Sensitivity time control for chirp transmission

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1. Introduction
In medical ultrasonic imaging, pulsed ultrasound is transmitted into a human body and a diagnostic image is generated by an echo signal. The signal-to-noise ratio (S/N) of the echo signal is improved by increasing the pressure of the sound transmission; however, there is a limitation on the maximum allowable pressure due to safety concerns. To overcome this issue, research has focused on the use of a modulated wave with a long signal length, such as a chirp signal, for the transmission signal. This method enables the improvement of the S/N ratio of the echo signal without increasing the peak value of the transmitted sound pressure.

With regard to the use of chirp signals for transmission signals, Rao showed simulation results for the improvement in the S/N when a chirp signal is transmitted through a soft tissue [1]. Alternatively, a new estimation method for blood velocity using a chirp signal has also been proposed [2,3]. Tanabe et al. developed a split-and-merge strategy for chirp signals when the transmission and echo signals overlap due to a long signal length [4]. Additionally, Kawamura and Tanaka showed a signal separation circuit for detecting an echo signal that overlaps with the transmission signal [5]. Furthermore, Khairah et al. investigated the pulse compression of linear chirp signals [6]. However, the sensitivity time control (STC) for chirp systems has not yet been investigated. Because ultrasound is attenuated in the human body, it is essential that the attenuation is compensated by the STC process.

Conventional STC compensates for the attenuation of pulse signals by increasing the amplifier gain over time. However, this technique cannot be applied to chirp signals because the propagation delay time does not correspond to the target distance. When applying conventional STC to chirp signals, the echo signals are increasingly amplified with increased distance from the starting point of the chirp signal. In this case, the echo signal will be saturated due to excessive amplification. When the point spread function is calculated using the saturated echo signal, many range side lobes are generated. In this paper, we describe an STC method for chirp transmission that properly compensates for attenuation without excessive amplification.

2. STC for chirp transmission
First, we consider the compensation of attenuation for linear chirp signals. The frequency function \( f(t) \) of a linear chirp signal can be expressed as follows:

\[
f(t) = F_L + \frac{F_H - F_L}{T} t,
\]

where \( F_L \) and \( F_H \) are the start and stop frequencies, respectively, and \( T \) is the signal length. The frequency is the time derivative of the phase shift; thus, the phase of the chirp signal at time \( t \) can be expressed as

\[
\theta_0(t) = \int_0^t f(\tau) d\tau = \frac{1}{2} \frac{F_H - F_L}{T} t^2 + F_L t + \varphi.
\]

If the initial phase is \( \varphi = 0 \), the transmission signal can be expressed as

\[
s(t) = \begin{cases} A(t) \cdot \sin \left( \frac{1}{2} \frac{F_H - F_L}{T} t^2 + F_L t \right) & (0 \leq t \leq T) \\ 0 & \text{(otherwise)} \end{cases}
\]

where \( A(t) \) is the envelope function.

The basic concept of the proposed STC is illustrated in Fig. 1. The echo signal can be represented by the time shift of \( s(t) \), as shown in Fig. 1(a), and the frequency of the echo component is shown in Fig. 1(b). The chirp signal has a time-varying frequency; thus, the difference in frequency at a specific propagation time can be used to distinguish the difference in the target depth. The proposed STC employs an amplifier with different gains that are selected according to the signal frequency. Figure 1(c) shows the requisite gains for frequencies \( F_L \) and \( F_H \). Figure 1(d) shows the frequency response of the STC amplifier for different propagation times, i.e., \( T_1, T_2, \) and \( T_3 \). The proposed STC compensates for the attenuation of the chirp signal by increasing the gain over time while fixing this frequency response. The fixed frequency response is determined by the attenuation coefficient of the medium and the frequency function of the chirp signal.

In general, the attenuation coefficient for a biological tissue is expressed in dB/cm-MHz. When frequency-dependent attenuation is ignored, as in conventional STC, the attenuation coefficient can be expressed in dB/cm. Assuming that the STC amplifier compensates for all attenuation, its gain \( G \) for frequency \( F_L \) at propagation time \( t \) can be expressed as

\[
G = Kc \cdot t \ [\text{dB}],
\]

where \( K \) is the attenuation coefficient and \( c \) is the speed of sound.
sound. Similarly, the gain for frequency $F_H$ at the same time can be expressed as

$$G = \frac{Kc(T - T)}{F_H - F_L} \text{ [dB]}$$

(5)

Because the frequency of a linear chirp signal increases linearly, the gain function is expressed by a function that is also linear with frequency. The gradient $a$ of the gain function can be expressed as

$$a = \frac{Kc(T - T)}{F_H - F_L} = -\frac{Kc}{F_H - F_L}$$

(6)

The intercept $b$ can be expressed as

$$b = Kct + \frac{KcT}{F_H - F_L} \cdot F_L$$

(7)

The gain function $G(f, t)$ can therefore be expressed as

$$G = -\frac{KcT}{F_H - F_L} f + \frac{Kc(t - T)}{F_H - F_L}$$

(8)

where $f$ is the frequency.

Next, we consider the simplicity of implementing the STC process in hardware. The STC amplifier is designed as an analog circuit because STC processing is performed before analog-to-digital conversion. As mentioned above, the STC gain function is a linear function. However, the gradient of the frequency response of a single-pole low-pass filter is $-6 \text{ dB/oct}$; thus, its response is not proportional to frequency. To achieve a good approximation for the gain function, multiple circuit components are required, which would complicate the circuit. However, it is easy to first determine the frequency response of the STC and then determine the frequency function of the chirp signal to appropriately compensate for the attenuation. In this case, the frequency of the transmission chirp signal increases exponentially with time.

3. Simulation results

The validity of the proposed STC is confirmed through computer simulations of the point spread function. If the point spread function with the proposed STC is the same as that without attenuation, we can conclude that the attenuation is appropriately compensated for.

First, we performed a simulation with a linear chirp transmission. The transmission signal used the values of $F_L = 1 \text{ MHz}$, $F_H = 3 \text{ MHz}$, and $T = 200 \mu\text{s}$. For a target placed at a depth of 0.15 m, the echo signal was generated with $0.8 \text{ dB/cm}$ attenuation. Figure 2 shows the gain function of the STC used in this simulation. A filter for which the frequency response is shown in Fig. 2, was realized digitally. The echo signal was applied to the STC. Then, the point spread function was calculated using a pulse compression technique based on the cross-correlation. Figure 3 shows the resulting point spread function. The solid line indicates the result calculated by compensating for the attenuation using the proposed STC.
whereas the crosses show the result calculated without attenuation. Because the crosses and the solid line overlap, it is confirmed that the attenuation has been appropriately compensated for with the proposed STC methodology.

Second, we performed a simulation with a nonlinear chirp transmission and an easily designable amplifier. For the amplifier, we used a sixth-order low-pass filter (−36 dB/oct) designed from several CRs. Figure 4 shows the gain function of the STC used in this simulation, and Fig. 5 shows the frequency function of the transmission signal, which was calculated from the frequency response of the filter. All other parameter values were the same as those in the previous simulation. Figure 6 shows the resulting point spread function. As in the case of the linear-chirp transmission signal, because the crosses and solid line overlap, it is confirmed that the attenuation is appropriately compensated for with the proposed STC methodology.

4. Summary

In this research, we described an STC methodology for chirp transmission. By software-based simulation, it was confirmed that the attenuation of a chirp echo signal was appropriately compensated for with the proposed method. Moreover, to realize this method more easily, we considered a procedure that uses an easily designable amplifier. This procedure was also confirmed through computer simulations.

References