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Study about ultrasound high precision imaging/therapy with frequency modulation and nonlinear processing

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1. Introduction

We have been developing ultrasound echo imaging methods with high spatial resolution and high signal-to-noise ratio, vectoral Doppler imaging and high spatial resolution HIFU (High Intensity Focus Ultrasound) treatment methods. In this paper, we report 2 approaches for improving the accuracy of these methods, i.e., with modulating the carrier frequency of the transmitted and received signals,[1)] and the nonlinear processing methods.[2)]

2. Method

Analog or digital beamforming with analog or digital modulation of the carrier frequency can improve the spatial resolution in the lateral direction by performing synthetic aperture (SA) with respect to the generated high-frequency signals. The frequency modulation can be performed within the observation object or device by shifting the spectrum in the frequency domain; or multiplying a modulation signal to the target signal in the space-time domain. Detection can also be included. Nonlinear processing and nonlinear phenomena can also be applied to SA. In this case, simultaneously broadbanding (high resolution) and high contrast can be achieved in all directions. Coherent compounding in an analogue or digital fashion of several differently modulated high/low frequency or broadbanded signals can also effectively increase the bandwidth. We have also reported in the past the reduction of speckle by incoherent compounding in these cases [1, IEICE's reports, etc.].

For example, scattering media or other dedicated media and devices can be applied for increasing a frequency in an analogue fashion, whereas attenuator can be used for decreasing a frequency similarly. Beamforming based on pseudo-harmonic generation by multiplication or power operations was also developed as mentioned above. Similarly, analog nonlinear processing (e.g., media and devices as mixers) is useful in addition to the digital processing. Increasing the frequency and/or bandwidth can be performed actively inside the sensor body or by intervention between the sensor and the observation site such as using microbubbles. Needless to say that it is harmonic imaging when using microbubbles inside the observation site. These processes enable the generation of high-spatial resolution ultrasound echo signals even with a narrower effective aperture than usual and also enable HIFU treatment including inside the body, etc., thereby increasing targets. Microbubbles are also useful in improving the heating effect of HIFU, especially by the nonlinear effect. Wave superposition and crossing are also useful.

Analytic signals are useful in modulation and nonlinear processing. Spectral overlap can be avoided and aliasing, if it occurs, can be easily compensated by broadening process with zero-spectrum padding in the frequency domain. In the spatio-temporal domain, the number of processes increases, so the analytic signal should be used as needed. In any case, beamforming after broadening by zero-spectrum padding is computationally more expensive, but the number of signal values increases and the signal-to-noise ratio can be earned. Beamforming with pixel-wise or finer bandwidth (Fourier beamforming) is also useful. Processing on scattering media is particularly attractive.

In Doppler observations, even if aliasing occurs, the correct phase change due to displacement can be often obtained without broadbanding, and the instantaneous frequency can be corrected analytically and processed. This process avoids the deterioration of signal-to-noise ratio due to broadbanding, and thus the loss of observation accuracy. Until now, Doppler observations have also been sought about a higher resolution by us. Breaking away from the narrow bandwidth observation of the past, we have been developing vectoral Doppler methods that enable precise, high-resolution observation of human soft tissue dynamics and blood flow using high-resolution echo signals for echo imaging.[3)] Doppler provides better accuracy at higher frequencies,[4)] and therefore, detection as well as high-frequency and broadband processing through high-frequency modulation and nonlinear processing, is useful, and their processing before or during beamforming is useful. However, nonlinear processing is associated with bandwidth broadening, which may degrade the signal-to-noise ratio. Therefore, additive processing in the case of powers and multiplications should be performed. When performing nonlinear processing after beamforming, regularization process was required to stabilize the measurement.[2)]

3. Examples of Imaging and Doppler Observation

In this paper, to demonstrate the fundamental performance, we report the results of echo imaging and vectoral Doppler observation obtained on an agar phantom (ALOKA SSD5500, 7.5 MHz).

