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Reconstruction of sawtooth waves using phase compensation of surface waves excited by focused airborne nonlinear ultrasound

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1. Introduction

We have studied a pulse compression methods using nonlinear chirp signals and frequency interpolation by mixing. The purpose of this research is to improve the accuracy [1] of nondestructive testing [2] using an elastic source scanning method using an airborne ultrasound phased array (AUPA).

In this method, surface acoustic waves (SAW) are excited by focused ultrasound, which causes phase distortion in the pulse compression result due to the phase shift of each harmonic component. To remove the phase distortion, it is necessary to remove the phase shift of each harmonic component.

In this report, we proposed the reconstruction of a sawtooth wave using phase compensation of each harmonic component. We also verified the effectiveness of the proposed method.

2. Phase shift in nonlinear focused airborne ultrasound

Figure 1 shows the schematics of the phase shift of the SAW excited by the AUPA. As shown in Fig. 1, high-intensity ultrasounds emitted from the AUPA generate harmonics at the focal point, and each harmonic component has a phase shift of 90° multiple of the harmonic order. As a result, the sawtooth distortion wave was transformed into the upward convex waveform, and the SAW excited by such the ultrasounds also propagates with the upward convex waveform.

3. Phase shift compensation by the proposed method

We propose pulse compression using a nonlinear chirp signal and frequency interpolation by mixing. In this method, the discontinuous frequency bands that occur between each harmonic were interpolated using a chirp signal generated by mixing. Thereby, continuous frequency characteristics were obtained over a wide band. Here, the phases of the harmonics are different at the focusing point. Hence, the phases of the chirp signals generated by mixing

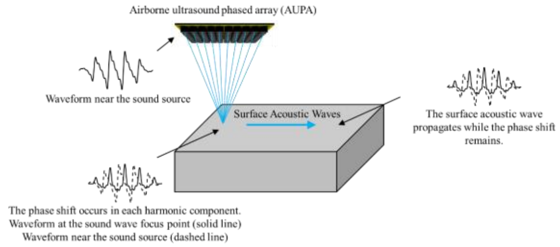

Fig. 1. Schematics of the phase shift of the SAW excited by the AUPA.

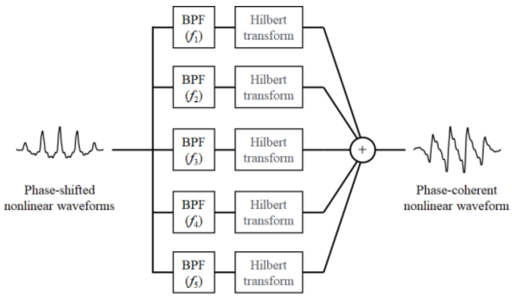

Fig. 2. Schematics of phase compensation for each harmonic component of nonlinear focused ultrasound.

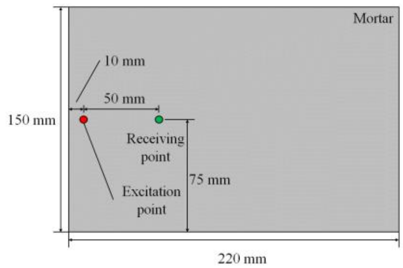

Fig. 3. Schematics of the analysis.

were also different. This causes phase distortion in the pulse compression result. In order to suppress pulse distortion, it is necessary to compensate the phase of each harmonic and match the phase of the fundamental wave and the harmonic. Figure 2 shows the schematics of the proposed method for phase compensation of each harmonic component in the nonlinear focused ultrasound. First, each harmonic component is extracted from the phase-shifted nonlinear waveform using a band pass filter (BPF). Next, phase compensation is performed by multiple

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Hilbert transforms. At this time, the phase of each harmonic component is matched with the fundamental wave. After that, each phase-compensated frequency component is added to obtain a nonlinear waveform with a consistent phase.

