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Multi-source and Multi-directional Shear Wave Generation with Intersecting Steered Ultrasound Push Beams

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Abstract

Elasticity imaging is becoming established as a means of assisting in diagnosis of certain diseases. Shear wave-based methods have been developed to perform elasticity measurements in soft tissue. Comb-push ultrasound shear elastography (CUSE) is one of these methods which apply acoustic radiation force to induce the shear wave in soft tissues. CUSE uses multiple ultrasound beams that are transmitted simultaneously to induce multiple shear wave sources into the tissue, with improved shear wave signal-to-noise-ratio (SNR) and increased shear wave imaging frame rate.

We propose a novel method that uses steered push beams (SPB) that can be applied for beam formation for shear wave generation. In CUSE beamforming, either unfocused or focused beams are used to create the propagating shear waves. In SPB methods we use unfocused beams that are steered at specific angles. The interaction of these steered beams causes shear waves to be generated in more of a random nature than in CUSE. The beams are typically steered over a range of $3\text{--}7^\circ$ and can either be steered to the left ($-\theta$) or right ($+\theta$). We performed simulations of 100 configurations using Field II and found the best configurations based on spatial distribution of peaks in the resulting intensity field. The best candidates were ones with a higher number of the intensity peaks distributed over all depths in the simulated beamformed results. Then these optimal configurations were applied on a homogeneous phantom and two different phantoms with inclusions. In one of the inhomogeneous phantoms we studied two spherical inclusions with 10 and 20 mm diameters, and in the other phantom we studied cylindrical inclusions with diameters ranging from 2.53–16.67 mm. We compared these results to those obtained using conventional CUSE with unfocused and focused beams. The mean and standard deviation of the resulting shear wave speeds were used to evaluate the accuracy of the reconstructions by examining bias with nominal values for the phantoms as well as the contrast-to-noise ratio in the inclusion phantom results. In general the CNR was higher and the bias was lower using the SPB method compared to the CUSE realizations except in the largest inclusions. In the cylindrical inclusion with 10.4 mm diameter, the range of CNR in CUSE methods ranged between 18.52 and 22.02 and the bias

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ranged between 5.50 and 11.12% while for SPB methods provided CNR values between 23.07 and 48.90 and bias values between 3.78 and 9.22%. In a smaller cylindrical inclusion with diameter of 4.05 mm, CUSE methods gave CNR between 14.69 and 22.28 and bias ranging between 28.95 and 29.28% while the SPB methods provided CNR values between 16.7 and 25.2 and bias values varying from 25.54 to 30.44%. The SPB method provides a flexible framework to produce shear wave sources that are widely distributed within the field-of-view for robust shear wave speed imaging.

Introduction

The mechanical properties of soft tissue can be characterized using shear wave-based elastography, which is a noninvasive method helping to evaluate the state of tissue health [1]. Ultrasound radiation force can be used to induce motion into tissue, and the resulting shear wave is tracked to characterize the mechanical properties of the tissue, [2, 3]. If we assume that the soft tissues are incompressible, isotropic, linear and elastic, the shear wave propagation speed c_s in tissue can be defined as [3]

$$\mu = \rho c_s^2, \quad (1)$$

where ρ is the mass density and can be assumed for all tissue to be 1000 kg/m³ [4], thus by measuring the shear wave propagation speed it is possible to estimate the shear modulus of tissue.

According to these concepts, different methods have been developed. Sarvazyan, *et al.*, [1] introduced the shear wave elasticity imaging method based on applying radiation force to generate shear waves and measure their propagation. Since this seminal paper, many methods have been developed to distribute the ultrasound intensity in particular ways to change the acoustic radiation force excitation.

Acoustic radiation force impulse (ARFI) methods apply impulsive acoustic radiation force to create shear wave as presented by Nightingale, *et al* [5]. Bercoff, *et al.*, [6] proposed Supersonic Shear Imaging (SSI) which produces a shear wave with sharp wave front and large depth extent from the combination of several separate radiation force pushes positioned at different depths. Chen, *et al.*, [7] developed a method called Shear wave Dispersion Ultrasound Vibrometry, (SDUV), based on measuring the shear wave propagation speed in tissue at multiple frequencies to measure both the elasticity and viscosity quantitatively.

A method called Spatially Modulated Ultrasound Radiation Force (SMURF), used unique methods of apodizing and applying focusing delays to array elements to create a shear wave with a known spatial pattern. This approach was used that to characterize the shear modulus of the tissue [8].

