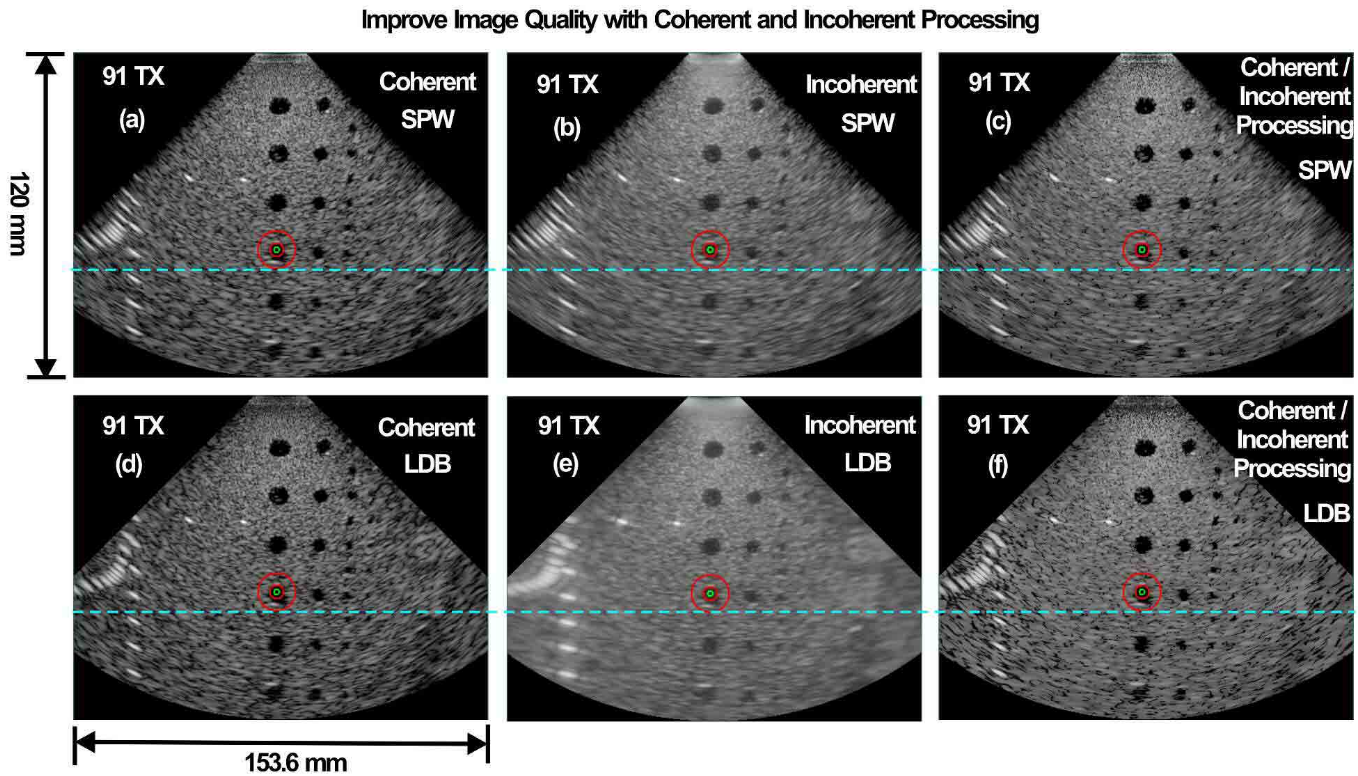


**Figure 3.** Images obtained with the coherent superposition ((a) and (d)), incoheren superposition ((b) and (e)), and the new coherent and incoherent processing ((c) and (f)) using 91 sub-images (corresponding to 91 transmissions or 91 TX) recontructed with the steered plane wave (SPW) ((a), (b), and (c)) and limited-diffraction-beam (LDB) ((d), (e), and (f)) methods. The threshold for (c) and (f) is 3.16 for the ratio image. The Fourier-based method were used to reconstruct all images [1][2][4][5]. (The results of coherent and incoherent superposition are similar to those of [17].)

**Table 1.** Speckle signal-to-noise ratio (SNR) along dashed lines (cyan colored lines in **Figs. 2** and **3**) of images reconstructed with the coherent superposition, incoherent superposition, and the new coherent and incoherent processing of sub-images reconstructed with the steered plane wave (SPW) and limited-diffraction-beam (LDB) methods. Results of both 11 and 91 transmissions are shown. (The results of coherent and incoherent superposition are similar to those of [17].)

| SNR | 11 Transmissions (11 TXs) | | 91 Transmissions (91 TXs) | |
|---|---|---|---|---|
| | SPW | LDB | SPW | LDB |
| Coherent | 39.23 | 45.40 | 41.33 | 39.23 |
| Incoherent | 50.72 | 70.10 | 54.26 | 76.73 |
| Coherent and Incoherent | 43.66 | 52.93 | 50.35 | 48.27 |

**Table 2.** Contrast of the cystic object indicated by the red and green circles in the images (**Figs. 2** and **3**) reconstructed with the coherent superposition, incoherent superposition, and the new coherent and incoherent processing of sub-images reconstructed with the steered plane wave (SPW) and limited-diffraction-beam (LDB) methods. Results of both 11 and 91 transmissionsare are shown. A larger absolute value indicates a higher image contrast. (Cystes have negative contrasts).

| Contrast (dB) | 11 Transmissions (11 TXs) | | 91 Transmissions (91 TXs) | |
|---|---|---|---|---|
| | SPW | LDB | SPW | LDB |
| Coherent | -12.82 | -15.37 | -26.03 | -24.47 |
| Incoherent | -11.27 | -10.52 | -12.85 | -10.99 |
| Coherent and Incoherent | -12.15 | -14.14 | -26.08 | -27.17 |

## IV. Results

Figs. 2 and 3 show images obtained with 11 (11 TX) and 91 (91 TX) transmissions, respectively. In both figures, images reconstructed with SPW and LDB methods are shown in the first (Panels. (a), (b), and (c)) and second (Panels. (d), (e), and (f)) rows, respectively. Images obtained with coherent superposition (Panels. (a) and (d)), incoherent superposition (Panels. (b) and (e)), and the new coherent and incoherent processing (Panels. (c) and (f)) are in the first, second, and third columns, respectively. The signal-to-noise ratio (SNR) and image contrast of the reconstructed images are given in Tables 1 and 2, respectively. The SNR was calculated with the average versus the standard deviation of pixel values along each horizontal dashed line (cyan color) in both Figs. 2 and 3. The contrast (in unit of dB) was calculated by 20 times the logarithm of the ratio between the average of the pixel values within the green circle and the average of pixel values within the two outer rings in both Figs. 2 and 3. All the calculations were performed before the images were log compressed.

Results show that for both 11 and 91 TX, images reconstructed with coherent superposition have the highest image contrast and resolution, but have the lowest SNR on speckle. Images reconstructed with incoherent superposition have the lowest image contrast and resolution, but have the highest SNR. However, images reconstructed with the new coherent and incoherent processing have contrast and resolution close to those of coherently-superposed images while the SNR values are close to those of incoherently-superposed images.

## V. Discussion and Conclusion

Images reconstructed with the new coherent and incoherent processing can obtain high image contrast and resolution while having low speckle noise (high SNR). This method has a potential to be used in existing commercial imaging systems because it is simple and easy to implement (for imaging systems that use the D&S, SPW, or LDB methods for image reconstruction). The high SNR on speckle will improve the accuracy of image segmentations for various applications.

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