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Ultrasound Imaging Using Super Resolution FM-chirp Correlation Method
超解像手法を用いた超音波イメージング

Masaki Fujiwara[1†], Kan Okubo[1] and Norio Tagawa[1] ([1]Guradate School of System Design Tokyo Metropolitan Univ.)
藤原幹己 [1‡]，大久保寛 [1]，田川憲男 [1] （[1] 首都大学東京大学院　システムデザイン研究科）

1. Introduction

In recent years, there has been growing demand for ultrasound imaging in clinical diagnosis. Ultrasound diagnosis requires images with high resolution and high SN ratio. For this purpose, narrow and high-power pulses must be transmitted. However, transmission has restrictions on the power consumption in a living body. Therefore, the pulse-compression technique (PCT) [1, 2] has been introduced. In the meantime, the PCT resolution is insufficient when multiple scatterers are in close formation. The resolution depends on the sharpness of the auto-correlation function of the transmitted signal. Therefore, for FM-Chirp PCT, the time resolution of echoes is limited by the sweep-frequency bandwidth.

As described in this study, to improve the resolution performance, we propose the Super resolution FM-Chirp correlation Method (SCM). SCM is based on the multiple signal classification (MUSIC) algorithm [3, 4]. On the other hand, the Super resolution Pulse-compression Method (SPM) [5, 6] has been proposed to analyze the multipath structure of radiowave propagation. SPM uses a pseudo-noise (PN) sequence (actually the M-sequence) for the transmitted signal. PCT with a FM-chirp signal, however, might be more convenient for ultrasonic measurement because of the bandwidth limitation of ultrasound transducers. Simulations were conducted using FM up-chirp signals having a 2 MHz of bandwidth, a 10 MHz of center frequency, and a 2.0 μs of pulse width. SCM was applied to model signals assuming multiple scatterers. We confirmed that SCM can generate a sufficiently high-resolution signal through the simulation. Additionally, we presented instances of ultrasound imaging using SCM.

E-mail : m.fujiwara.tmu@gmail.com

2. Outline of SCM Algorithm

We review how SCM employs the MUSIC algorithm to improve the imaging resolution. Assuming that the received echo signal comprises multiple echo signals from unknown D scatterers with different delay times, an impulse response $h(t)$ is given as

$$h(t) = \sum_{i=l}^{D} h_i \delta(t - \tau_i)\,, \qquad (1)$$

where $\{h_i\}$ is a set of complex amplitudes and $\{\tau_i\}$ is a set of propagation delays required to be estimated. Furthermore, $\delta(\bullet)$ is the Dirac delta function. The correlator output $z(\zeta)$ is the superposition of scaled copies of the chirp signal's auto-correlation. It is difficult to separate echoes having a small delay in relation to each other. Assuming the transmission of a linear FM chirp signal $s(t)$, the cross-correlation of echo with $s(t)$ is

$$v(\zeta) = \sum_{i=l}^{D} h_i r(\zeta - \tau_i) + \eta(\zeta)\,. \qquad (2)$$

Therein, $r(\zeta)$ is the autocorrelation function of the chirp signal and $\eta(\zeta)$ is the cross-correlation of the chirp signal and the noise process $n(\zeta)$. Here, we assume that $n(\zeta)$ is generated by the Gaussian white noise process with the variance equal to σ^2.

The received signal is described in the base band as follws

$$z(\zeta) = \sum_{i=l}^{D} h_i e^{-j\omega_0 \tau_i} r(\zeta - \tau_i) + \mu(\zeta)\,. \qquad (3)$$

Subsequently, the covariance matrix $R = E\{zz^H\}$ can also be written as

$$R = \sum_{i,j} E\{h_i h_j^*\} e^{j\omega_0(\tau_j - \tau_i)} r(\tau_i) r(\tau_j)^H + E\{vv^H\}\,. \qquad (4)$$

