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# Pulse compression of parametric ultrasound with M-sequential coded excitation

M 系列信号によるパラメトリック超音波のパルス圧縮

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## 1. Introduction

High-frequency ultrasounds are used in acoustic imaging. However, since ultrasound at high frequencies is much attenuated by medium viscosity, the penetration depth is limited. One of the solutions to resolve this problem is to use a directive sound source at low frequency, such as a parametric sound source[1]. However, since the generation of parametric sound is a secondary effect induced by the nonlinear propagation of finite-amplitude ultrasounds as primary sound, the amplitude of parametric ultrasound may not be enough to obtain sufficient signal-to-noise ratio (SNR).

In order to improve the SNR of parametric ultrasound echo, we have applied the pulse compression (PC) technique with chirp modulation to the parametric ultrasound[1]. The experimental results indicated that the PC technique is a useful to improve the SNR of parametric ultrasounds, in addition, we can obtain low-frequency ultrasound image using the parametric ultrasound at several hundred kHz applied by the PC technique[3,4]. However, the PC with chirp signal indicates high time sidelobe level in the compressed signal.

In this study, to reduce the sidelobe level of compressed parametric ultrasound, we apply maximal length sequential (M-sequential) code excitation to the parametric ultrasound. It is known that the PC of M-sequential signal improves the sidelobe level, however, this application has been considered only in a linear signal. In order to verify the application of M-sequential code to the PC of parametric ultrasound, we confirm the generation M-sequential coded parametric ultrasound, and evaluate the performance of reduction of sidelobe.

## 2. Method

A single-element ring-type transducer with the outer and inner diameters of 32 and 8.5 mm, respectively, was placed in water as a transmitter for primary ultrasounds[3,4]. The transmitter was driven by the modulated signal at the center frequency of 2.8 MHz to generate the parametric ultrasound at 400 kHz with 4th and 8th order M-sequences. One-code of M-sequence corresponds to one-cycle of the 400-kHz signal. For a comparison, chirp-modulated parametric ultrasound with frequency from 100 to 500 kHz was generated. Primary ultrasounds are radiated from the transmitter as tone-burst signals with durations of about 33.3 μs for the chirp signal, and 37.5 and 637.5 μs in the M-sequence with the orders of 4 and 8, respectively.

Parametric ultrasounds generated from the primary ultrasounds were received by a hydrophone at 16 cm from the transmitter. The cross-correlation function (CCF) between the received signal and a reference signal was computed to compress the signal. Reference signals were desired parametric ultrasound signals, that is, M-sequential coded signals of 400 kHz and a chirp modulated signal with frequency from 100 to 500 kHz.

## 3. Results and discussion

**Figure 1** shows received parametric ultrasound signals. These signals are normalized by each maximum amplitude. The time at which ultrasound arrives indicates the relative time of 0 s.

Chirp modulated parametric ultrasound signal in Fig. 1(a) indicates the variation of instantaneous frequency from low to high frequency with time. Noise in the chirp signal is larger than that in M-sequential signals in (b) and (c). This is caused by the amplitude of driving voltage for chirp signal was lower than that for M-sequential coded signal.

Parametric ultrasound signals coded by M-sequence in Figs. 1(b) and (c) indicate abrupt signal changes in amplitude at the time when codes are changed from 0 to 1 or from 1 to 0. However, the phase changes according to the code are not accurately occurred. The most likely cause for this imperfect phase change is that the limitation of frequency bands of generated parametric ultrasound, the hydrophone with pre-amplifier are too narrow to accurately reproduce M-sequential coded the signal.

