# 2E2-1

# Evaluation of Golay pulse compression in contrast enhancement ultrasound with Sonazoid

## Sonazoid 造影超音波における Golay パルス圧縮の評価

Shinnosuke Hirata[1†], Yuki Hagihara[1], Kenji Yoshida[1], Tadashi Yamaguchi[1], Matthieu E.G. Toulemonde[2], and Meng-Xing Tang[2] ([1]Chiba Univ.; [2]Imperial College London)

平田慎之介 [1†]，萩原佑樹 [1]，吉田憲司 [1]，山口匡 [1]，Matthieu E.G. Toulemonde[2], Meng-Xing Tang[2] ([1] 千葉大, [2]Imperial College London)

## 1. Introduction

In contrast-enhanced ultrasound (CEUS), the nonlinear echoes from the microbubbles (MBs) are used for contrast-specific image construction. Therefore, low-amplitude ultrasound waves have to typically be transmitted to prevent from the MB destructions. To further improve the contrast-to-noise ratio (CNR) of the CEUS image, employment of pulse compression have been investigated. In pulse compression using binary sequences, the linear components of the echo sequences are compressed as a pulse (enhanced) by cross-correlation between the received signal and the reference (transmitted) signal. However, the nonlinear components, which correspond the contrast of the CEUS image, cannot be adequately compressed, and the sidelobe can occur around the compressed pulse. For pulse compression using Golay complementary sequences (GCSs), the selection of the optimal sequences for CEUS has been proposed, and the application to CEUS with SonoVue has been reported[1]. In this report, Golay pulse compression using the optimal sequences are applied to CEUS with Sonazoid. Then, the compressed pulse and the sidelobe by the nonlinear components from the Sonazoid MBs are evaluated in computer simulation.

## 2. Optimal GCSs for CEUS

In pulse compression using binary sequences, cross-correlation consists of the multiplications of 1 or -1, and the accumulation of 1 or -1 (results of multiplications). When the received signal and the reference signal match, the accumulation of all 1 becomes the compressed pulse in the cross-correlation function. Otherwise, the accumulations of 1 and -1 become the low correlation values as the sidelobe. GCSs are a pair of binary sequences whose sidelobes are inverted. Therefore, the only compressed pulse remains in the summed cross-correlation function.

In CEUS, the nonlinear components of the positive echoes (1) and the negative echoes (-1) have to be compressed. They are almost the second harmonic of each echo. However, the second

shin@chiba-u.jp

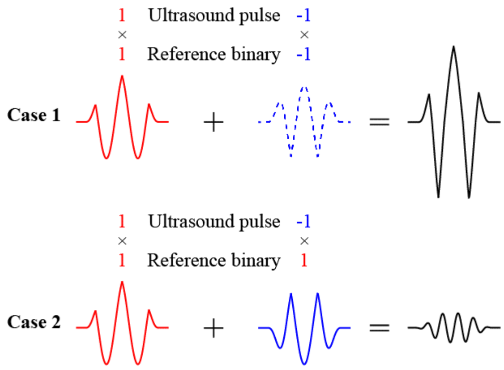


Fig. 1 Accumulations of the positive echo (1) and the negative echo (-1).

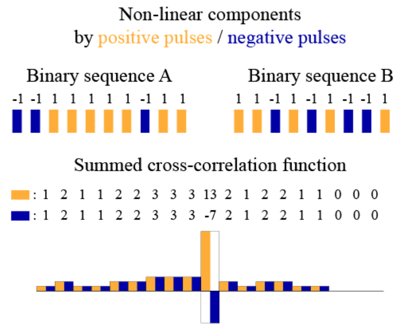


Fig. 2 Optimal 10-bit GCSs for CEUS and the nonlinear components (sidelobe) in the summed cross-correlation function.

harmonic can be cancelled by the accumulation, as illustrated in the case 1 of **Fig. 1**. Therefore, the nonlinear components in the compressed pulse can be reduced. Furthermore, the second harmonic other than the compressed pulse can remain as a sidelobe, as illustrated in the case 2 of **Fig. 1**. In the optimal GCSs for CEUS, the reduction of the second harmonic in the compressed pulse is the smallest. Moreover, the maximum amplitude of the nonlinear sidelobe is smallest in GCSs with the smallest second-harmonic reduction, as illustrated in **Fig. 2**.