Another method of generating shear waves was performed by applying the crawling wave technique which results from the interference of oscillation of two travelling waves in

opposite directions [9], [10], [11]. This method used both conventionally focused beams as well as axicon beams.

Recently, Zhao, *et al.*, [12] reported using an unfocused beam to perform shear wave speed measurements. While the unfocused beam can provide accurate measurements over a large depth-of-field, the resulting waves have smaller displacement compared to those from a focused beam. To account for this shortcoming, Song, *et al.*, [13] developed a method called Comb push Ultrasound Shear wave Elastography (CUSE), which has the ability to reconstruct a full field-of-view 2D shear wave speed map in only one rapid data acquisition. To generate shear waves in this method, multiple focused or unfocused beams are arranged in a comb pattern (comb-push).

Hybrid beamforming methods presented by Nabavizadeh, *et al.*, [14] combine traditional focusing methods and axicon focusing to induce shear wave in tissue with elongated field of view compared to traditional focused beam forming methods. Recently, Lee, *et al.*, [15] described a new beamforming method to enhance the shear wave motion by using an axicon beam and aperture apodization to create the push beam used to produce the shear wave, which resulted in a higher signal-to-noise ratio (SNR), and thus higher accuracy in shear wave speed estimation.

With any of the aforementioned methods to perform the excitation with acoustic radiation force, the shear wave motion can be analyzed to create an elasticity image. Depending on the excitation, it may be necessary for one or more excitations at different locations to measure the motion throughout the field-of-view (FOV) in order to estimate the shear wave speed at all spatial locations. One main reason for this is that shear wave attenuation in soft tissues can be significant enough to make it difficult to robustly estimate shear wave speed because the motion may be too small to be reliable.

It is therefore a desirable goal to develop a method where shear wave sources can be distributed throughout a FOV so that the effects of shear wave attenuation are diminished. This was one advantage of the CUSE method in terms of distributing shear wave sources within the FOV. However, an even denser distribution of shear wave sources may be able to make better localized shear wave speed measurements.

In this paper we introduce new beamforming methods called Steered Push Beam (SPB) methods. The objective of this method is to create multiple foci generated by the interference of different ultrasound push beams to create shear waves. The method uses segments of an ultrasound aperture and applies steering angles to the segments to create overlapping beams that interfere to create multiple focal points that have sufficient intensity to generate shear waves.

This method can use focused or unfocused push beams and the steering angles can be assigned in a deterministic or random fashion. This is an alternative method to using single or multiple unfocused or focused push beams to generate a shear wave motion field.

The paper will be organized as follows. We will present the methods for designing the ultrasound intensity distributions using deterministic and randomized techniques. We will

present results in phantoms that are homogeneous and have spherical and cylindrical inclusions. The paper will be concluded with a discussion and summary.

Methods

For this SPB method we can consider an ultrasound array transducer, either one-dimensional array or two-dimensional array. For simplicity, we will describe the one-dimensional array case in detail. The aperture of the array transducer consists of N elements. We can divide this aperture into segments of N_s elements. Each segment can have a transmit profile which assigns an apodization weighting to the amplitude of signals applied to the elements in the segment, a steering angle with either positive or negative signed inclination, as well as a delay profile. We will primarily concentrate the descriptions to the use of unfocused beams, but focused beams could be used as well.

These parameters can be determined in a manner to create specific types of beams or configurations, or the parameters can be left for random assignment. We will discuss both the deterministic and random configurations.

Deterministic Configurations

It may be desirable to mimic certain configurations. For example the CUSE method employs push beams that are deterministically placed in the field-of-view (FOV) to create shear waves from known positions [3, 16, 17]. With steering we can also generate beams in specified positions as shown in Fig. 1.

