Proceedings of Symposium on Ultrasonic Electronics, Vol. 31 (2010) pp. 129-130
6-8 December, 2010

Applications of Lateral Modulation (LM) and A Steering Angle (ASTA)

横方向変調(LM)と一つのステアリング角度(ASTA)の応用

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1. Introduction

We have realized the beamformings [1–6] by using beam steering and apodization for accurately measuring tissue or blood displacement vectors or strain tensors using the multidimensional cross–spectrum phase gradient method (MCSPGM), and autocorrelation and Doppler methods (MAM and MDM) [2,3].

In [1-5], we reported lateral modulation (LM) methods in addition to a multidirectional synthetic aperture method (MDSAM) and a multiple transmitting method (MTM). As shown, the coherent superimposition of the steered beams performed in LM has a higher potential for realizing a more accurate measurement of a displacement vector than the synthesis of the displacement vector using the accurately measured axial displacements performed in MDSAM and MTM. However, in LMs, MDSAM and MTM can also be used to obtain multiple steered beams. If necessary, multiple transducers are also used (e.g., for heart). These modulations can also be used for B–mode imaging simultaneously. Particularly, in [4,5], we reported optimization methods for yielding the best apodization function in a linear least squares sense and a nonlinear manner, i.e., truncation of the feet of the apodization function.

Alternatively, we also reported another beamforming. This method involves the steering of beams through a steering angle (ASTA) [6]. With ASTA, displacement vector measurements can be made, but the number of available methods is limited, and being dependent on the measurement method, only a lateral displacement measurement can be made even if the methods are multidimensional ones. The comparison of LM and ASTA was also performed [6]. However, for instance, the division of spectra in a frequency domain allows the use of MAM and MDM for the displacement vector measurement [6,7].

In addition, the rotation of coordinate was also reported by us [6]. For LM and ASTA, when beamforming is preformed, after receiving echo signals for a beamforming or after obtaining synthesized steering beams, by rotating the coordinate in the spatial or frequency domain, the axial, lateral and elevation frequencies can also be controlled. For LM, this rotation also allows the use of nonsymmetric steering angles with 1D displacement measurement methods [6].

In this study, a version of ASTA is reported. A physically steering beam is not used. Strictly, only the coordinate rotation is used together with a non-steering beam. The beamfroming will yield a larger bandwidth than the beam steering. A conventional B-mode imaging (i.e., no modulation) can be performed simultaneously. Moreover, this method also allows no use of a transmission focusing, i.e., the use of a plane wave transmission. Such a beamforming yields a more accurate 3D displacement vector measurement than a conventional 3D beamforming. Experiments are performed on an agar phantom. For comparison, results obtained using LM and ASTA with the spectra division are also shown.

2. Method

2.1 Spectra division

ASTA yields a single quadrant or octant spectra in a frequency domain. Such a single spectra can be divided in a frequency domain such that the same number of divided spectra can be obtained as that of the unknown displacement components [6]. The division should be performed such that the numerically independent equations can be obtained. That is, more largely different instantaneous frequencies can be obtained in all directions. Proper windows will also be used for the spectra division. This spectra division can also be applied for LM. For instance, to increase a measurement accuracy, low frequency spectra can be disregarded. This will be reported elsewhere [8].

2.2 Rotation of coordinate system

The rotation of the axial and lateral directions can be performed at beamforming [6]. Alternatively, the rotation can also be performed after obtaining a synthesized steering beam [6]. In such a case, an interpolation of ultrasound signals is performed numerically or using a Fourier’s transform.

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Generally, the data density in a lateral direction is small. Therefore, for all the cases, the lateral pitch of data is made properly small. Because the numerical interpolation involves an approximation, before performing such an approximate interpolation, the bandwidth must be increased in a frequency domain in advance by zero padding [6]. The numerical interpolation can be completed faster than another interpolation.

3. Results

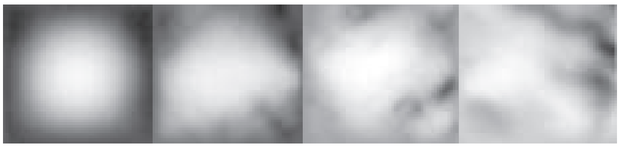
Experiments were performed using the same agar phantom as that used in [1,2]. The target agar phantom [40 (axial, x) x 96 (lateral, y) x 40 (elavational) mm^3] had a central circular cylindrical inclusion (dia., 10mm; depth, 19 mm) with a shear modulus different from that of the surrounding region, and shear moduli of 2.63 and 0.80 x 10^6 N/m^2 in the inclusion and surrounding regions, respectively (i.e., relative shear modulus, 3.29). Manually, the phantom was compressed by 2 mm in the lateral direction. The contact surfaces of the linear array type transducer (7.5 MHz, 0.2 mm US element pitch) and phantom were separated by less than 0.3 mm by immersing them in water in a tank. A rectangular ROI 13.7 (axial, x) x 13.2 (lateral, y) mm^2 was centered on the inclusion (depths from 12.2 to 25.9 mm). For the apodizations of all the beamformings, the same parabolic functions were used as those described in [1,2]. For displacement measurements, MAM was used.

For LM and ASTA, transmission and reception spherical focusings were performed. The achieved lateral modulation frequency was 3.75 MHz. For the new version of ASTA, the coordinate was rotated with 45 degrees. Thus, the achieved lateral modulation frequency was 5.3 MHz. However, note that the axial frequency decreased down to 5.3 MHz. Here, a plane wave was used for the transmission. That is, the spherical focusing was performed only at a receiving. The results obtained using both transmission and reception spherical focusings will be shown elsewhere [8], because a larger bandwidth and a higher measurement accuracy can be obtained. For both ASTA's, the single quadrant spectra was divided using a line passing through a maximum spectrum position in trials, i.e., diagonally, orthogonal to the diagonal direction, vertically or horizontally. Here, any window was not used for the spectra division. The accuracies obtained were compared.

Table I shows the means and standard deviations (SDs) of magnitude and angle of measured displacement vectors at the central circular region with a 3 mm radius. For ASTA's, only diagonal and vertical divisions yielded stable results (other results omitted). In the table, those of shear moduli reconstructed are also shown. **Fig. 1** shows the reconstructed shear modulus reconstructions. A 2D stress assumption [2] was used. Although the displacement vector was accurately measured using all the beamformings, the new version of ASTA yielded inaccurate shear modulus reconstruction. However, recall that a conventional beamforming (neither modulation nor rotation) cannot yield any useful reconstructions geometrically and quantitatively [2].

Table I. Means and SDs of measured displacement vectors and reconstructed shear moduli in a central circular region. Parentheses used for SDs.

Forming Spectra division	Displacement vector Magnitude (mm)	Displacement vector Direction (degree)	Relative shear modulus
(a) LM	0.845 (0.019)	7.60 (1.18)	3.28 (0.33)
(b) ASTA Diagonal	0.851 (0.037)	7.66 (1.16)	2.54 (0.18)
(c) ASTA Vertical	0.851 (0.044)	7.63 (1.29)	1.84 (0.20)
(d) ASTA Rotation	0.963 (0.057)	6.77 (1.23)	1.47 (0.34)



(a) (b) (c) (d)

Fig. 1. Reconstructed shear moduli (a) to (d).

4. Conclusions

The feasibility of the new version of ASTA was verified through phantom experiments. It was confirmed that the method has a high potential for realizing a more accurate real-time 3D blood flow measurement than a conventional one. Measurement accuracy was dependent of the spectra division. A more proper division method will be realized. A transmission focusing will also be performed [8].

References

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