025 ECHO IMAGING, DISPLACEMENT MEASUREMENT AND HIFU TREATMENT WITH NONLINEAR SIGNAL PROCESSING.

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Paper Body: New harmonic echo imaging using arbitrary magnitude ultrasound (US) wave is proposed, i.e., not accumulated actual physical nonlinear effects but calculated at each point on the basis of nonlinear signal processing, for instance, exponentiation and multiplication etc. Simultaneous generation of harmonic and detected signals with larger bandwidths than original basic signals. Heterogeneous high and low frequency signals can also be generated via the nonlinear processing. These allow a high quality echo imaging with a high spatial resolution and a high contrast, and a simple and accurate displacement vector measurement.

Background: High resolution ultrasound (US) echo imaging, high accuracy tissue displacement measurement/imaging and high spatial resolution HIFU treatment are clinically important. As far, for instance, we have performed such processing using multiple beams in a linear sense, i.e., lateral modulation (LM) with superposition of crossed beams [1]. For HIFU treatment, the application of a high frequency US is effective, and then intense harmonic waves are often generated using micro bubbles. The actual physical nonlinear effects are accumulated during propagation.

Aims: In this report, with respect to variously received echo signals, increases in the carrier frequency, bandwidth and contrast are achieved via nonlinear calculations such as exponentiation or multiplications. The processing yields new high resolution echo imaging and displacement measurement.

Methods: Via nonlinear calculations at each point, the harmonic signals with wide bandwidths can be enhanced or generated newly or virtually together with a wide-banded base-band signal; and with respect to the harmonic signals, the detection can also be achieved in an arbitrary direction (e.g., axial, lateral directions) with fewer calculations than conventional detections. Being different from a conventional harmonic imaging, there is no effect of an attenuation determined by the harmonic frequency. Thus, measurement of a displacement vector as well as a displacement component can be performed using a 1D measurement method such as the 1D autocorrelation method with 2D moving-average. Increase in a frequency making a phase rotation rapid will increase an accuracy of displacement measurement.

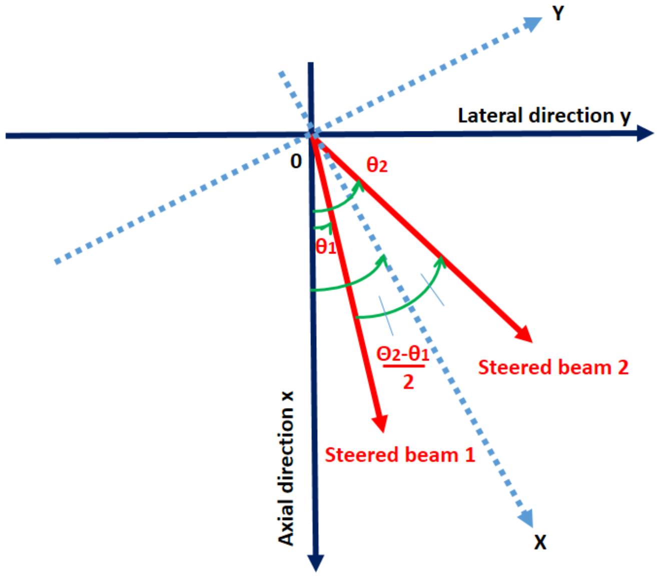


Fig. 1. Schematics of beamforming.

(1) Exponentiation of one beam or one plane wave with steering angle Θ

A monochromatic echo signal with a wavelength λ and a steering angle Θ is expressed in (x,y) coordinate system (see Figure 1) by

$$A(x,y)\cos[2\pi(2/\lambda)(x\cos\theta+y\sin\theta)],$$

and for instance, the 2nd exponentiation is expressed by

$$(1/2)A^2(x,y)\times\{1+\cos[2\pi(2\cdot 2/\lambda)(x\cos\theta+y\sin\theta)]\},$$

i.e., the 2nd harmonic signal and the corresponding base-banded signal including a direct current (DC). The harmonic and base-banded signals have larger bandwidths than original basic signal, i.e., high spatial resolutions in all directions (short pulse length and narrow beam width), which are yielded via multiplication of signal components with plural different frequencies. Higher order exponentiation yields a much higher frequency and a much larger bandwidth.

