064 **LATERAL MODULATION IMAGING USING SIMPLE NON–STEERING BEAMFORMING.**

Chikayoshi Sumi[1], Yuuki Takanashi[1], Yousuke Ishii[1], Naoto Yamazaki[1].*

[1]Sophia University, 7–1, Kioi-cho, Chiyoda–ku, Tokyo 102–8554, JAPAN.

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1. Introduction

Various ultrasonic (US) displacement/velocity measurement methods have been extensively developed for measurements of blood flow, tissue strain and for sonar data and other target motions. Sumi's developed several displacement vector measurement methods [eg, multidimensional autocorrelation method (MAM) etc] together with lateral modulation (LM) methods (eg, [1-3]). LM measurements can be achieved by using the superposition of steered, crossed beams (eg, [1]). This is the superposition of multiple steered beams with different steering angles obtained using the multiple transmission method (MTM) or synthesized from a set of received echo data using the multidirectional synthetic aperture (SA) method (MDSAM). For MTM, simultaneous or successive transmissions/receptions of an ultrasound (US) signal can be used. With this type of beamforming, multiple transducers can also be used. The use of Sumi's developed demodulation method permits the use of the 1-dimensional autocorrelation method (AM) instead of MAM [4,5]. However, the calculation amount increases and the measurement accuracy also decreases. The LM method also permits echo imaging where the lateral resolution is almost the same as the axial resolution.

Recently, Sumi also developed a new beamforming method which is simpler than LM, MTM and MDSAM, ie, ASTA (A defined STeering angle, eg, [4,6]) which uses only a steering angle. When performing a simple ASTA for displacement vector measurements, a spectra frequency division (SFDM) is performed. ASTA can also be used for lateral displacement measurements. As a version of ASTA, a non-steering beam is also used for yielding LM after beamforming by using SFDM and removal of low lateral frequency spectra [4-6]. Also see ref. 7, in which a rectangular function is used in an apodization function properly.

For a rapid scanning over a region of interest (ROI), a non-steered plane wave transmission is used, particularly when using a 2-dimensoinal array transducer. In Sumi's case, such a wave is used with a steering for measuring a rapid target motion (ie, displacement, velocity, strain etc) including when using a 1-dimensional array transducer [1-3,6]. For instance, blood flow in a carotid artery is rapid. A shear wave propagating speed is also our measurement target (ARFI etc). Such measurements permit the estimation of the target mechanical properties [8].

In Sumi's new approach, a beam angle is measured with a high spatial resolution for all beamformings including conventional focused beamformings, and the displacement in the beam direction is accurately measured to obtain the displacement of an arbitrary direction of the target motion of which direction is known (eg, depth, lateral, radial etc) [6,9,10]. The approach is referred to as a BA (Beam Angle) approach. Such a measurement had been performed for a displacement vector measurement using LM with MAM [ie, MTM or MCB (multiple crossed beams) method with the new approach] [1-3,6,9,10]. Also when generating no plural transmissions, such a new approach can also be used together with SFDM [6,9,10].

As far, for all the measurements, only a theoretically required beams were generated by convnetional beamforming, or ASTA or LM with a transmission focusing or not. That is, for measurements of one displacement componet, and 2- and 3-dimensional displacement vector components, the same numbers as those of unknown displacement components were obtained for the beam generations, respectively. However, the beams generated include various noises (eg, electric noise, digital noises etc). To reduce such noises, we previously proposed to superpose the beams generated or data measured under the same condition. That is, if no target motion is generated during echo data acquistion, the measurement accuracy increases. Here, as an alternative approach, the least squares method is used for an over-determined system obtainable by prforming more numbers of transmissions than theoretically required transmissions or applying SFDM extensively.

In this report, the measurement accuracy is evaluated using agar phantoms for all the measurements using the focused beamformings or plane wave transmissions. For a non-flat aperture such as concave, convex transducers, such plane wave transmissions correspond to laterally wide wave transmissions. In this report, a spherical dynamic focusing is used for the transmission focusing.