Such an arrangement can be compared between an unfocused CUSE (U-CUSE) configuration and so-called axicon CUSE (AxCUSE) configuration because one of the beams is formed with an axicon-like arrangement using the steering of $+\theta$ and $-\theta$ for adjacent segments of elements [14, 18]. The acoustic radiation force density, $\vec{F}$, in an absorbing medium can be written as

$$\vec{F} = \frac{2\alpha \vec{I}}{c}, \quad (2)$$

where α is the ultrasound attenuation of the medium, $\vec{I}$ is the ultrasound intensity, and c is the ultrasound speed in the medium. It should be noted that the force and intensity are both vector quantities. The force is proportional to the intensity, so the acoustic radiation force distribution can be explored by simulating the ultrasound intensity using a simulation package such as Field II [19, 20] or FOCUS [21–23]. A simulation of the U-CUSE and AxCUSE configurations depicted in Fig. 1 are shown in Fig. 2 for unfocused beams of 16 elements and using $\theta = 3^\circ$. A linear array transducer mimicking the L7-4 transducer (Philips Healthcare, Andover, MA) was used for the simulations using Field II with an ultrasound frequency of 4.0 MHz.

Many parameters such as the number of elements, angle of inclination, positions of beam segments, ultrasound frequency, medium ultrasound attenuation, and transducer geometry

can be varied to optimize the ultrasound intensity distribution for specific applications. Simulations of the intensity distributions can be used to explore this wide parameter space for optimal configurations.

Randomized Configurations

It may be advantageous to generate multiple shear wave sources in the FOV for the purposes of creating a multitude of shear waves that are propagating in the medium. Shear wave attenuation in some materials or tissues can be quite significant so shear wave sources may be spaced too far apart to generate shear waves in certain areas in the FOV. Increasing the number of shear wave sources in the FOV provides a higher probability that all areas of the FOV will encounter a propagating shear wave that can be used for later analysis to estimate shear wave velocity or other parameters related to material characterization of elasticity or viscoelasticity.

One other consideration is that the acoustic output for push beams can be very high. These levels are regulated by the Food and Drug Administration (FDA). To reduce the peak levels of pressure a wider distribution of the ultrasound pressure in the FOV may help to avoid having to reduce input voltage levels and achieve maximum power deposition for shear wave imaging.

As an example let the total number of elements $N = 128$ and the number of elements in a segment be $N_s = 8$. For each segment an angle of inclination can be assigned as either $+\theta$ or $-\theta$. In this example let $\theta = 4^\circ$. The sign of the angle can be randomly assigned such that the signs for each of the segments may be $- - + - - + + - - + - - + +$. The sign of the segments can be determined using a random number generator with a starting seed value applied to the number generator so that previously used seeds can be used to obtain the same result with subsequent simulations.

The time delays applied to the aperture and the resulting ultrasound intensity field are shown in Fig. 3.

In the previous example, the value of θ was fixed and only the sign was allowed to randomly change. Additionally, the value of θ could be allowed to vary over a specified range of values to change the distribution of the intensity in the FOV. In this example, the values of θ were allowed to vary over $[3^\circ, 4^\circ, 5^\circ, 6^\circ]$.

An example of the time delays and resulting ultrasound intensity field is shown in Fig. 4 with the following values for the segments $[-4^\circ, -6^\circ, +6^\circ, -6^\circ, -5^\circ, +3^\circ, +6^\circ, -6^\circ, -5^\circ, -5^\circ, +5^\circ, -5^\circ, -5^\circ, +5^\circ, -5^\circ, +3^\circ]$.

To evaluate for optimal intensity fields we designed an automated method to determine how many foci were created at a given depth in the FOV. The optimal fields will have many foci at each depth such that there are many shear wave sources distributed through depth. For a given intensity field a region in depth was averaged together over 1 mm, though this segment could be larger. In order to evaluate the number of foci, represented by peaks in the intensity, we used an averaged profile, $I_n(x, z)$ using the equation

$$I_m(x, z) = I_n^2(x, z) - \overline{I_n^2(x, z)}, \quad (3)$$

$$\overline{I_n^2(x, z)} = \frac{1}{N_x} \sum_{x=1}^{N_x} I_n^2(x, z), \quad (4)$$

where $\overline{I_n^2(x, z)}$ is the mean of the squared average profile. We used the square intensity instead of the intensity to increase the contrast between the generated peaks within the intensity signal.

Next, we need to assess how many peaks there are at a given depth. One such way is to perform spatial frequency analysis because more peaks in the $I_m(x, z)$ signal will translate into higher spatial frequencies. A spatial Fourier transform was then taken on the signal $I_m(x, z)$ in the x -direction and the peak spatial frequency, k_x , was evaluated. Examples of the $I_m(x, z)$ and their associated spatial Fourier transforms from the intensity distribution shown in Fig. 4(b) at depths of $z = 15, 25, 35$ mm are shown in Fig. 5.

