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Verification of High-order Harmonic Components of Nonlinear Airborne Ultrasound Using Pulse Inversion Method

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1. Introduction

We have proposed the Harmonic Imaging (HI) using airborne ultrasounds with the nonlinear effects[1,2]. In this report, we applied the Pulse Inversion method (PI) to airborne ultrasounds in order to perform the HI using high-order harmonics with a high Signal-to-Noise Ratio (SNR). In addition, the PI using over two signals was performed to extract high-order harmonics with the high SNR[3].

2. Principle of pulse inversion method

The phase of the n th harmonic generated by the nonlinear effects is rotated by n times of an initial phase. Here, a finite-amplitude sound wave $P(t)$ is given by

$$P(t) = \sum_{n=1}^{N} P_n(t) = \sum_{n=1}^{N} p_n \sin\{n(2\pi f_0 t + \theta)\}. \quad (1)$$

θ is the initial phase, p_n is the amplitude of the n th harmonic, f_0 is a fundamental frequency, n is the order of the harmonics, and $P_n(t)$ is the n th harmonic at the initial phase θ.When the initial phases of m signals are

$$\theta = \phi_0, \phi_0 + \frac{1}{m}(2\pi), \dots, \phi_0 + \frac{m-1}{m}(2\pi), \quad (2)$$

the equation to extract an arbitrary order harmonic is given by

$$P(t)|_{\theta=\phi_0} + P(t)|_{\theta=\phi_0+\frac{1}{m}(2\pi)} + \cdots P(t)|_{\theta=\phi_0+\frac{m-1}{m}(2\pi)} = \sum_{n=m}^{mk} m p_n \, sin(2\pi n f_0 t),$$
$$(n = m, 2m, \dots, mk). \quad (3)$$

ϕ_0 is the initial phase at $m = 1$ and k is the natural number. Eq. (3) shows that the amplitude of m th multiple harmonics is increased by m times. In addition, Eq. (3) shows the other harmonic components are eliminated. For an example, we extract the third multiple harmonics from Eq. (3). Substituting $\phi_0 = 0$ and $m = 3$ for Eq. (3), the equation is given by

$$P(t)|_{\theta=0} + P(t)|_{\theta=\frac{2}{3}\pi} + P(t)|_{\theta=\frac{4}{3}\pi} = \sum_{n=3}^{3k} 3p_n \sin(n\omega_0 t) \quad (n = 3,6,\dots,3k). \quad (4)$$

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From the above theory, we performed experiments for $m = 3$ to extract the third multiple harmonics.

3. Outline of Experiment

3.1 Outline of experimental devices

Figure 1 shows the schematic of the experimental devices. The experimental devices ware composed of an Airborne Ultrasound Source (AUS), a 1/8 inch microphone, and peripheral equipment. The AUS consists of 400 ultrasound emitters (resonant frequency: 40 kHz) arranged along the hemisphere with the radius of 150 mm. The sound waves radiated from the AUS are focused at the center of a sphere. The AUS was driven with the driving frequency of 40 kHz, the applied voltage of 50 Vpp, and the sinusoidal wave of 10 cycles.

The measurement was synchronized with the rising edge of the input signal to the AUS, and sound pressure waveforms were acquired at the sampling frequency of 1 MHz.

3.2 Experimental methods

The experiments ware performed as follows. First, the microphone was placed at the sound wave focus point. Second, the AUS was driven by the signal with the initial phase of 0°($\theta = 0$) under the experimental conditions described in Section 3.1, and the sound pressure waveform was acquired by the microphone. Next, under the above experimental conditions, the AUS was driven by the signal with the initial phase of 120° ($\theta = 2/3\,\pi$) , 240° ($\theta = 4/3\,\pi$) and the sound pressure waveforms were also acquired by the microphone. Finally, three sound pressure waveforms acquired above ware added.

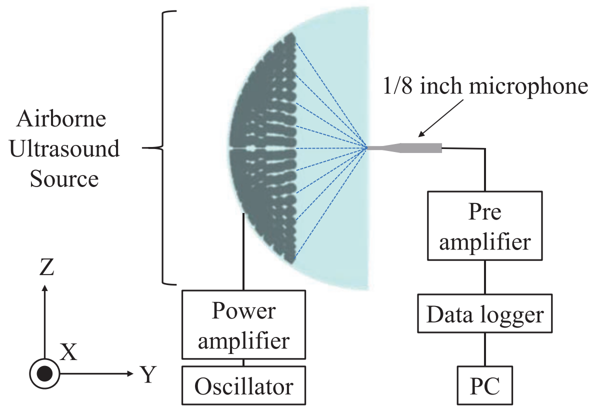

Fig.1 Experimental devices.