(2) Lateral modulation (LM), superposition of beams or waves with steering angles θ_1 and θ_2

Crossed two beams or waves are simultaneously generated or not. See Figure 1. The crossed beams are superposed as

$$A(x,y)\cos[2\pi(2/\lambda)(x\cos\theta_1+y\sin\theta_1)]$$
$$+A'(x,y)\cos[2\pi(2/\lambda)(x\cos\theta_2+y\sin\theta_2)] \quad \cdots(0')$$

and assuming about reflection or scattering magnitudes of two beams or waves,

$$A(x,y)=A'(x,y)$$

expresses an LM signal in the coordinate system (X,Y) with the central direction (X) between two beams or waves propagation directions and direction orthogonal to the central direction (Y),

$$A(x,y)\times\cos\{2\pi(2/\lambda)\cos[(1/2)(\theta_2-\theta_1)X]\}$$
$$\times\cos\{2\pi(2/\lambda)\sin[(1/2)(\theta_2-\theta_1)Y]\}. \quad \ldots(0)$$

Two echo signals may have different frequencies. Nonlinear processing can also be implemented on LM signals as follows.

(2A) Exponentiation of LM signal

For instance, the second order exponentiation of eq. (0) is expressed by

$$A(x,y)^2\times\cos^2\{2\pi(2/\lambda)\cos[(1/2)(\theta_2-\theta_1)X]\}$$
$$\times\cos^2\{2\pi(2/\lambda)\sin[(1/2)(\theta_2-\theta_1)Y]\}$$
$$=A(x,y)^2\times[1$$
$$+\cos\{2\pi(2\cdot 2/\lambda)\cos[(1/2)(\theta_2-\theta_1)X]\}$$
$$+\cos\{2\pi(2\cdot 2/\lambda)\sin[(1/2)(\theta_2-\theta_1)Y]\}$$
$$+\cos\{2\pi(2\cdot 2/\lambda)\cos[(1/2)(\theta_2-\theta_1)X]\}$$
$$\times\cos\{2\pi(2\cdot 2/\lambda)\sin[(1/2)(\theta_2-\theta_1)Y]\}],$$

i.e., two harmonic signals, those detected in an alternative direction, and a base-banded signal including a DC with larger bandwidths and higher spatial resolutions than the original LM signal.

(2B) Multiplication of two signals used for LM

The multiplication of two signals, for instance, when the corresponding propagation directions are symmetric with respect to x-axis,

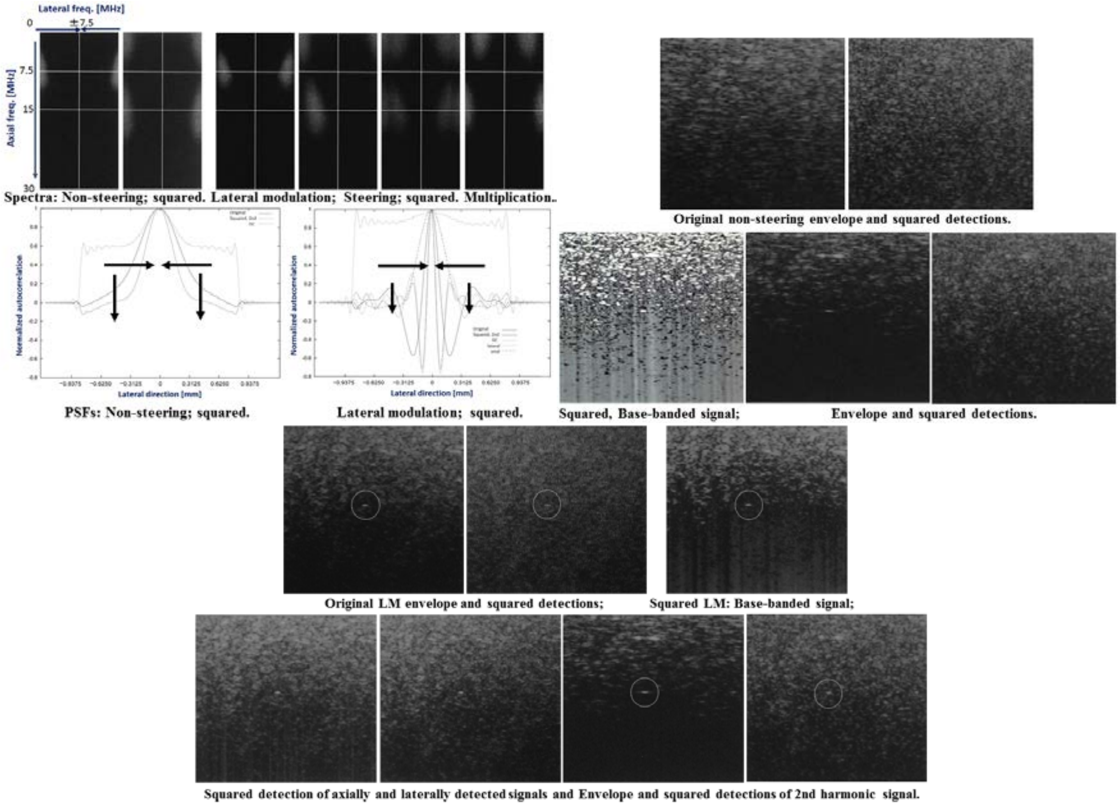
$$\theta_1 = -\theta_2,$$

$$A(x,y)\cos[2\pi(2/\lambda)(x\cos\theta_1 + y\sin\theta_1)]$$
$$\times A'(x,y)\cos[2\pi(2/\lambda)(x\cos\theta_1 - y\sin\theta_1)]$$
$$= A(x,y)\,A'(x,y)$$
$$\times\{\cos[2\pi(2\cdot 2/\lambda)\cos\theta_1 x]$$
$$+\cos[2\pi(2\cdot 2/\lambda)\sin\theta_1 y]\},$$

i.e., two harmonic waves detected in an alternative direction.