The spatial peak frequency indices are stored (Fig. 6(a)) and then summed over the depths of interest as it has shown in Fig. 6(b), which is 50 mm in this case. In Fig. 6 these spatial peak frequencies were stored for many different configurations of the case where $\theta = [3^\circ, 4^\circ, 5^\circ, 6^\circ]$ by varying the seed value of a random number generator. This sum can be compared against the sums from other configurations. The sum over a specified depth range can be used as the optimization metric. It should be noted that the amplitude of the peaks through the depths was not incorporated in the summation. The spatial frequency of the intensity peaks that serve as shear wave sources was the primary parameter being used to define the optimal configurations. Figure 6 shows the configurations that are chosen among the 101 random cases based on the magnitude of peaks appear in Fig. 6(b) and specified by arrows. The configurations resulting from these peaks are shown in Fig. 7 with the random number (RN) seed values associated with those configurations.

The starting seed value for the random number that generated the maximal sums can be stored for later use in implementing the optimal configuration. This approach was used for finding optimal configurations for implementing for phantom experiments.

Experiments

We performed simulations in Field II [17, 18] to determine optimal random configurations. We used the L7-4 transducer geometry, ultrasound frequency of 4 MHz, $\alpha = 0.5$ dB/cm/MHz, $N = 128$, $N_s = 8$. We implemented the AxCUSE cases with $\theta = 3^\circ, 4^\circ, 5^\circ$. Each tooth used 32 elements. In one case we fixed $\theta = 4^\circ, 5^\circ, 6^\circ$ and only allowed the sign of the angle to be randomly assigned, and these are denoted as fixed angle (FA). In another case we used ranges of $\theta = 3-6^\circ$ and $\theta = 4-7^\circ$ and allowed both the sign and the angle to be randomly assigned, and these are denoted as varied angle (VA). We used starting seed values ranging from 0–100 in MATLAB (The MathWorks, Natick, MA) for the random number generators. We used the algorithm described above to find the optimal configurations for each case and tested them in elastic tissue-mimicking phantoms. In addition to the random configurations,

U-CUSE and focused CUSE (F-CUSE) configurations were also applied. The U-CUSE configuration used 4 teeth of 16 elements separated by 22 elements. The F-CUSE configurations used 4 teeth with 32 elements for each tooth and focal depths of 20, 25, and 30 mm. The optimal configurations are shown in Fig. 8 and are each normalized to the same absolute scale with a dynamic range of 25 dB.

We implemented the optimal configurations on the Verasonics V-1 system (Verasonics, Inc., Redmond, WA). We tested these configurations in a homogeneous phantom with a shear wave velocity of $c_s = 1.55$ m/s (CIRS, Inc., Norfolk, VA) and phantoms with spherical and cylindrical inclusions of different sizes (Models 049 and 049A, CIRS, Inc., Norfolk, VA). We applied the configurations in the CIRS 049 phantom on the Type IV spherical inclusions of diameters of 10 and 20 mm. The background material of the CIRS 049 phantom has a Young's modulus of 25 kPa and the Type IV material has a Young's modulus of 80 kPa. The corresponding shear wave velocities of the background and inclusion materials are 2.89 and 5.16 m/s, respectively, by using the relationship $E=3\rho c_s^2$ assuming that the medium is nearly incompressible. The CIRS 049A phantom has cylindrical inclusions of different diameters. We imaged the inclusions with diameters of 2.53, 4.05, 6.49, 10.40, and 16.67 mm. The background and inclusion materials have shear wave velocities of 3.11 and 5.16 m/s, respectively. A 400 μ s tone burst was used to produce the acoustic radiation force. After the push was completed compound plane wave imaging was used with three angles (-4° , 0° , 4°) for shear wave motion tracking [24]. In-phase/quadrature (IQ) data was saved from the Verasonics. One-dimensional autocorrelation was used to estimate the particle velocity from the IQ data [25].

We processed the data similar to data acquired using CUSE. We applied directional filters to extract the left-to-right (LR) and right-to-left (RL) propagating waves [16]. A two-dimensional shear wave velocity calculation algorithm was used to estimate the shear wave velocity at each location [26]. The shear wave velocity maps from the LR and RL waves were combined similar to the method described by Song, *et al.*, for CUSE [16], which uses cross-correlation to determine the time delays associated with the wave propagation evaluated at different spatial locations. We also calculated the correlation peak width in the results in the homogeneous phantom to evaluate the robustness of the correlation calculations for the different configurations similar to shown in Song, *et al.* [16].

