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# Golay-Encoded Pulse-Inversion Subtraction for Real-Time Ultrasound Monitoring of HIFU Therapy

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***Abstract*—Ultrasound (US) imaging is often used for guidance of high-intensity focused ultrasound (HIFU) treatment due to its high temporal resolution and low cost. However, real-time US monitoring is often hindered when the strong HIFU interference overwhelms the imaging echoes. In this study, a method of Golay-encoded pulse-inversion subtraction (PIS) is proposed to better visualize the change of imaged object during the HIFU treatment. It effectively eliminates HIFU interference patterns in real-time US imaging and also improves the signal-to-interference ratio (SIR). In PIS method, the received imaging echo of positive transmit is subtracted from that of negative transmit to cancel the HIFU component. When Golay excitation is adopted, imaging echo after PIS is further decoded by matched filters for pulse compression. The performance of the proposed method was evaluated through experiments with both PVA phantom and *ex-vivo* swine liver. Results show that 4-bit Golay transmit can improve the SIR from -15.0 dB of un-coded transmit to 3.5 dB. With PIS, the SIR of 4-bit Golay further increases to 15.9 dB.**

***Keywords—US-gHIFU, Golay Excitation, Pulse-inversion Subtraction, HIFU Therapy***

## I. Introduction

High-intensity focused ultrasound (HIFU) is a non-invasive treatment that destroys tissue in the body using high acoustic energy. Its strong focusing can cause coagulation necrosis in the target site without damaging the surrounding tissue and is thus widely used in cancer treatment [1-2], hemostasis [3], blood-brain barrier opening [4] and other non-invasive treatments [5].

In HIFU treatment, an accurate and immediate guidance method is needed to monitor the changes of tissue caused by acoustic ablation. Both magnetic resonance imaging (MRI) and ultrasound image (US) can be used for HIFU therapy guidance. The advantage of MRI is that it measures the temperature change of the tissue and provides image information of arbitrary cross-section in 3D space. However, MRI requires longer time for image acquisition and thus cannot monitor the HIFU treatment in real-time [6-7]. On the contrary, US-guided HIFU (US-gHIFU) has the potential to achieve real-time monitoring during treatment because of its higher temporal resolution and relatively lower cost [8-10].

In US-gHIFU therapy, however, the challenge is that the presence of HIFU backscattering often leads to severe interference patterns over the entire US image, which make monitoring of tissue ablation difficult. These interference patterns are generated by high-amplitude HIFU component that dominates the entire received echo. In addition, the bubble and cavitation effects caused by HIFU may also be another reason that produces interference. Therefore, suppression of HIFU interference is essential for US-gHIFU treatment. Previous studies include synchronization of the imaging system with the HIFU transmit to create an image window with no interference [9] or using adaptive noise cancellation to remove the HIFU interference [10]. Alternatively, the acoustic interference pattern itself can act as a marker to locate the HIFU focal point [11]. Pulse-inversion (PI) sequence of HIFU transmit also helps to suppress interference pattern by summing the corresponding echoes as in HIC-PI method [12]. Nonetheless, residual artifacts often remain visible due to potential tissue motion and clock jitter. In this paper, Golay-encoded pulse-inversion subtraction (PIS) is proposed to eliminate HIFU interference together with improvement of signal-to-interference ratio (SIR) of imaging signal.

## II. Theory

### *A. Pulse-Inversion Subtraction (PIS)*

PI sequence is a widely adopted in ultrasonic harmonic imaging by transmitting a pair of imaging pulse with inverted phase on the same scanline. Even-order harmonics can be effectively extracted by summing the corresponding echoes. For US monitoring of HIFU treatment, the imaging system is synchronized with the HIFU system so that the positive and negative transmit on one scanline will be contaminated by the same HIFU waveform. Therefore, in order to construct an US image without HIFU interference, the pair of echo has to be subtracted from each other. In this way, not only the HIFU interference can be effectively eliminated but the imaging signal also doubles in magnitude as shown in Fig. 1.

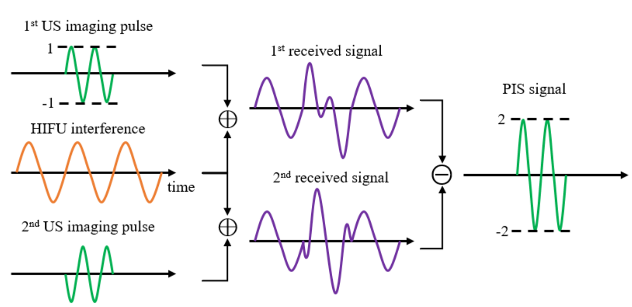


Fig. 1. Elimination of HIFU interference using PIS sequence

### B. Golay Excitation with PIS sequence

The PIS sequence can be further combined with Golay excitation to improve the signal amplitude of US image. Golay excitation boosts the transmit power using a complementary pair of bipolar bit sequence. The number of bits in the sequence determines the code length and a chip waveform is generally used to modulate the bit sequence to fit the transmit frequency of transducer. For its decoding, matched filtering is performed for each echo in the Golay pair and their corresponding output is then summed to achieve pulse compression. After decoding, the signal amplitude increases by 2*N* where *N* represents the bit length of Golay sequence.