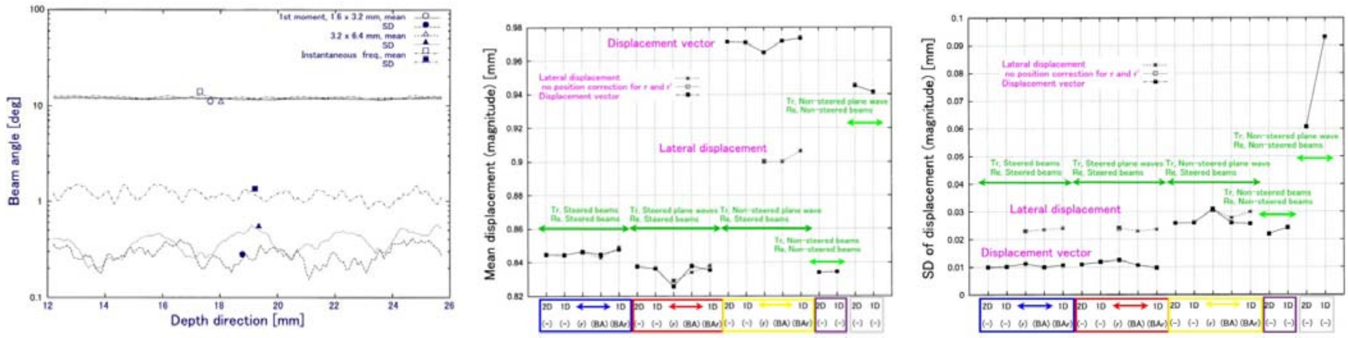
2. Agar phantoms using plane waves and/or non-steered beams

Using beamforming designs other than ASTA, MCB and LM, and using the transmission (Tr) and reception (Re) of steered spherical focusing beams with a dynamic focus (see the generated steering angles shown in Fig. 1a, of about 11.9 degrees vs a designed, 14.0 degrees), the lateral displacement and displacement vector were measured on the same laterally compressed agar phantom (images omitted). The agar phantom used was the same as that used in refs. 2 and 3, in which a circular region had a larger shear modulus than the surrounding region (a cylindrical inclusion with a dia. = 10 mm and a depth of 19 mm), ie, a relative value of 3.29 (2.63 vs 0.80 × 10^6 N /m^2). The ultrasound (US) frequency was 7.5 MHz. For apodizations, parabolic functions were used [2,3]. Here, only the 1D AM approach [6,9,10] was used (ie, the SFDM approach [6,9,10] is omitted). Specifically, the lateral displacements and lateral strains were also measured using the global rotation (r), BA and BAr (ie, local rotation with BA data) methods, respectively for the transmission of a steered plane wave (ie, non-focused) with the same steering angle as that of the received, steered spherical focusing beams with a dynamic focus, and for the transmission of a non-steered plane wave (ie, non-focused with a steering angle of 0 degrees). For the strain measurements using a global rotation with accurate BA data (ie, obtained using the 1st moments of global spectra), non-relocated results were also obtained (in this case, the strain data should be relocated). Alternatively, the strain measurements using BA or BAr method were achieved without any rotation processing, ie, by using the differential filter properly.

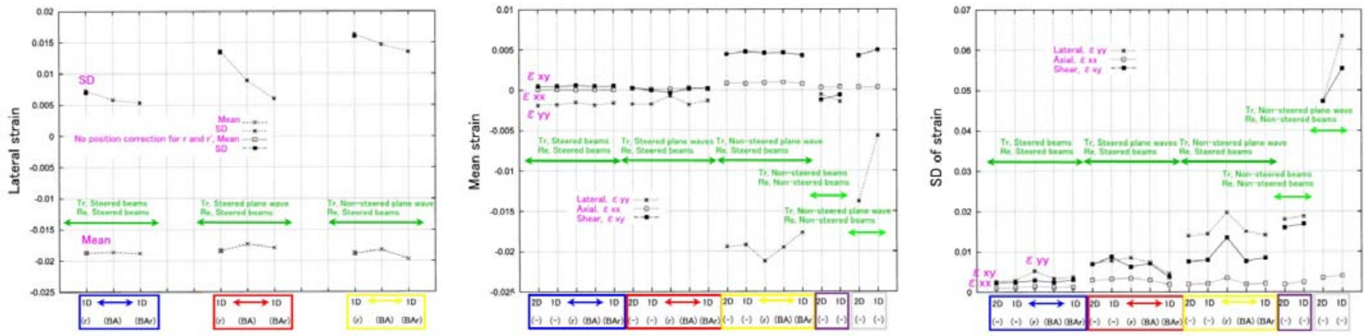
Moreover, for MCB and LM using the same transmission and reception with the corresponding, laterally symmetric beams, the displacement vector components, strain tensor components and shear moduli (using a 2D stress assumption [8]) were measured using the global rotation (r), BA and BAr methods with MCB, and 2D AM [1-3] and 1D AM with demodulation [4,5] with LM (images omitted). The designed and generated steering angles were respectively, 14.0 vs 11.9 degrees and 7.1 vs 6.4 degrees (omitted). Both of the evaluated SDs of the BAs were smaller than those of the dynamic focused transmission of steered spherical focusing beams.