The noise correlation matrix $\mathbf{R}_n$ can be expressed as $\mathbf{R}_n = E\{\mu\mu^H\} = \sigma^2 \mathbf{R}_0$, where R_0 is a Hermitian matrix whose *kl*th element is $r(\zeta_k - \zeta_l)$. SCM relies on a generalized eigendecomposition of the following form:

$$\mathbf{R}\mathbf{e}_i = \lambda_i \mathbf{R}_0 \mathbf{e}_i\,;\quad i = 1,2,\cdots,M\,. \tag{5}$$

To estimate the delay, we use a measure of orthogonality of the steering vectors to $\{e_i\}_{i=D+1}^{M}$. Accordingly, a super-resolution profile S(τ) based on the MUSIC algorithm might be defined as

$$S(\tau) = \frac{r(\tau)^H R_0^{-1} r(\tau)}{\sum_{i=D+1}^{M} \left| r(\tau)^H e_i \right|^2}\,, \tag{6}$$

where $r(\tau)^H R_0^{-1} r(\tau)$ is a normalizing factor, which is particular to the present method.

3. Simulation Method

We consider simulations of ultrasound imaging using the PZFLEX, which is a standard FEM simulator for ultrasound propagation. In this simulation, we used an FM chirp signal with a central frequency of 10 MHz, a bandwidth of 2 MHz and a pulse width of 2μs as a transmitted pulse. **Figure 1** shows the simulation model.

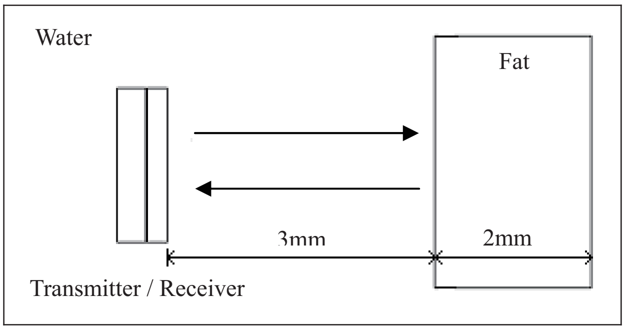

Fig. 1 Simulation model

4. Results and Discussions

The simulation results of one line ultrasound imaging are shown in **Fig. 2**. The broken line and the dotted line in Fig. 2 represent PCT results of the transmitted chirp signals with 2 MHz (9–11 MHz) and 4 MHz (8–12 MHz) bandwidth respectively. The solid line presents result of high-resolution estimation obtained using the super-resolution profile $S(\tau)$. In addition, we assume that the sweep frequency band is limited to 8–12 MHz and that the sampling frequency is 1GHz. Figs. 2 indicates that SCM provides higher resolution than the conventional PCT method. SCM can clearly detect the delay time from the target.

5. Conclusions and Future Work

This study make a fundamental examination for ultrasound imaging using the super resolution FM-chirp correlation method (SCM), which is based on PCT and the MUSIC algorithm. We analyzed the performance of the proposed method for estimation of time delays of multiple echo signals through simulations. The results clarified that the super-resolution profile achieves higher resolution estimation than the conventional PCT.

In the near future, we consider the realization of multiple line imaging simulation. As another work aspect we are interested in examination including an actual vibrator system.

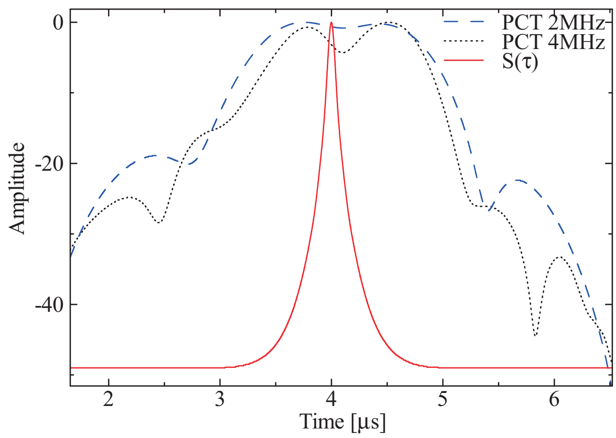

Fig. 2 Simulation Result of the one line ultrasound imaging

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