Accuracy comparison of axial and lateral strain measurements achieved using plural steered beams and plane waves and super-resolution imaging

Chikayoshi Sumi
Information Science
Graduate School of Science and Technology
Sophia University
Tokyo Japan
c-sumi@Sophia.ac.jp

ITEC Sep 21-24 2015, Lake Garda (ID, 040)
Submission on Sep 21, 2015.
Corrections of typographical errors in page 6 (Nov 23, 2015).

Next-generation US beamformer for imaging, displacement vector measurement, HIFU and ARFI

- Beam steering and apodization
- Computation, digital signal processing

Increases in echo SNR, frequency, bandwidth and accuracy

- Use of crossed beams

(1) Plural transmissions of beams
Use of a transducer or plural transducers
Simultaneous or successive transmissions

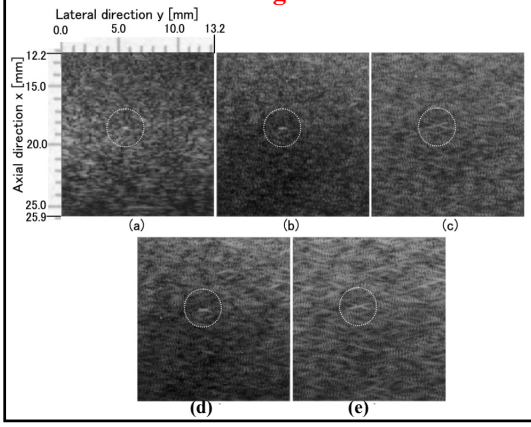
(2) Synthetic aperture (SA)
- Synthesis of steered plural beams from a set of echo data, i.e., MDSAM (Multidirectional synthetic aperture method)

C. Sumi et al, 1st Int Tissue Elasticity Conf (2002);
IEEE Trans UFFC (Dec 2005, Jan 2008, Dec 2008);
JJAP, 47(5B), 4137-4144, 2008.

Ultrasonic imaging by lateral modulation (LM)
– Increase in lateral resolution

C. Sumi et al, IEEE Ultrason symp (2007); JJAP, 47(5B), 4137-4144, 2008; IEEE Trans. UFFC, 55, 2607-2625, Dec 2008.

Coherent superposition of crossed, steered waves or beams;
cf. Fraunhofer approximation by Jensen et al.
Apodaization, parabolic function, Hanning window, Gaussian function, rectangular window etc.

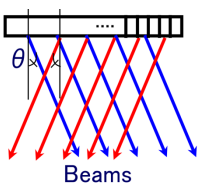


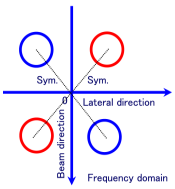
For transmission,
Method 1 uses spherical focussing, whereas Method 2 uses plane waves.

B-mode images obtained using
(a) no modulation;
and modulations, i.e.,
Prabolic apod. with (b) Method 1 and (c) Method 2;
Gaussian apod. with (d) Method 1 and (e) Method 2.

Measurement of displacement vector u (= (ux,uy,uz)T)

By calculating multidimensional complex signals extending 1D analytic signal





2D case

we solve simultaneous equations, i.e.,

Autocorrelation method (MAM) using autocorrelation function phase (3D case):

$$\theta+\frac{\partial}{\partial x}\theta u_x+\frac{\partial}{\partial y}\theta u_y+\frac{\partial}{\partial z}\theta u_z=0,$$

Doppler method (MDM) using analytic signal phase:

$$\frac{\partial}{\partial t}\theta\Delta t+\frac{\partial}{\partial x}\theta u_x+\frac{\partial}{\partial y}\theta u_y+\frac{\partial}{\partial z}\theta u_z=0.$$

C. Sumi, IEEE Trans. on UFFC, vol. 55, 24-43, January 2008;
Tech Rep of Jpn Soc of Ultrason in Med, pp. 37-40, 2001 etc.

Over-determined system

For yielding an over-determined system for a vector measurement,

more beams are generated than the theoretically required beams.

(i) When Doppler equations are obtained as

$$Ax = b,$$

the least squares (LST) measurement can be accomplished by solving the equations as follows,

$$A^T Ax = A^T b.$$

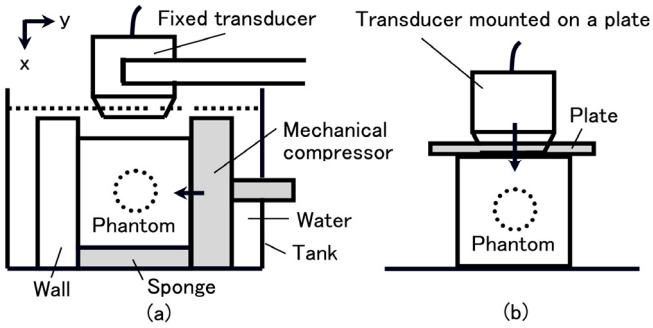
(ii) Averaging of measurements,

(iii) Coherent superposition of echo data.