Speed map results for the homogeneous phantom with multiple configurations are shown in Fig. 9. The correlation width maps were constructed in the same way as the speed maps from the directionally filtered data, and were shown in Fig. 10. Table 1 gives the mean and standard deviations for the shear wave velocities and correlation widths measured in the homogeneous phantoms from a large rectangular region-of-interest (ROI) centered in the images (dashed line box in the U-CUSE panel in Fig. 9).

The results for the inclusion phantoms with multiple configurations are shown in Figs. 11–17 for the spherical inclusions with 10 and 20 mm diameters and the cylindrical inclusions with diameters of 2.53, 4.05, 6.49, 10.40, and 16.67 mm, respectively.

Table 2 gives the mean and standard deviations for the shear wave velocities measured in the background and inclusions. Additionally, the contrast-to-noise ratio (CNR) was computed for each inclusion and is listed in Table 2 as well for the different configurations. The CNR was calculated as

$$\text{CNR} = \frac{|c_I - c_B|}{\sigma_B} \quad (5)$$

where c_I and c_B are the mean shear wave velocity values in the inclusion (I) and background (B), respectively, and σ_B is the standard deviation of the shear wave velocity values in the background [16]. The bias of the measurements was evaluated with the nominal shear wave velocities, c_N , given by the phantom manufacturer using

$$\text{Bias} = \frac{c_I - c_N}{c_N} * 100\%. \quad (6)$$

The inclusion ROIs used to measure the CNR and bias were defined with a circle with the same diameter of the inclusion and were defined in the B-mode images. For the background, a square ROI that has sides with length of the diameter of the inclusion was placed above the inclusion for all of the studied inclusions except the one in spherical inclusion with 10 mm diameter (Fig 11) where the square is defined beneath the inclusion. Therefore, the ROI sizes were adapted to the inclusion size. Table 3 provides a summary of the bias evaluated in the two spherical lesions with the different implemented configurations. Table 4 summarizes the estimates of c_B , c_I , and CNR and Table 5 gives the bias values for the different cylindrical inclusions evaluated with the different configurations studied.

Discussion

The image results show that the methods based on using steered push beams can make shear wave velocity images similar to those made by the U-CUSE and F-CUSE implementations. In the homogeneous phantoms, the variation for the SPB implementations were generally on the same order or better than those measured with U-CUSE or F-CUSE. The SPB methods demonstrated a uniform shear wave velocity measurement with depth in many cases.

The correlation width maps showed a large spatial variation of the correlation peak width. A correlation peak with a small width is desirable and is an indicator of robust time delay estimation for shear wave speed calculation and could be used as a quality metric for image formation. Additionally, lower correlation widths are indicative of a concentration of shear wave sources that were designed for in the optimization process. Most of the correlation widths summarized in Table 1 for the SPB methods were smaller or similar to those realized for the U-CUSE and F-CUSE configurations. This is one indication that the design criteria yielded desired results. In the F-CUSE maps, the low values of correlation width corresponded to the focal depths of the push beams. The Ax-CUSE configurations provided larger regions of low correlations widths. The FA and VA configurations gave correlation width maps that varied more widely with space. In some cases, the correlation width was

high on one side of the map and low on the other. Multiple images with complementary correlation maps can be compounded with weighting controlled by the correlation peak width to form a more robust final image.

The images taken of the various inclusions showed the SPB methods could provide good depictions of the inclusions. In particular, the AxCUSE implementation with $\theta = 3^\circ$ in Fig. 12 can show the bottom of the inclusion that none of the other configurations can provide. The CNR was also found to be equivalent or in many cases better for the SPB configurations as compared to the CUSE results. It is also evident that certain configurations can image inclusions of different sizes and at different depths more optimally than others. One such example is that the AxCUSE $\theta = 3^\circ$ configuration provides a more circular inclusion shape where the shape of the inclusion has been elongated using U-CUSE. One explanation for the differences in optimality of imaging the inclusions with different configurations is that the SPB method generates shear waves with many different propagating directions which may achieve a shear compounding effect that improves the signal-to-noise ratio (SNR) and the shape of the inclusions.