The measurements obtained with both of the plane wave transmissions were less stable than the corresponding measurements obtained with the dynamically focused transmission (Tr) of steered spherical focusing beams, particularly those with transmission of non-steered plane waves rather than those with steered plane waves. The measurement accuracies were also evaluated and confirmed statistically as shown in Fig. 1b, together with those obtained for the transmission of steered spherical focusing beams. Previously, the measurement accuracies were evaluated only for 2D AM with LM [2,3]. Also for the new BA or BAr method with MCB, the same order of measurement accuracy was confirmed: dynamically focused transmission of steered spherical focusing beams > transmission of steered plane waves > transmission of non-steered plane waves. Also, as confirmed, in a manner similar to that for dynamically focused transmission of steered spherical focusing beams, the order of measurement accuracy for both of the plane wave transmissions is 2D AM > 1D AM with demodulation > BA method (no rotation) > BAr method (local rotation) > r method (global rotation). The measurement accuracy of the displacement vector is also higher than that using lateral displacement. For the global echo rotations (r), the four dead corners were also generated (thus the relative shear modulus measurements were not obtained). All of these were obtained using the reception (Re) of steered dynamic spherical focusing beams.

In addition, in Fig. 1b, the statistics were evaluated and are also shown for 2D AM and 1D AM with demodulation using no steered beam, ie, using the Re values from non-steered dynamic spherical focusing beams together with the Tr values from non-steered dynamic spherical focusing beams (see images in Figs. 1E and 1F in ref. 5), and the Tr values from a non-steered plane wave (images omitted). Both of the designed beam angles are 0 degrees; and the corresponding synthesized beam angle from the laterally symmetric spectra frequency division (ie, a synthesized LM using non-steering, or SFDM using a version of ASTA with non-steering shown in Figure 1B with 0 degrees in ref. 6) had angles of respectively 3.4 and 2.6 degrees. Although the synthesized beam angles for the transmission and reception of non-steered dynamic spherical focusing beams (3.4 degrees) were smaller than those obtained by the transmission of the non-steered plane



(a) (b) Continued.



(b)

Fig. 1. (a) For the transmission of steered focusing beams, depth vs means and standard deviations (SDs) of the beam angles (BAs) measured using the 1st moments of spectra obtained with a high spatial resolution (1.6 × 3.2 mm^2), with a low spatial resolution (3.2 × 6.4 mm^2), and instantaneous frequency moving-average with 0.5 × 0.6 mm^2, respectively. (b) For plane wave and non-steered plane wave transmissions, and the focused beamformings, statistics in the central circular region in the stiff inclusion of the displacement magnitudes, lateral strain on the basis of lateral displacemnt measurement, strain tensor components and relative shear moduli on the basis of displacement vector measurement using 2D AM and 1D AM with demodulation for LM, and 1D AMr, 1D AMBA and 1D AMBAr for MCB.

wave with reception of the steered spherical focusing beams (6.4 degrees), the corresponding images obtained were stable (Figs. 1E and 1F in ref. 5). Also, notice the more accurate means and the smaller SDs, except for the lateral and shear strains, than for the values obtained using a transmission of the non-steered plane wave and a reception of the steered spherical focusing beams (Fig. 1b). Moreover, for transmission, the use of a non-steered, non-focused plane wave yields less accurate and less stable measurements than the use of steered or non-steered, dynamic spherical focusing beams (see again Fig. 1b). Such measurements using no steering and no focused beams may be improved with SFDM [6] and details will be reported elsewhere.

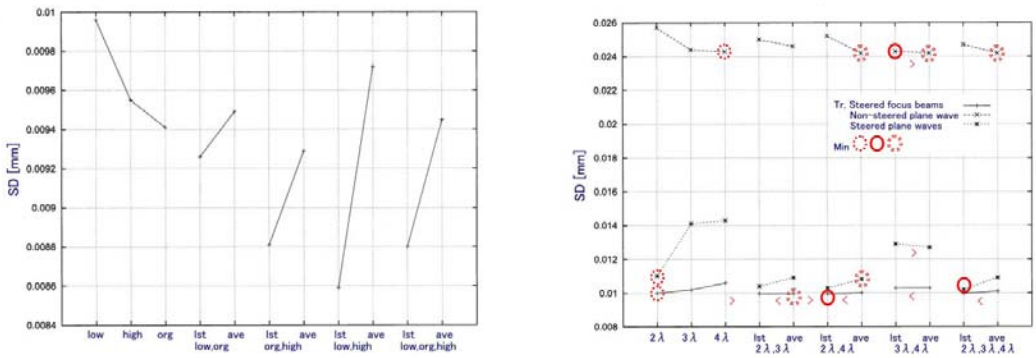
3. Over-determined system

To yield an over-determined system for axial (conventional), lateral and vector measurements, more beams are generated than the theoretically required beams using MTM or MDSAM. For the same purpose, SFDM can also be used for LM and ASTA. A non-steering beam can also be used.