4. Verification by numerical simulation

We conducted a numerical simulation, to verify the effectiveness of the proposed method. Figure 3 shows the schematics of the analysis. The sample was assumed to be mortar, and the analysis area was 220 × 150 × 60 mm. The analysis conditions are as follows. First, the SAW excitation condition was assumed to be irradiation of airborne ultrasound, and an excitation source with a diameter of 20 mm was set at the excitation position shown by the red dot in the figure. Assuming irradiation of airborne ultrasound, the input waveform to the excitation source was the waveform [2] measured by a microphone of the sound pressure at the sound wave focal point of the AUPA. The analysis was performed using COMSOL 6.0 under the simulation conditions and material constants shown in Table 1. At this time, the acceleration waveform at the position shown by the green dot was extracted, and the signal processing described in Section 3 was applied.

5. Result

The analysis results are shown in Fig. 4. Fig. (a) shows the entire analysis time, and Fig. (b) shows an enlarged view of the time range from 100 to 600 μs in Fig. (a). Focusing on the results, it was confirmed that the SAW propagates with the phase shift due to sound focusing with respect to the harmonics generated by nonlinearity. This tendency is particularly evident from 200 μs onwards, when the amplitude rises.

Next, we verified the effectiveness of the proposed method. Figure 5 shows the analysis results when the proposed method was applied. The results confirmed that the sawtooth wave was reconstructed by matching the phase of each harmonic component. In particular, it can be clearly seen that the sawtooth wave was reconstructed after 200 μs, when the waveform rises in Fig. 4.

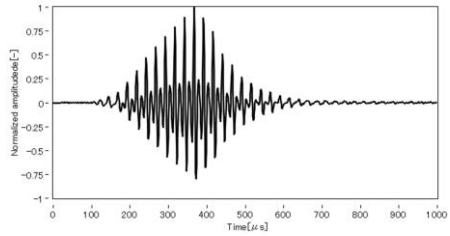
6. Conclusion

In this report, we proposed the method to reconstruct the sawtooth wave by phase compensation of each harmonic component of the SAW excited by nonlinear focused ultrasound, and verified its effectiveness.

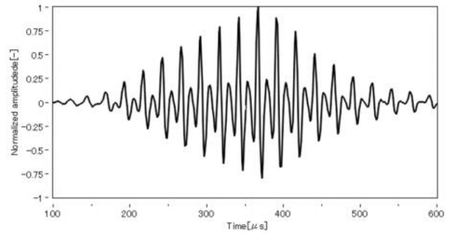
As a result, we confirmed that the proposed method can reconstruct the SAW excited by nonlinear focused ultrasound into the sawtooth wave.

Table 1. Simulation conditions and material constants.

Material	Mortar
Density	2300 [kg/m^3]
Young's modulus	25 [GPa] ([N/mm^2])
Poisson's ratio	0.2
Mesh shape	Free mesh tetrahedron
Mesh size	0.5 ~ 10 [mm]
Sampling Frequency	1 [MHz]
Sample Time	1 [ms]

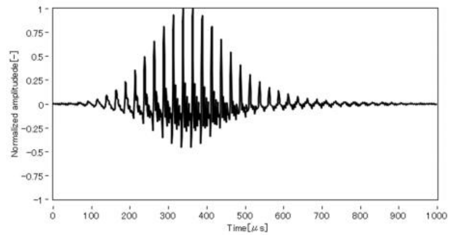


(a) Overall analysis time.

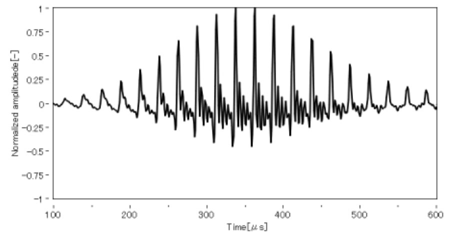


(b) Enlarged at t = 100 to 600 μs.

Fig. 4. Analysis results.



(a) Overall analysis time.



(b) Enlarged at t =100 to 600 μs.

Fig. 5. Analysis results after phase compensation.

Acknowledgment

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References

1) K. Shimizu et al, Jpn. J. Appl. Phys. **62**, SJ1046 (2023).
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