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Application of Pulse Compression Technique to Parametric Difference Frequency Sound
パラメトリック差音へのパルス圧縮技術の適用

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1. Introduction

The directivity of parametric difference frequency sound (hereinafter referred to as the parametric sound) is narrower than that of linear sound at the same frequency radiated from a sound source with the same aperture size.[1,2] In addition, the parametric sound can propagate in a long distance in a dissipative medium, because sound absorption at low frequency is less than those at ultrasound frequencies for usual ultrasound measurements and medical imaging system.[3] However, for applications of parametric sound for measurements and imaging, that has a disadvantage of low range resolution.

To improve the range resolution of parametric sound, we have proposed the application of pulse compression technique to parametric sound.[4] To verify our proposal, we estimated the pulse compression of parametric sound using a numerical simulation, and the simulation results indicated that the pulse compression is also useful for the parametric sound.

In this study, to evaluate the realization of low frequency directive sound source with high range resolution, we estimate experimentally the pulse width of compressed parametric sound and compare between the results obtained from the simulation and experiment.

2. Theory

The pulse compression is archived by transmitting a modulated signal and the cross-correlating between receiving and reference signals, and is originally used in rader to cope with spatial resolution and detection distance range. In this study, a chirp signal is used as a modulated transmitting signal, however, a chirp excited parametric sound is needed.

To generate a parametric difference frequency sound, two intense ultrasounds (primary sounds) $s_1(t)$ and $s_2(t)$ at different but neighboring frequencies are radiated in coaxial direction, where t is the time variable. To generate chirp excited parametric sound, a sound source is driven by the added signal of $s(t)=s_1(t)+s_2(t)$, where

$$s_1(t) = \begin{cases} A_1 \sin\left(2\pi\left[\left\{f_0 + \frac{f_{\mathrm{start}}}{2}\right\} + \frac{\mu t^2}{4}\right]\right), & 0 \le t \le T_{\mathrm{s}} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$s_2(t) = \begin{cases} A_2 \sin\left(2\pi\left[\left\{f_0 - \frac{f_{\mathrm{start}}}{2}\right\} - \frac{\mu t^2}{4}\right]\right), & 0 \le t \le T_{\mathrm{s}} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

so that the instantaneous frequency of parametric sound is a linear sweep frequency $f_{\mathrm{d}}(t)$,

$$f_{\mathrm{d}}(t) = f_{\mathrm{start}} + \mu t = f_{\mathrm{start}} + B\frac{t}{T_{\mathrm{s}}}, \tag{3}$$

where f_0 is the center frequency, A_1 and A_2 are amplitudes, $\mu=B/T_{\mathrm{s}}$ is the frequency sweep ratio, $B=f_{\mathrm{stop}}-f_{\mathrm{start}}$ is the sweep width, f_{stop} and f_{start} are the stop and start frequencies of sweep, respectively, and T_{s} is the sweep time.[4]

The distance between an object and an observer is estimated from delay time of an echo signal from the target object using the cross correlation between the echo and a reference signal. In addition, mechanically or electrically scanning of radiated ultrasound beams, we can obtain two and three dimensional images.

3. Experiment

In practical usage, cross-correlating of echo and reference signals is used to measure a distance and image, however, as a fundamental study, we calculated an auto-correlation of receiver chirp excited parametric sound to evaluate the pulse compression. In addition, we carried out an experiment using a transducer as the transmitter and a hydrophone as the receiver, although, in practical situations, ultrasounds are transmitted and received by one transducer or an integral transducer consisting of transmitter and receiver.

Experiments were carried out in underwater. The circular aperture planar type transducer with one inch in diameter is driven by the signal $s_1(t)+s_2(t)$ with both amplitudes of 30 kPa at the center frequency.