Agar phantom experiments

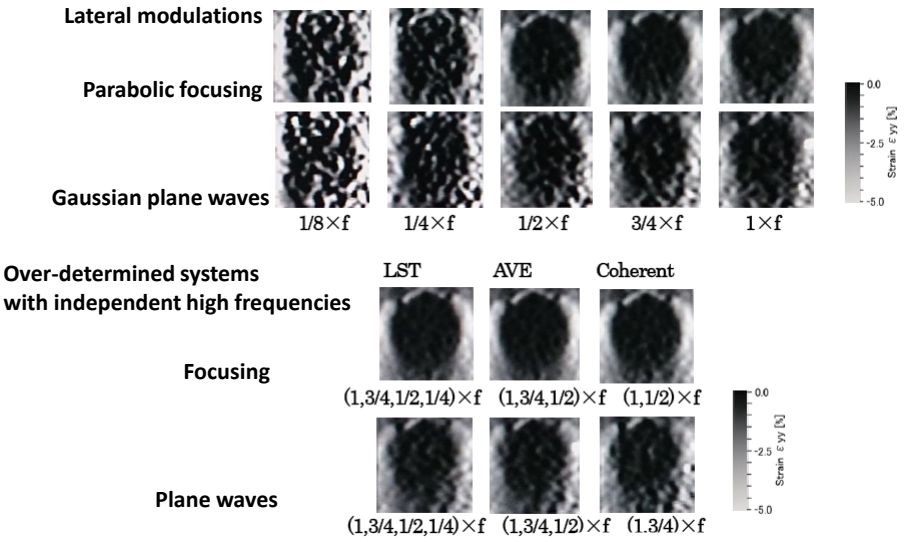
Cylindrical inclusion, 10 mm rad.;

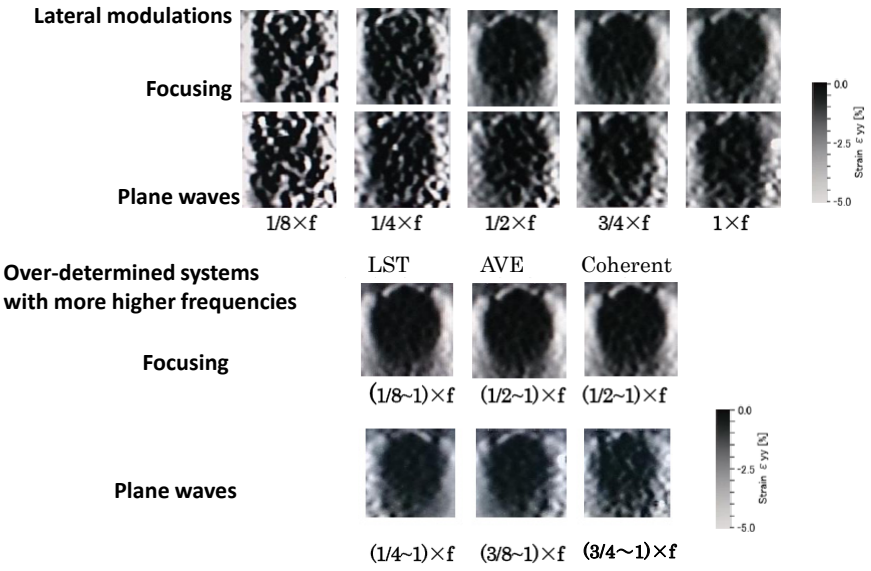
Relative shear modulus, 3.28; US freq., 7.5 MHz