3.1 Axial displacement measurement

First, a non-steering beamforming was performed using a linear array type transducer. The agar phantom used was the same as that used in ref. [11], of which a circular region had a larger shear modulus than the surrounding region (a cylindrical stiff inclusion with dia. = 15 mm; depth, 15 mm), ie, a relative value, 3.33 (2.96 vs 0.89 × 10^6 N / m^2). The agar phantom was compressed in the depth (axial) direction. The nominal US frequency of the transducer was 7.5 MHz. Here, the agar phantom was compressed with a global strain 1.5% in the axial direction.

The SDs of displacements evaluated at the central circular region (dia. = 6.4 mm) of the inclusion was



(a) (b)

Fig. 2. SDs of displacements evaluated (a) for a non-steering beam case and (b) LM cases on agar phantom [mm].

summarized in Fig. 2a (means, about 0.21 mm). To obtain an over-determined system, SFDM was used. Specifically, the spectra were divided into the two local spectra using horizontal line passing through the axial first moment of 2D spectra. The two local spectra generated respectively have low and high frequencies. The least squares measurements were performed for all the combinations of the original spectra and two local spectra. For comparison, the measurements respectively obtained were also superposed.

As shown, for the respective combinations, the least squares measurements are more accurate than the measurements superposed, and the least squares measurement using the combination of two local spectra (high and low) are the most accurate and stable of all, because a low dependency was obtained for Doppler equations. Another accurate result such as of 2D AM (ie, SFDM with a vertical division) has also been presented in ref. 8. Other divisions and other combinations such as vertical and horizontal divisions were also effective rather than four independent divisions and will be reported in detail elsewhere. The combination with original spectra (not-divided one) is also effective.

In ref. 7, the incoherent superposition is also reported for a speckle reduction.

3.2 Displacement vector measurement

For comparison, MDSAM was used together with a linear array type transducer to generate an over-determined system. The agar phantom used was the same as that used in section 2 (ie, refs. 2 and 3). For apodizations, the same parabolic functions were used. Laterally symmetric steering beams with several LM wavelengths were generated, ie, 2λ, 3λ, and 4λ (λ: US wavelength). For comparison, the transmission of a plane wave with no steering angle and plane waves with the same steering angles as those of receptions were also performed.

Similarly, the SDs were evaluated. For instance, only the results of displacement magnitudes are shown (Fig. 2b; means, about 0.84 mm). The least squares measurements are effective for the combinations of original LMs and those of LMs with steered plane wave transmissions, whereas the superposition of measurements is effective for those of LMs with no steering transmission. For the strain tensor measurements using the steered plane waves, the superposition were more effective than the least squares measurements (not shown). Increasing of the measurement stability obtainable by the least squares measurement and superposition are confirmed, particularly for the low SNR beamformings. Except for the non-steered plane wave transmission, the use of a high lateral frequency yields a higher accuracy than that of a low frequency.

4. Discussions and conclusions

The measurement accuracies of a lateral displacement and a displacement vector were examined for the use of plane waves and/or non-steered beams for ASTA, MCB and LM. The measurement accuracies were lower than those obtained by the corresponding focused beamformings [6,9,10]. The order of measurement accuracy obtained by 2D AM, 1D AM with demodulation, BA, BAr and r methods were also the same as that obtained by the focused beamforming (ie, 2D AM > 1D AM demodulation > BA > BAr > r method) [6,9,10]. See also the new results shown in ref. 7. We also confirmed an effectiveness of the over-determined system for the non-steering and LM cases. The least squares measurement or superposition yielded accurate measurements. Results were also obtained on other beamformings and combinations, and a lateral displacement measurement as well as a displacement vector measurement, for instance, ASTA with SFDM (similarly for transmission of focused beam, or steered or non-steered plane wave, a vertical division is effective [6]), nonsteering with nonfocus case with SFDM, LM with no steering beam (ie, ineffective when the parabolic apodization is used) or SFDM (particularly, a horizontal division and/or the simultaneous use of original spectra is effective) etc [6]. The increase in a measurement accuracy by the spectra division number (>2) were also confirmed. Over numbers of divisions were ineffective. The spectra division is effective for a large bandwidth signal or large bandwidth local spectra with a high SNR. For a more accurate measurement, a lateral frequency should be large [1]. However, the use of an overly large steering angle also decreases the echo SNR. Almost the combination with such a low SNR echo signal decreases the measurement accuracy. Such results will also be reported in detail together with a proper window for the spectra division.

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