As a matter of fact, we had reported some

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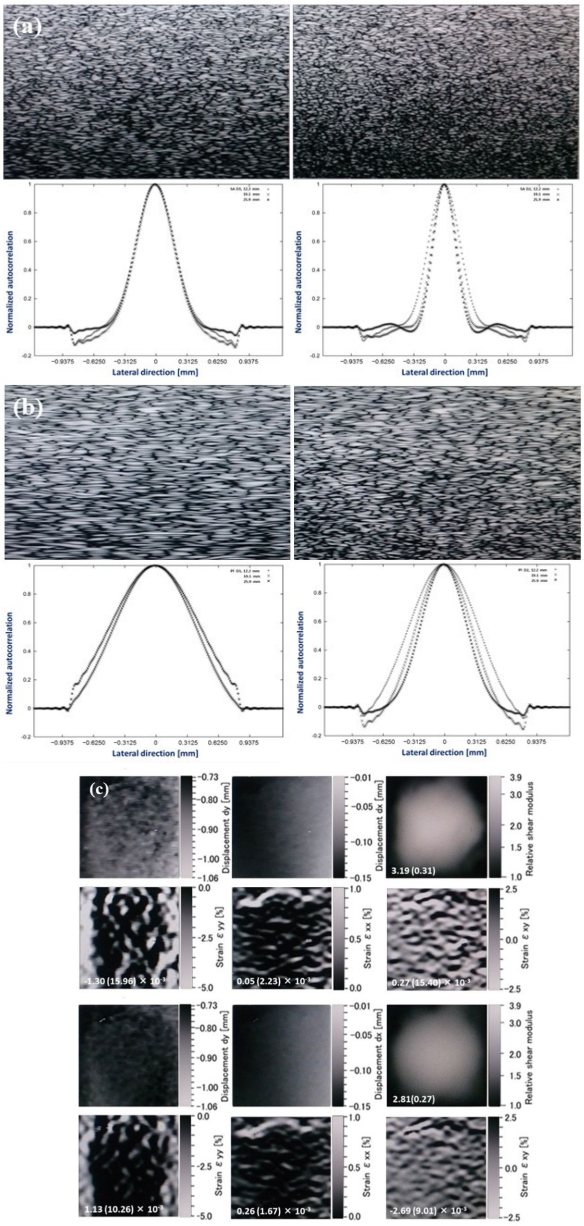

Fig.1 Echo images and estimated PSFs for (a) SA and (b) PW (left) without and (right) with modulation; and (c) vectoral observation results for SA (upper) without and (lower) with modulation, with depicted means (and standard deviations).

results obtained through an interesting frequency modulation, at the IEICE US meeting (Feb 2016),[5] with about SA processing using delay-and-summation (DAS) and Fourier beamforming and however, we omitted the specific explanation about the modulation. Specifically, the frequency was gradually increased in the depth direction (x), although it would normally modulate to the same frequency at each depth (omitted here). The modulation was performed together with the pixel-wise DAS using a complex modulation function. **Fig. 1** shows (a) for SA and (b) plane wave (PW) transmission with reception dynamic focusing the echo images and the lateral (y) profiles of estimated sound pressure or point spread function (PSF,

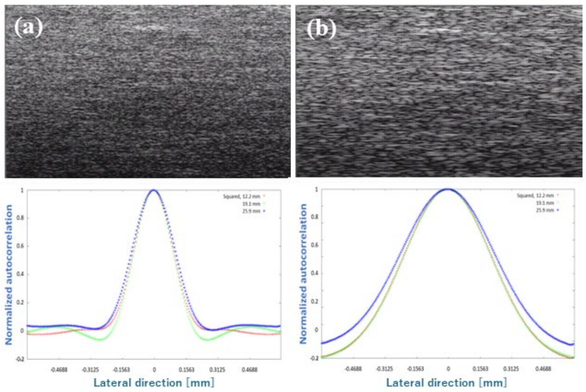

Fig. 2 Echo images and estimated PSFs for (a) SA and (b) PW beamforming with 2nd power reception signals in DAS.

autocorrelation function) at depths of 12, 19 and 26 mm (left) without and (right) with the modulation. As shown, the spatial resolution in the lateral direction increases with depth. And, **Fig. 1c** shows for SA the vectoral observation results (upper) without and (lower) with the modulation, i.e., displacements, strains and shear modulus. Accordingly, all the accuracy of observation increases with depth.

Non-linear processing was also performed. Unlike the results[2)] previously reported with after beamforming, these are obtained with before beamforming.[2)] Similarly to with after plural wave beamforming, multiplication can be performed between reception signals instead of summation, however, with combination of summation, in DAS. Alternatively, **Fig. 2** shows echo images and estimated PSFs obtained by summing the n-th powers of signals (a) for SA and (b) PW. The spatial resolutions were the much higher than those with after beamforming[2)]. Since the decrease in signal-to-noise ratio due to broadbanding led instability slightly, the regularization was required.

4. Conclusion

The above will be reported elsewhere in more detail. The applications of this approach are not limited to the above. For instance, we have been reporting for superresolution with the combination of inverse filtering [IEICE's reports, etc.]. Various applications can also be expected with electromagnetic and thermal waves.

References

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