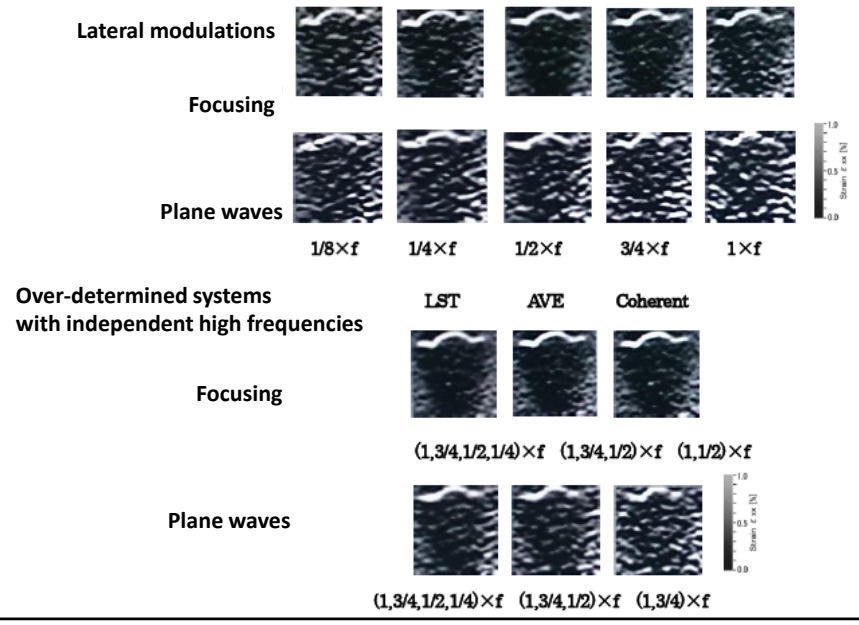
The comparison of measurement accuracy is performed on (a) lateral compression case.

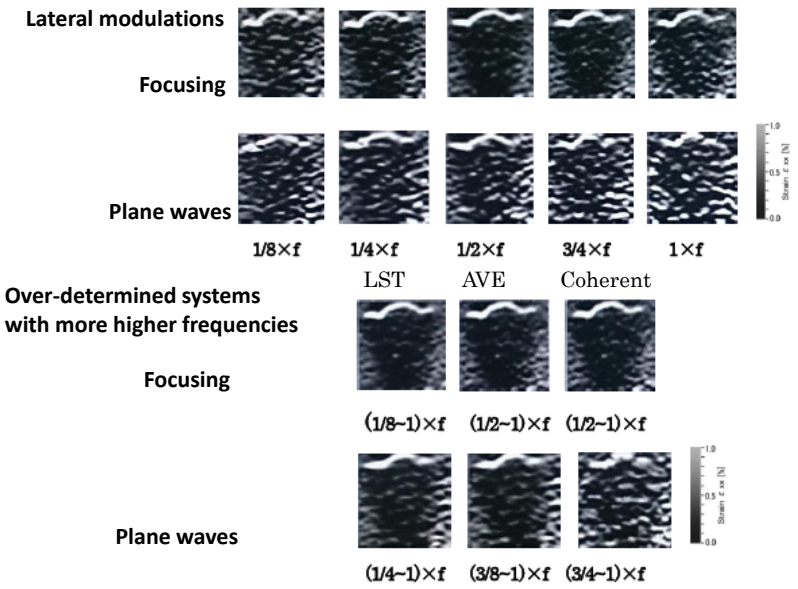
Lateral strains





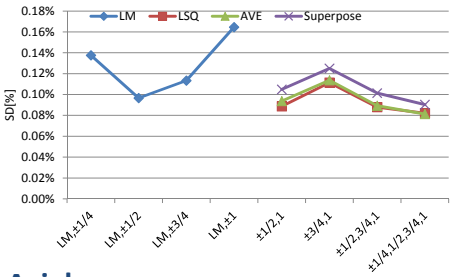
Axial strains





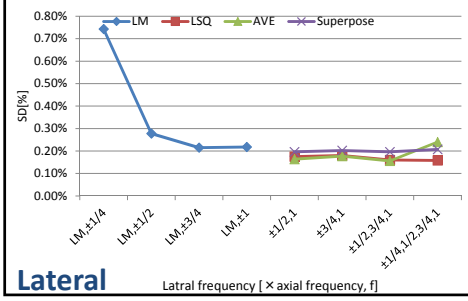
With independent high frequencies

Focusing



Axial

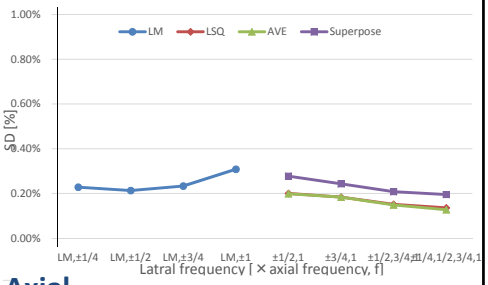
Latral frequency [× axial frequency, f]



Lateral

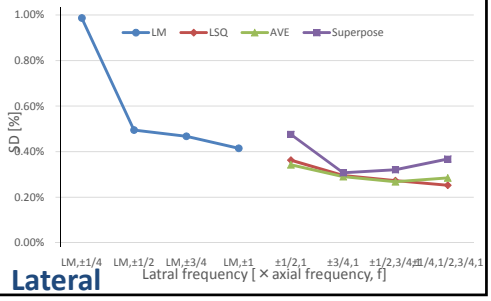
Latral frequency [× axial frequency, f]