The center frequency f_0 and the start

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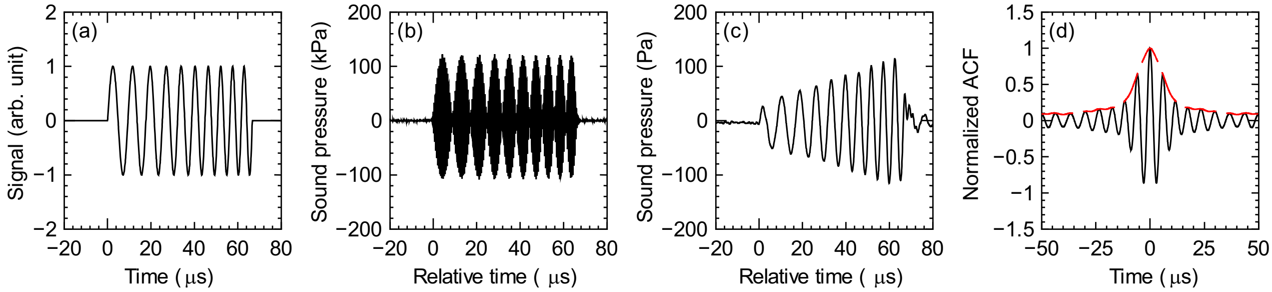

Fig. 1 Received ultrasound for chirp excited parametric difference frequency sound of B=100 kHz at 10 cm from the sound source: (a) reference signal, (b) received nonlinearly propagating ultrasound, (c) extracted chirp excited parametric sound and (d) auto-correation function (ACF) of the parametric sound, where solid and dashed curves indicate the RF component and envelope of ACF, respectively.

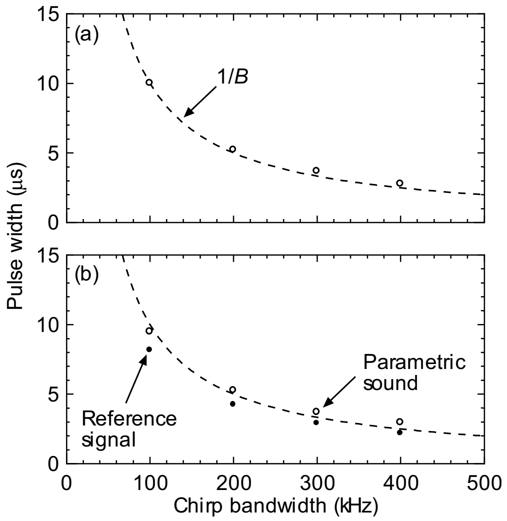

Fig. 2 Compressed pulse width: (a) experimental and (b) simulation. The pulse width is estimated at the width at −3 dB of maximum amplitude of the envelope of ACF.

frequency f_{start} were set to 2.1 MHz and 100 kHz in constant, respectively. Sweep times T_s were set to 66.7, 50.0, 40.0 and 33.3 μs for sweep band widths B of 100, 200, 300 and 400 kHz, respectively, to generate 10 cycles of parametric sound.

Fig. 1 shows an example of experimental result observed at 10 cm from the sound source for a chirp bandwidth B of 100 kHz . This result shows that the instantaneous frequency of the parametric sound (c) incleases with time, and the waveform of that is similar to that of the reference signal (a) which is desired difference frequency signal.

In addition, the width of compressed parametric sound, that is the auto-correlation function (ACF) of parametric sound, is narrower than that ofreceivingd ultrasound (b).

Fig. 2(a) shows the dependence of the width of the envelope of ACF as the pulse width on the chirp bandwidth. The pulse width is estimated at the width at −3 dB of the mamimum of amplitude. The dashed curve indicates the theoretical width $1/B$. The experimental results agree well with the theoretical values.

As the reference, compressed pulse width of the parametric sound obtained from simulations[4] and reference signal are plotted in Fig. 2(b). From this comparison, the experimental results agree well with the simulations, and are slightly wider than the width obtained from the reference signal, which is ideal pulse compression.

4. Conclusion

In this study, we experimentally evaluated the application of pulse compression technique to the parametric sound to improve the range resolution of the parametric sound as a directive low frequency sound. The results indicate that the pulse compression is also useful for the parametric sound, and similar performance to simulation is obtained. This is suggestive of a realization of low frequency directive sound source with high range resolution.

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