4. Experimental results

Figure 2 is the sound pressure waveform acquired by the microphone and a frequency analysis result. In Fig. 2(b), the frequency analysis result is normalized by amplitude of a fundamental component (40 kHz) is equaled as 0 dB.

As shown in Fig. 2(a), the sound pressure waveform shows that a maximum positive sound pressure is about 10000 Pa. On the other hand, a maximum negative sound pressure is about 4000 Pa. Therefore, the nonlinear effects occur in the acquired sound pressure waveform. In addition, the frequency analysis result in Fig. 2(b) shows that harmonic components are appeared up to the fourth harmonics.

Figure 3 is the results of applying the PI to the above acquired sound waveforms. As shown in Fig. 3(a), the amplitude of the sound pressure waveform has the sound pressure of about 4000 Pa at the peak of the positive and negative sound pressures. Fig. 3(b) shows the result of a frequency analysis. Observing the changed amplitude of each frequency component, the amplitude of the fundamental component in Fig. 3(b) is decreased by 13.8 dB compared to that of the fundamental component in Fig. 2(b).

In addition, the amplitude of second harmonic component in Fig. 3(b) is also decreased by 13.8 dB compared to that of second harmonic component in Fig. 2(b). However, the amplitude of the third harmonic component in Fig. 3(b) is increased by 8.7 dB compared to that of the third harmonic component in Fig. 2(b). That is, the amplitude of the third harmonic component is increased by about 22.5 dB relative to that of the fundamental and second harmonic components.

5. Conclusion

We applied the PI to airborne ultrasounds in order to perform the HI using high-order harmonics with the high SNR. As the results, it was confirmed that the fundamental and second harmonic components were decreased and the amplitude of the third harmonic component was increased. These results indicated the possibility of the HI using high-order harmonic components with the high SNR.

Acknowledgment

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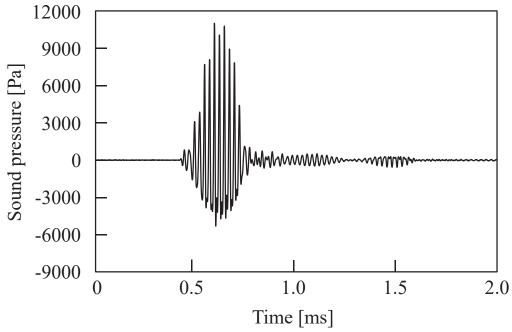
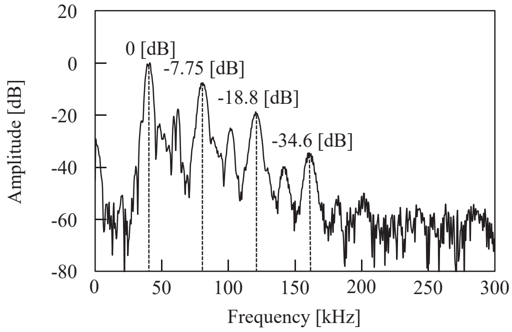
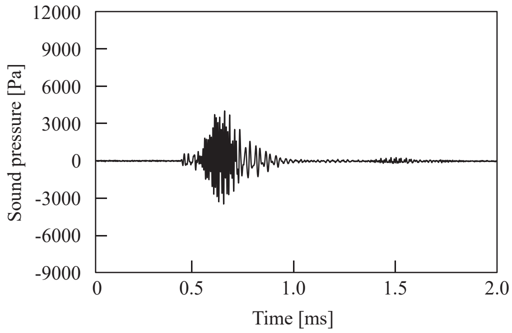


(a) The sound pressure waveform ($\theta = 0$).

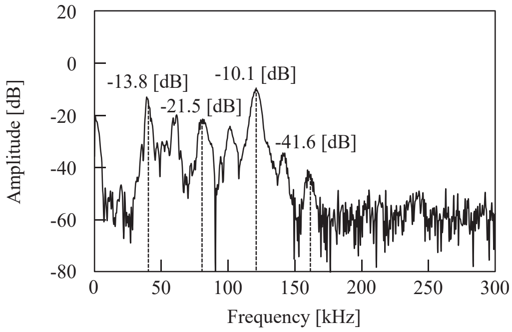


(b) The frequency spectrum ($\theta = 0$).

Fig.2 Results of the time waveform and frequency analysis.



(a) The sound pressure waveform.



(b) The frequency spectrum.

Fig.3 Results of applying the PI.

References

1) A. Osumi et al, Jpn. J. Appl. Phys. Vol 58, SGGB142 (2019)
2) A. Osumi et al, *Acoust. Sci.& Tech.*, Vol 41, pp. 885–890 (2020).
3) Qingyu Ma et al 2007 Phys. Med. Biol. 52 1879.