Plane waves



Axial

Latral frequency [× axial frequency, f]

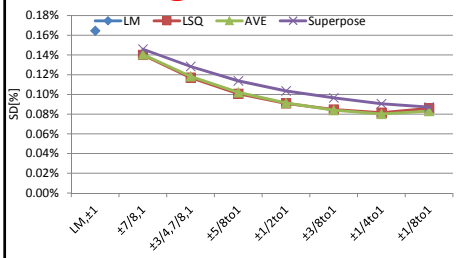


Lateral

Latral frequency [× axial frequency, f]

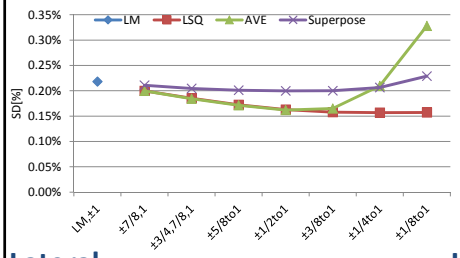
With more higher frequencies

Focusing



Axial

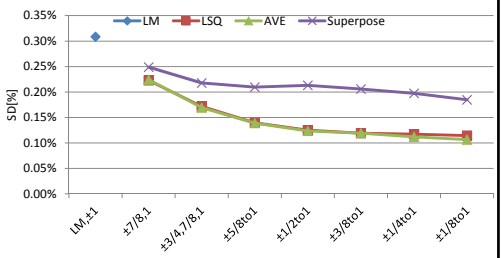
Latral frequency [× axial frequency, f]



Lateral

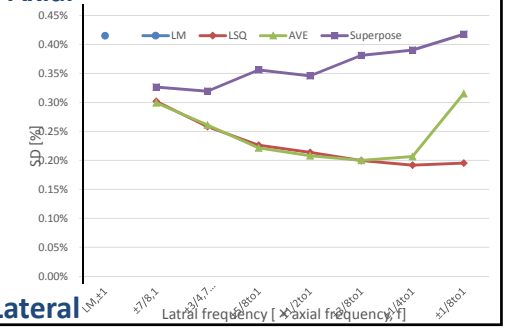
Latral frequency [× axial frequency, f]

Plane waves



Axial

Latral frequency [× axial frequency, f]



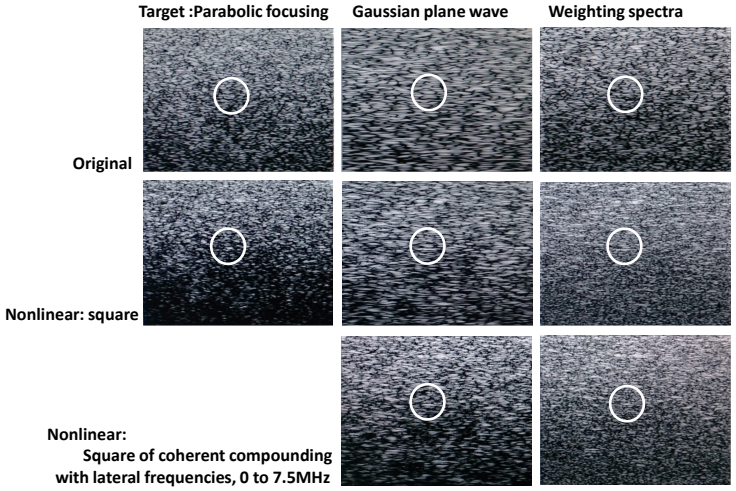
Lateral

Latral frequency [× axial frequency, f]

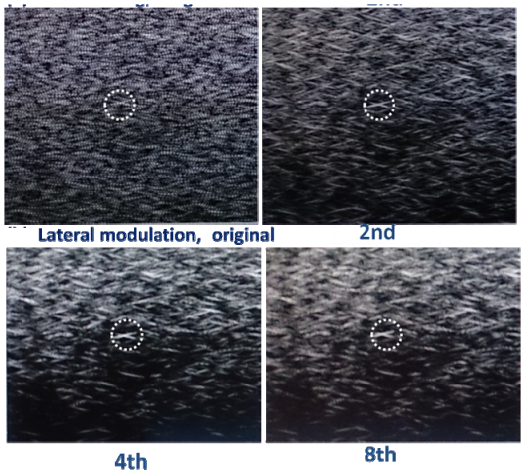
Superresolution using nonlinear processing (2014 ITEC etc) and weighting spectra (2012 ITEC etc)

Widebanding via coherent compounding

e.g., Visualizing a strong scattering on agar phantom.