**Figure 2** shows the PC of the parametric

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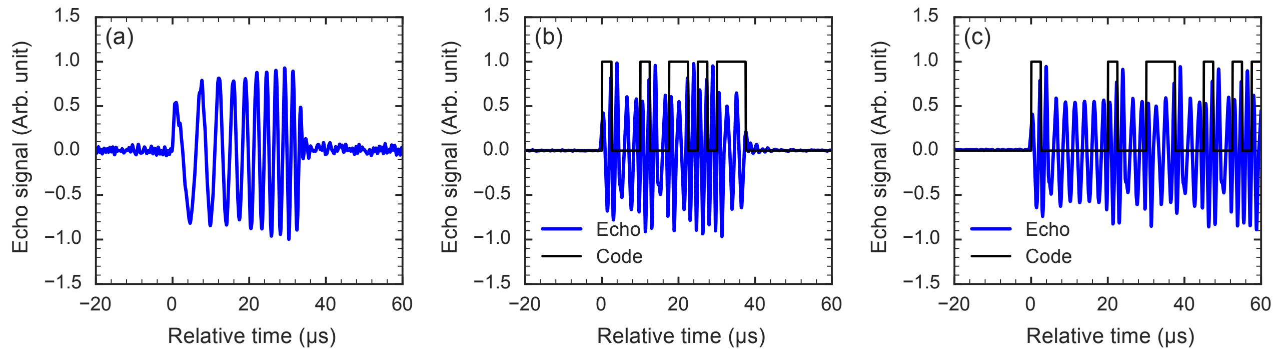


Fig. 1 Received echo. (a) Parametric ultrasound with chirp signal and (b) and (c) are parametric ultrasounds with M-sequential code of the order of 4 and 8, respectively. In (b) and (c), M-sequential codes of the order of 4 and 8 are plotted with together, respectively. Relative time 0 means arrival time of echo at 16 cm from the sound source.

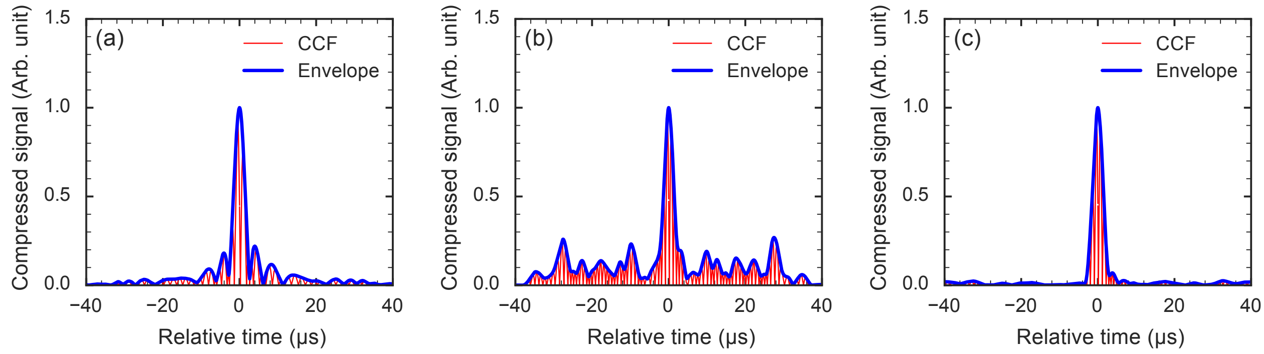


Fig. 2 Pulse compressed signal. (a) Parametric ultrasound with chirp signal and (b) and (c) are parametric ultrasounds with M-sequential code of the order of 4 and 8, respectively. Relative time 0 means arrival time of echo at 16 cm from the sound source.

ultrasound signal. The compressed pulse is plotted as the absolute value of CCF and the envelope of that. Experimentally obtained mainlobe widths, which are defined by the half-width at half maximum, are about 3 μs for chirp-modulated and M-sequential coded parametric ultrasounds, and these values agree well with the theoretical value.

The PC of the chirp signal in Fig. 2(a) indicates a concentrated pulse at relative time 0 s. However, sidelobes, which affect the SNR of low-frequency ultrasound images[3,4], are generated around the mainlobe. The PC of M-sequence in Fig. 4(b) has multiple large sidelobes. To reduce the sidelobe, we increase the order of M-sequence to 8. The result indicates no sidelobes in the compression of the parametric ultrasound in Fig. 4(c).

Sidelobe amplitude decreases theoretically to $1/(2^M-1)$ of mainlobe for continuous $M$-th order M-sequence as a pseudo random signal. Although the excitation by tone burst signals in this experiment does not improve the sidelobe level as much as theory, the experimental result shows that introducing the M-sequential coded excitation to the PC of parametric sound is one of the effective methods to reduce sidelobes.

## 4. Conclusions

In this study, to reduce the sidelobe level of compressed parametric ultrasound, we applied the M-sequential coded excitation. The experimental results indicate that the application of M-sequential code to parametric ultrasound is one of the effective methods to improve the SNR of low-frequency ultrasound imaging using the parametric ultrasound compared with the PC of the parametric ultrasound with chirp-modulation.

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