These results were obtained with steered unfocused push beams so they could be compared against the results of U-CUSE. Using all the elements in the aperture can provide better shear wave coverage over the FOV. The depth-of-field (DOF) defined as the point where the noise in the shear wave velocity map increases substantially is higher for the SPB configurations compared to that for U-CUSE and is comparable in many cases to the performance of F-CUSE.

This method provides a high level of flexibility for configuring the arrangements of the steered beams and the present optimization criteria can be used, or the optimization metric could be adjusted for specific applications. The optimization in this paper was based on the spatial distribution of the intensity peaks. The amplitude of these peaks was not directly taken into account, which could be included in future implementations of the optimization scheme. Also, the distribution of peaks was optimized for uniformity through all depths of the FOV. This could be more limited to a specific depth if desired.

One other aspect of the simulations that needs to be addressed is that the intensity and thereby the resulting forces are vector quantities and have both axial and lateral components. In this study, it was assumed that the intensity and force contributed only axial forces which is a good assumption for the small steering angles used ($3-7^\circ$), but if larger steering angles are to be used in future implementations, the contributions of the axial and lateral components of the force will need to be accounted for in the optimization process with simulations. Though we did not account for the contributions related to lateral forces in the simulations, we did take advantage of the multi-directional shear waves generated through the intersecting steered push beams. The 2D shear wave velocity algorithm used also accounts for the multi-directional shear wave field [26].

Additionally, the optimization process used randomly generated configurations. This is a generalized approach. In this phantom study, we imaged inclusions with known size and location, and if this information is known *a priori*, more optimal configurations could have

been designed. However, in practice when scanning patients, the location and shape of inclusions may not be known. Therefore, a randomly generated configuration that is optimized for many depths holds promise for adapting to many situations. However, it is conceivable to use this method to generate configurations that are optimized for a given set of depths for imaging.

One limitation of this study is that we only simulated 100 configurations for each of the different steering situations. We assumed that these 100 configurations were representative of all of the possible combinations of the steering directions and angles. Figure 6 showed that the spatial frequency sum has a relatively tight distribution with some peaks. We did not find peaks that were substantially different from the mean of these sums. To simulate all the possible combinations would be restrictive, so we used these 100 simulations to represent this population.

Compared with the F-CUSE methods, the SPB method used in this paper does not use focused beams so the peak intensity in the field is less than that in the F-CUSE cases (Fig. 8). However, the distribution of the energy within the tissue is advantageous for SPB to keep under the acoustic output limits. On the other hand, it should be noted that in SPB all the elements in the aperture were used at the same time so there may be risk of damaging the transducer due to excessive heating. While this paper deals with the methodology related to the SPB method and the associated phantom study, we will investigate the use of these techniques for imaging of *ex vivo* and *in vivo* tissues in the future.

Conclusion

Steered push beams can be used in deterministic or randomized configurations to produce high quality shear elasticity maps. This method produces a multi-source and multi-directional shear wave field. The results shown in this paper demonstrate that uniformity and depth-of-field for shear elasticity maps compare equivalently or better than CUSE implementations. The SPB method is very flexible and could be optimized for a wide spectrum of clinical applications.

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Fig. 1.
Schematic drawings for U-CUSE and axicon CUSE.

Fig. 2. Intensity simulations. (a) U-CUSE, (b) axicon CUSE. Each of the fields are normalized independently and are plotted on a log scale.

Fig. 3. Results for a random configuration for the angle sign using a fixed $\theta = 4^\circ$. (a) Transmit delays, (b) Intensity field.

Fig. 4. Results for a random configuration for the angle sign and random angles in the range $\theta = [3^\circ, 4^\circ, 5^\circ, 6^\circ]$. (a) Transmit delays, (b) Intensity field.

Fig. 5.

Intensity profiles and spatial Fourier transforms. (a) Spatial profile of $I_m(x, z)$ at $z = 15$ mm, (b) Spatial profile of $I_m(x, z)$ at $z = 25$ mm, (c) Spatial profile of $I_m(x, z)$ at $z = 35$ mm, (d) spatial Fourier transform of $I_m(x, z)$ at $z = 15$ mm, (e) spatial Fourier transform of $I_m(x, z)$ at $z = 25$ mm, (f) spatial Fourier transform of $I_m(x, z)$ at $z = 35$ mm.

Fig. 6.

(a) Spatial frequency index for averaged intensity profiles for varying depth and random number seed values for $\theta = 3\text{--}6^\circ$ degree randomized configurations. (b) Sum of peak spatial frequency through depth. The arrows depict the six highest values among these random number seed values.