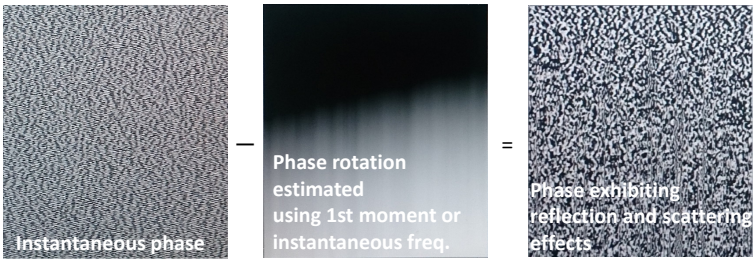


Lateral modulation cases using crossed, two plane waves - Exponentiation -

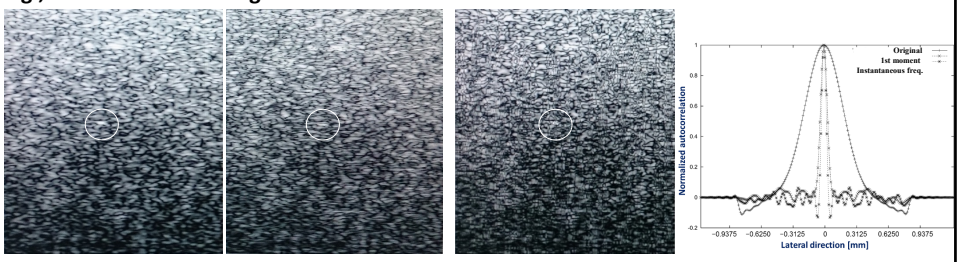


New superresolution with removing phase rotation

e.g., Lateral modulation case:



e.g., Frontal beamforming case:



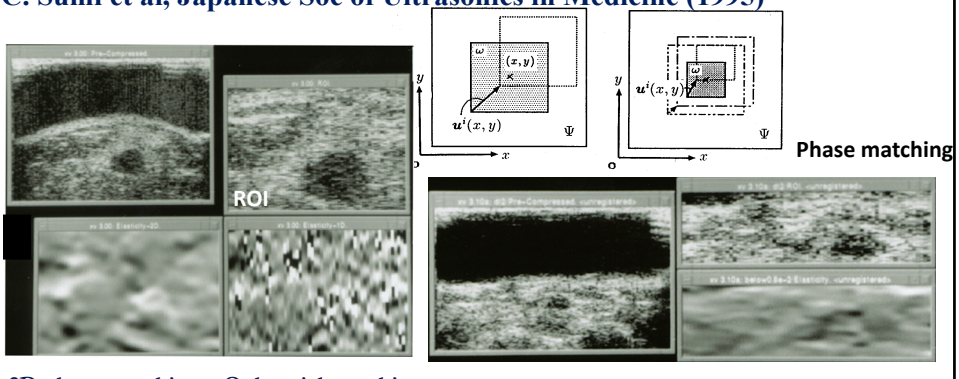
Envelope and square detections — 1st moment (square) — PSFs (lateral profiles)

Originals — Results

Using the calculated sensitive phase solo cannot yield any measurement due to out-of-plane motion, changes in reflection and scattering etc. Performing spectra weighting with phase rotation and phase matching have enabled us to measure a displacement (WFUMB1994). Next trial: 3D measurement using the calculated sensitive phase.

Review on *in vivo* human breast tissues

C. Sumi et al, Japanese Soc of Ultrasonics in Medicine (1995)



2D phase matching — Only axial matching — Scirrhous carcinoma (43 years old)

Small strains surrounding hematoma due to inflammation after surgery (69 years old)

Conclusions

- Similarly to for the lateral strain measurement, for axial strain measurement with spherical focusing, the independency of beams is more important than the number of beams; and for with plane waves, vice versa.
- For axial strain measurement, the averaging is the most effective of all.

Spherical focusing	Plane waves
▪ For lateral strain measurement, the averaging and the least square solution are effective.	▪ For lateral strain measurement, the least square solution is the most effective of all.
▪ The small numbers of independent beams yield almost the same accuracies as those of the large numbers of beams.	▪ The large numbers of beams yield the more accurate measurements than the small numbers of independent beams.

- Measurement and superresolution imaging

New methods have already been effective for imaging. The corresponding 3D methods will also be effective for measurements. Details will appear elsewhere in the near future.