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# Overdetermined system for displacement measurement using plural beamforming and spectra division
複数のビームフォーミングやスペクトル分割を用いた
過剰システムにおける変位計測

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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 measuremnt methods [eg, multidimensional autocorrelation method (MAM) etc] together with lateral modulation (LM) methods (eg, [1,2]). 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 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 (eg, [3]) 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.

As far, only a theoretically required beams were generated by convnetional beamforming, or ASTA or LM with SFDM or not. That is, for one displacement componet, and two- and three-dimensional displacement vector measurements, the same number was obtained for beams as that of unknown displacement components, respectively. However, the beams generated include various noises (eg, electric noise, digital noises etc). To degrease 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 use of an over-determined system is proposed.

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## 2. Methods

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.

For instance, when Doppler equations are obtained as

$$\mathbf{A}\mathbf{x} = \mathbf{b},$$

where a matrix **A** and vector **b** are respectively composed of instantaneous frequencies (or 1st moments of spectra) and instantaneous phase change during frames, and vector **x** is composed of unknown displacement components.

The least squares measurement can be accomplished by solving the equations as follows,

$$\mathbf{A}^T\mathbf{A}\mathbf{x} = \mathbf{A}^T\mathbf{b}.$$

## 3. Agar phantom experiments

### 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. [4], 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 standard deviations (SDs) of displacements evaluated at the central circular region (dia. = 6.4 mm) of the inclusion was summarized in **Fig. 1** (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.

### 3.2 Displacement vector measurement

Next, 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 ref. 2, 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 agar phantom was compressed *in the lateral direction*. The US frequency was 7.5 MHz (wavelength, $\lambda$). For apodizations, parabolic functions were used.[2] Laterally symmetric steering beams with several lateral modulation wavelengths (LMs) were generated, ie, $2\lambda$ , $3\lambda$ , and $4\lambda$ . 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. For a high speed scanning, such a laterally wide wave can be used with an arbitrary array transducer. As far, such a wave was used for a non-steering case as well as ASTA or LM case.[1-3]

Similarly, the SDs were evaluated. For instance, only the results of displacement magnitudes are shown (**Fig. 2**; 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. Increasing the measurement stability by the least squares and superposition are confirmed, particularly for the low SNR beamformings. The use of a high lateral frequency yields a higher accuracy than that of a low frequency.

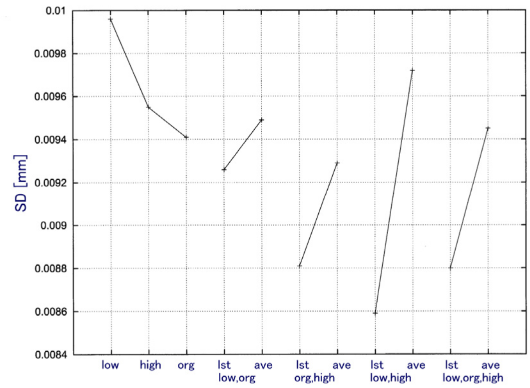


**Fig. 1.** SDs evaluated for a non-steering beam cases on agar phantom [mm].

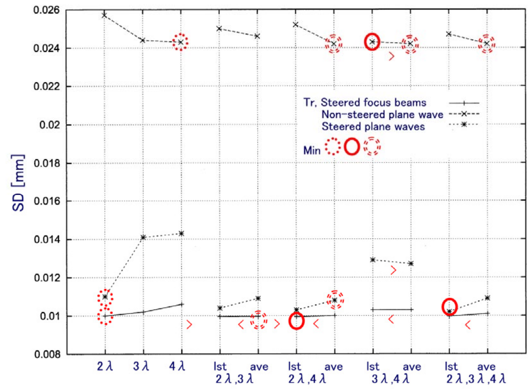


**Fig. 2.** SDs evaluated for LM cases on agar phantom [mm].

### 4. Discussions and conclusions

We confirmed an effectiveness of the over-determined system for the non-steering and LM cases. The least squares measurement yielded accurate measurements. We'll also report results obtained on other beamformings[1-3] and combinations, and a lateral measurement[2,3], for instance, ASTA with SFDM (similarly, transmission of focused beam, or steered or non-steered plane wave), nonsteering with nonfocus case with SFDM, LM with $0\lambda$ beamformings or SFDM etc. The effect on the measurement accuracy by the spectra division number (>2) will also be reported in detail. Recently, elasticity imaging becomes a useful clinical diagnosis modality. For a strain tensor measurement, an improvement of the displacement measurement accuracy is important. Such results will also be reported together.


### References

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