For a 3D LM, three crossed beams or waves are generated to yield lateral and elevational frequencies. In addition to the respective harmonic signals, those detected in one or two directions and a base-banded signal including a DC with larger bandwidths and higher spatial resolutions than the original LM signal.

Generated such low and high frequency beams or waves can also be used for reducing speckles via incoherent superposition (compounding). The calculations of harmonic components will also be effective for grasping the process of heat generation with HIFU, i.e., a relation of an acoustic pressure and a thermal dose. This will increase physical nonlinear effects and a non-invasiveness.



Spectra: Non-steering; squared. Lateral modulation; Steering; squared. Multiplication.

Original non-steering envelope and squared detections.

PSFs: Non-steering; squared.

Lateral modulation; squared.

Squared, Base-banded signal;

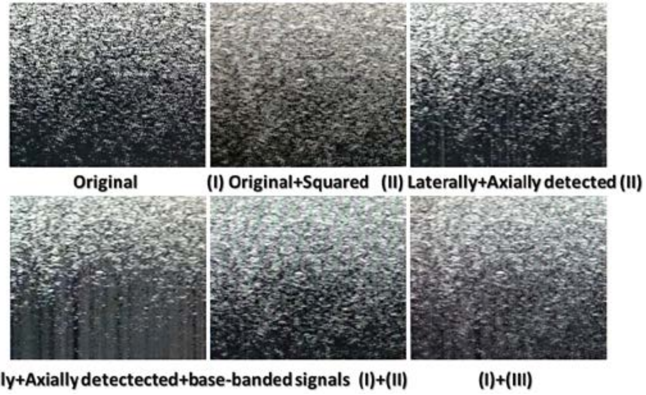
Envelope and squared detections.

Original LM envelope and squared detections;

Squared LM: Base-banded signal;

Squared detection of axially and laterally detected signals and Envelope and squared detections of 2nd harmonic signal.

Fig. 2. Phantom experiments: spectra, PSFs and B-mode images.



Original (I) Original+Squared (II) Laterally+Axially detected (II)

(III)Laterally+Axially detectected+base-banded signals (I)+(II) (I)+(III)

Fig. 3. Speckle reduction via incohenret superposition.

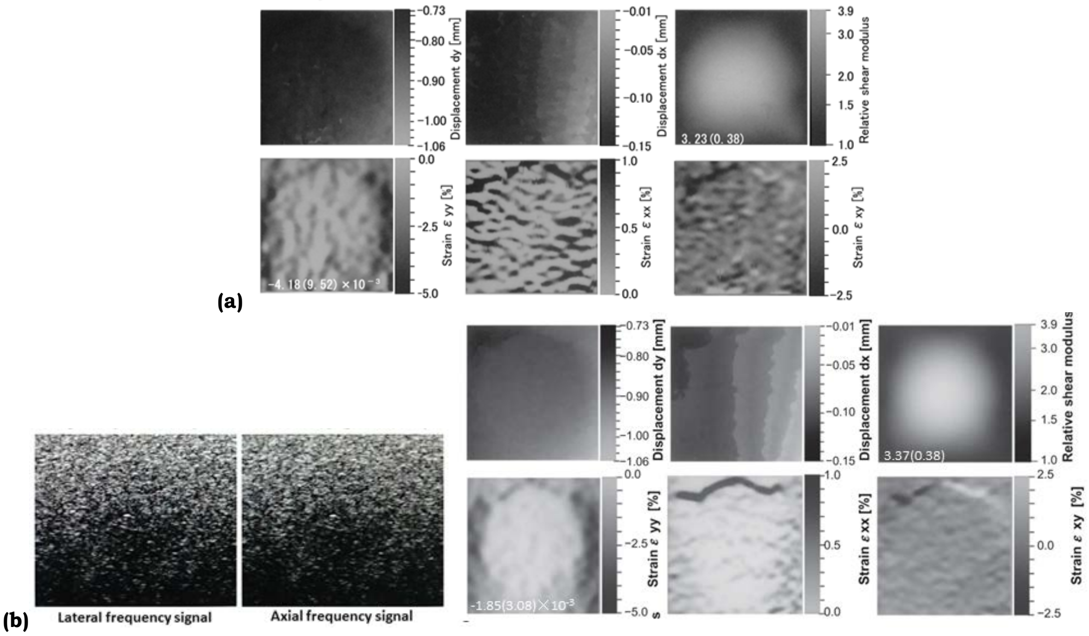
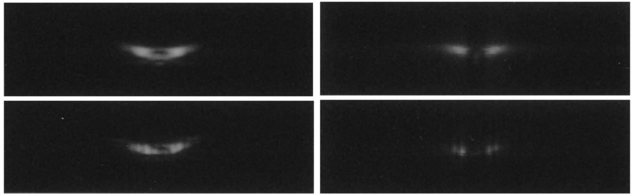