Fig. 7.

The random configurations selected based on the peaks appeared in summed spatial frequency shown in Fig. 6(b) by the arrows. (a) RN = 40, (b) RN = 95, (c) RN = 81, (d) RN = 11, (e) RN = 84, (f) RN = 74.

Fig. 8.

Intensity configurations used in experimental studies. All of the images are scaled to the same absolute scale.

Fig. 9.

Shear wave speed maps in homogeneous phantom with $c_s = 1.55$ m/s.

Fig. 10.
Shear wave correlation width maps in homogeneous phantom.

Fig. 11.
Shear wave speed maps for inclusion phantom with 10 mm diameter spherical inclusion.

Fig. 12.

Shear wave speed maps for inclusion phantom with 20 mm diameter spherical inclusion.

Fig. 13.
Shear wave speed maps for inclusion phantom with 2.53 mm diameter cylindrical inclusion.

Fig. 14. Shear wave speed maps for inclusion phantom with 4.05 mm diameter cylindrical inclusion.

Fig. 15. Shear wave speed maps for inclusion phantom with 6.49 mm diameter cylindrical inclusion.

Fig. 16.

Shear wave speed maps for inclusion phantom with 10.40 mm diameter cylindrical inclusion.

Fig. 17. Shear wave speed maps for inclusion phantom with 16.67 mm diameter cylindrical inclusion.

Table 1

Summary of shear wave velocities and correlation widths from different configurations in a homogeneous phantom.

Configuration	c_s , m/s	Correlation Width, ms
U-CUSE	1.56 ± 0.07	2.19 ± 0.16
F-CUSE, $z_f = 20$ mm	1.55 ± 0.05	1.89 ± 0.35
F-CUSE, $z_f = 30$ mm	1.55 ± 0.05	1.76 ± 0.30
AxCUSE, $\theta = 3^\circ$	1.54 ± 0.04	1.85 ± 0.26
AxCUSE, $\theta = 4^\circ$	1.54 ± 0.04	1.75 ± 0.25
AxCUSE, $\theta = 5^\circ$	1.55 ± 0.05	1.85 ± 0.24
FA, $\theta = 4^\circ$	1.53 ± 0.05	1.56 ± 0.40
FA, $\theta = 5^\circ$	1.54 ± 0.05	1.69 ± 0.45
FA, $\theta = 6^\circ$	1.54 ± 0.05	2.06 ± 0.73
VA, $\theta = 3-6^\circ$	1.54 ± 0.07	2.20 ± 0.79
VA, $\theta = 4-7^\circ$	1.54 ± 0.05	1.62 ± 0.35

Table 2

Summary of shear wave velocities and CNR from different configurations for spherical inclusion phantoms.

Configuration	10 mm			20 mm		
	c_B , m/s	c_I , m/s	CNR	c_B , m/s	c_I , m/s	CNR
U-CUSE	2.78	4.21	11.29	2.90	6.40	18.00
F-CUSE, $z_t = 20$ mm	2.82	4.25	13.83	2.82	6.41	20.86
F-CUSE, $z_t = 30$ mm	2.72	4.05	11.21	2.81	5.38	17.72
AxCUSE, $\theta = 3^\circ$	2.73	4.21	12.17	2.82	5.39	17.75
AxCUSE, $\theta = 4^\circ$	2.73	4.19	12.38	2.80	5.52	20.10
AxCUSE, $\theta = 5^\circ$	2.76	4.17	12.16	2.80	5.58	20.53
FA, $\theta = 4^\circ$	2.85	4.55	16.55	2.81	7.27	25.08
FA, $\theta = 5^\circ$	2.81	4.50	13.99	2.80	7.41	30.10
FA, $\theta = 6^\circ$	2.75	4.58	13.92	2.78	7.14	31.86
VA, $\theta = 3-6^\circ$	2.80	4.37	13.27	2.79	6.80	27.47
VA, $\theta = 4-7^\circ$	2.79	4.22	10.87	2.79	6.81	24.50

Table 3

Summary of bias from different configurations of spherical inclusion phantoms.