## 3. Estimation of echo from Sonazoid MB

The echo emitted from the Sonazoid MB can be simulated by the oscillation model of the MB with the encapsulating shell. In this report, Marmottant's ordinary differential equation was employed to calculate the MB radius[2]. The simulation parameters

Table I Simulation parameters of the MB oscillation model[3].

| *Sonazoid MB* | |
|---|---|
| Initial radius | 1.15 μm |
| Polytropic exponent | 1.07 |
| Shell elastic modulus | 0.53 N/m |
| Surface dilatational viscosity | $1.2\times10^{-8}$ Ns/m |
| Initial-radius surface tension | $20\times10^{-3}$ N/m |
| *Ambient water of 20°C* | |
| Depth of MB | $20\times10^{-3}$ m |
| Density | 998 kg/m$^3$ |
| Viscosity | $1.0\times10^{-3}$ Pa s |
| Sound speed | 1483 m/s |
| Surface tension | $72.8\times10^{-3}$ N/m |
| Pressure | $101.5\times10^{3}$ kPa |

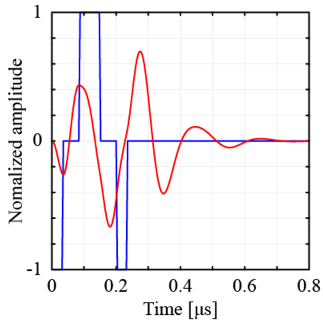


Fig. 3 The PWM excitation (blue) for a pulse wave of 5 MHz and the expected waveform (red) in the Vantage 256 platform with the L11-5v probe.

of the oscillation of the Sonazoid MB are indicated in **Table I**. The expected waveform transmitted by the PWM excitation of the Verasonics system, which is illustrated in **Fig. 3**, was used as the incident ultrasound pulse. The ordinary differential equation was solved using the Runge-Kutta 3/8 method (the time step of 1 ps). Then, the echo emitted from the Sonazoid MB was estimated form the MB radius and their 1st and 2nd derivatives.

## 4. Pulse inversion and amplitude modulation

The CEUS image is formed by pulse inversion and amplitude modulation (PIAM). First, the discrete binary sequences A and B (**Fig. 2**, the interval between the adjoining characters of 2 μs) convolved with the positive pulse (**Fig. 3**) are applied at full sound pressure. Next, the mirrored discrete binary sequences A' and B' convolved with the negative pulse are applied at half the sound pressure. The mirrored binary sequences are selected to prevent overlapping of the high-amplitude parts in nonlinear sidelobes (**Fig. 2**)[1]. Then, the echo sequences emitted from the Sonazoid MB are simulated and correlated with each discrete binary sequence. The cross-correlation functions A and B (A' and B') are summed to eliminate the linear sidelobe. As the PIAM signal, the summed cross-correlation

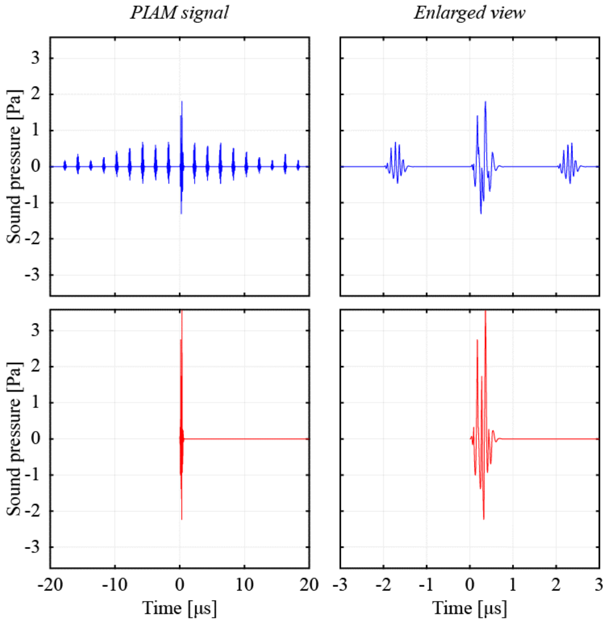


Fig. 4 In the case of full sound pressure of 225 kPa, the PIAM signal by pulse compression using 10-bit optimal GCSs and the typical PIAM signal by transmission of the positive and negative pulses.

signal AB and twice the summed cross-correlation signal A'B' are summed to eliminate the linear compressed pulse. In the PIAM signal, there are the nonlinear compressed pulse and the nonlinear sidelobe.

In the case of full sound pressure of 225 kPa (the mechanical index of 0.1), the PIAM signal by Golay pulse compression and the typical PIAM signal by transmission of the positive and negative pulses are illustrated in **Fig. 4**. In this case, the nonlinear compressed pulse of Golay pulse compression is reduced by 5.11 dB. The nonlinear compressed pulse is 9.36 dB larger than the maximum amplitude of the nonlinear sidelobe.

## 5. Conclusion

Pulse compression using 10-bit optimal GCSs is applied to CEUS with Sonazoid in this report. The reduction of the nonlinear compressed pulse and the amplitude of the nonlinear sidelobe could be estimated by simulation of the oscillation model of the Sonazoid MB.


## Acknowledgment

This work was partly supported by the Japan Society for the Promotion of Science Core-to-Core Program.


## References


1. S. Hirata, et al.: Jpn. J. Appl. Phys. **60** (2021) 066501.
2. P. Marmottant, et al.: J. Acoust. Soc. Am. **118** (2005) 3499.
3. A. Katiyar and K. Sarkar: J. Acoust. Soc. Am. **130** (2011) 3137.