Fig. 4. Displacement vector, strain tensor and shear modulus measurements using (a) nonlinear processing and (b) digital demodulation method [2,3].



Single aperture Duplicate apertures (± 5 deg.)

Fig. 5. Simulations of (upper) US pressures generated using concave transducers; (lower) squared pressures.

The method effectiveness is confirmed using the same experimental echo data as those in [1], i.e., synthetic aperture (SA) data (US freq., 7.5 MHz) obtained on an agar phantom having a cylindrical inclusion (10mm dia.) with a higher agar concentration than the surrounding, or simulations (Field II).

Results: Figure 2 shows spectra, lateral point spread functions and B-mode images obtained on an agar phantom via scanning with (1) a non-steered beam and (2) an LM using two steered beams. The squared echo data were generated from (1) and (2); and multiplied echo data were also generated from (2). B-mode images are shown only for harmonic LM with envelope and parabolic detections. Summarizing, the spatial resolutions increased; the side lobes decreased; the contrast increased (see the strong scattering position circled and top boundary of the inclusion). Figure 3 shows B-mode images with reduced speckles via incohenrent superposition of the nonlinearly processed signals (see also the same strong scattering position and top boundary of the inclusion). Figure 4 shows accurately measured displacements and strains, and shear modulus reconstruction, for instance, obtained for a lateral compression (lateral, y-axis; and axial, x-axis). Actually, spatially zoomed or enlarged echo signals were used via zero-spectra padding in a frequency domain. For comparison, those measured using the digitial demodulation method previously developed [2,3] are also shown, where multiplication and conjugate multiplication of analytic signals of two beams or waves were performed. Although such nonliner processing (i.e., only muliplication or exponentiation) achieves the detections with smaller calculation amonts than the previously reported method, SDs of measuremenets become larger (e.g., lateral strain, 9.52 vs 3.08 × 10^{-3}). Actually, also for the harmonic LM, the displacement vector measurement using the multidimensional autocorrelation method [4] became unstable (omitted). Zooming or enlarging echo signals makes such measurements sensitive to the echo noise. Then, a regularization will be effective, and will be reported in the near future. Figure 5 shows simulated US pressures to be generated with single and duplicate concave transducers (rad. 12 mm; focus, 30mm depth). Here, only the squared pressures are shown.

Conclusions: The new harmonic imaging achieved via nonlinear processing was effective for increasing image qualities, i.e., a spatial resolution and a contrast. Speckle reduction was also effectively performed via incoherent superposition. The detections achieved simultaneously was also effective, i.e., for echo imaging and displacement vector measurement. Heterogeneous high and low frequency signals can also be generated via the nonlinear processing. The processing will also be effective for physically generated harmonic signals, and will be reported in the near future. The coherent superposition will also be effective in further increasing a spatial resolution. The new harmonic imaging can be performed regardless the magnitude of a US wave including a small magnitude US, and will be useful for a microscope. Ultimately high or low frequency signals or mechanical sources not physically acquirable will also be generated and used for a microscope or deforming tissues etc. Over-determined system (e.g., [5]) will also be generated using such quasi-waves, superposition and spectra frequency division, i.e., for echo imaging as well as displacement measurement etc. For increasing a thermal effect and a non-invasiveness, the process of heat generation will also be experimentally investigated, i.e., a relation of an acoustic pressure and a thermal dose. We'll also use various nonlinear effects, for instance, an interference between different physical waves (electromagnetic waves, light etc). Nonlinear materials will also be installed into a transducer.

References:

[1] C. Sumi, IEEE Trans. UFFC, vol. 55, pp. 2607–2625, 2008.
[2] C. Sumi, Reports in Medical Imaging, vol. 3, pp. 61–81, 2010.
[3] C. Sumi et al, Reports in Medical Imaging, vol. 4 pp. 39–46, 2011.
[4] C. Sumi, IEEE Trans. UFFC, vol. 55, pp. 24-43, 2008.
[5] C. Sumi, Proc of 2014 ITEC (030).