Configuration	10 mm	20 mm
U-CUSE	-18.45	23.99
F-CUSE, $z_f = 20$ mm	-17.45	24.28
F-CUSE, $z_f = 30$ mm	-21.52	4.24
AxCUSE, $\theta = 3^\circ$	-18.39	4.42
AxCUSE, $\theta = 4^\circ$	-18.83	6.97
AxCUSE, $\theta = 5^\circ$	-19.27	8.21
FA, $\theta = 4^\circ$	-11.83	40.93
FA, $\theta = 5^\circ$	-12.76	43.57
FA, $\theta = 6^\circ$	-11.27	38.32
VA, $\theta = 3-6^\circ$	-15.32	31.77
VA, $\theta = 4-7^\circ$	-18.30	32.05

Table 4

Summary of shear wave velocities and CNR from different configurations of cylindrical inclusion phantoms.

Configuration	2.53 mm			4.05 mm			6.49 mm			10.40 mm			16.67 mm		
	c_B , m/s	c_I , m/s	CNR	c_B , m/s	c_I , m/s	CNR	c_B , m/s	c_I , m/s	CNR	c_B , m/s	c_I , m/s	CNR	c_B , m/s	c_I , m/s	CNR
U-CUSE	2.95	3.40	7.74	2.91	3.67	14.69	2.93	4.28	16.98	2.94	4.88	18.52	3.19	5.27	4.22
F-CUSE, $z_t = 20$ mm	2.76	3.26	22.76	2.78	3.45	17.11	2.83	4.00	23.45	2.87	4.59	20.52	3.00	5.21	8.46
F-CUSE, $z_t = 30$ mm	2.77	3.33	34.30	2.80	3.65	22.28	2.86	4.20	21.87	2.90	4.66	22.02	3.06	5.09	6.55
AxCUSE, $\theta = 3^\circ$	2.81	3.34	26.40	2.83	3.64	20.58	2.88	4.16	19.14	2.89	4.68	23.07	3.09	5.15	5.49
AxCUSE, $\theta = 4^\circ$	2.79	3.36	25.47	2.81	3.66	21.95	2.86	4.19	20.88	2.87	4.70	25.94	3.05	5.17	6.07
AxCUSE, $\theta = 5^\circ$	2.79	3.36	22.93	2.81	3.59	19.80	2.86	4.14	20.68	2.86	4.69	27.69	3.23	5.5	4.28
FA, $\theta = 4^\circ$	2.85	3.66	19.03	2.84	3.76	18.74	2.87	4.35	22.55	2.81	4.93	35.27	3.27	5.8	3.56
FA, $\theta = 5^\circ$	2.83	3.51	24.68	2.82	3.75	20.21	2.86	4.38	24.72	2.81	4.95	43.26	3.20	5.84	4.23
FA, $\theta = 6^\circ$	2.76	3.49	32.31	2.78	3.84	25.20	2.83	4.54	33.92	2.79	4.96	44.46	3.11	5.7	4.40
VA, $\theta = 3-6^\circ$	2.74	3.45	50.35	2.79	3.75	16.71	2.82	4.36	43.56	2.79	4.88	48.90	3.08	5.59	4.71
VA, $\theta = 4-7^\circ$	2.75	3.48	28.27	2.80	3.73	17.07	2.82	4.32	28.59	2.79	4.82	45.99	3.07	5.55	4.74

Table 5

Summary of bias results (%) for cylindrical inclusions of different diameter

Configuration	2.53 mm	4.05 mm	6.49 mm	10.40 mm	16.67 mm
U-CUSE	-34.09	-28.95	-17.09	-5.50	2.17
F-CUSE, $z_t = 20$ mm	-36.80	-33.22	-22.52	-11.12	0.97
F-CUSE, $z_t = 30$ mm	-35.55	-29.28	-18.58	-9.70	-1.31
AxCUSE, $\theta = 3^\circ$	-35.26	-29.52	-19.46	-9.22	-0.13
AxCUSE, $\theta = 4^\circ$	-34.97	-29.03	-18.79	-8.91	0.26
AxCUSE, $\theta = 5^\circ$	-34.86	-30.44	-19.77	-9.16	6.60
FA, $\theta = 4^\circ$	-29.08	-27.20	-15.64	-4.49	12.37
FA, $\theta = 5^\circ$	-31.95	-27.24	-15.13	-4.10	13.22
FA, $\theta = 6^\circ$	-32.42	-25.54	-12.05	-3.78	10.52
VA, $\theta = 3-6^\circ$	-33.09	-27.39	-15.59	-5.33	8.25
VA, $\theta = 4-7^\circ$	-35.33	-27.69	-16.24	-6.51	7.49