In Golay-encoded PIS imaging, the Golay pair is transmitted twice with inverted polarity so that the Golay encoding remains correct after pulse subtraction. Taking a 4-bit Golay as an example, a total of four sequences of $A^+ = [1\ -1\ -1\ -1]$, $A^- = -A^+$, $B^+ = [-1\ -1\ 1\ -1]$ and $B^- = -B^+$ will be sequentially transmitted on each scanline. Firstly, the HIFU interference will be eliminated by PIS using ($A^+$, $A^-$) and ($B^+$, $B^-$) pair as shown in Fig. 2. Then, Golay decoding of the A and B sequence is performed after PIS. Consequently, the magnitude of imaging signal in the Golay-encoded PIS sequence should be 16 times (i.e., 24 dB) higher than that in the uncoded counterpart while the axial resolution remains comparable. Note that the PIS sequence and the Golay sequence respectively provide 6 dB and 18 dB of the total increase in magnitude. When the temporal resolution is considered, it should be noted that the Golay-encoded PIS technique demands for four transmits in total on each scanline

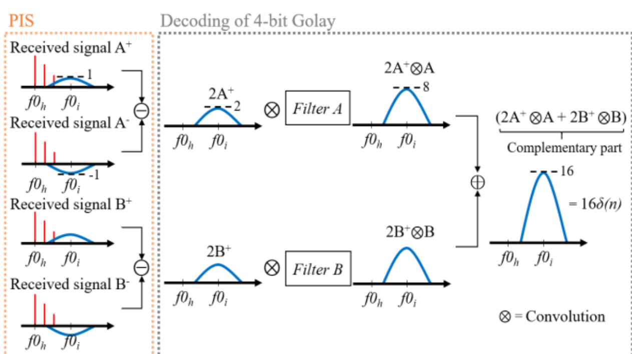


Fig. 2. Decoding of 4-bit Golay sequence with PIS

### C. Signal-to-Interference ratio (SIR) of Golay-encoded PIS

Here, the HIFU interference on the same scanline is assumed to be time-invariant among multiple transmits and thus the SIR value should increase proportionally to the magnitude of imaging signal. Note that US imaging with high SIR would provide better monitoring of the underlying tissue during the HIFU treatment. Assuming the un-coded transmit corresponds to an imaging magnitude of unity, *N*-bit Golay sequence without PIS should provide an imaging magnitude of 2*N*. On the other hand, when the pulse subtraction is adopted, *N*-bit Golay sequence with PIS should further double the imaging magnitude to 4*N*. This leads to another 6-dB increase of SIR. Moreover, the actual SIR in Golay-encoded PIS sequence also relies on the achievable HIFU cancellation in the process of pulse subtraction.

## III. Materials and Methods

B-mode image was acquired using an ultrasonic array research platform (S-Sharp, Prodigy). With a 5-MHz linear array (L7.5-12840C), raw channel data is received with transmit focusing at depth of 30 mm for off-line beamforming. Fig. 3 shows the experimental setup and the timing of system synchronization. The HIFU transducer (Sonic Concept, H-101) is held along the elevational axis of the linear array to place its focus in the image plane. The US image comprises 64 scanlines and the transmit pulse-repetition-interval (PRI) is set to be 500 μs. The HIFU transducer has a center frequency of 1.1 MHz with its geometric focus at 63 mm. Because of the geometric setup in the experiment, a time delay $T_d$ is added to the HIFU excitation waveform for manipulation of the arrival time of HIFU waveform relative to that of the imaging signal. The duty factor of HIFU excitation relies on $T_h$ to adjust the total acoustic power for treatment. In this study, $T_d$ and $T_h$ were set to 20 μs and 450 μs, respectively so that the corresponding duty factor is 90 %. In the experiment with low HIFU intensity, a custom-made PVA phantom is used as the imaged object to analyze the efficacy of HIFU suppression. In the experiment with high HIFU intensity, ablation is performed on an *ex-vivo* swine liver tissue for 300 seconds. Imaging sequences of un-coded transmit and Golay transmit without and with PIS are compared in this study. For Golay transmit with PIS, the received channel data is PI subtracted, Golay-decoded and then beamformed to construct the final US image. For comparison, the uncoded transmit (i.e., 1-cycle sinusoidal pulse) is also included as the image baseline. At 0 seconds (i.e., before HIFU ablation), one reference image is acquired for all transmit sequences.

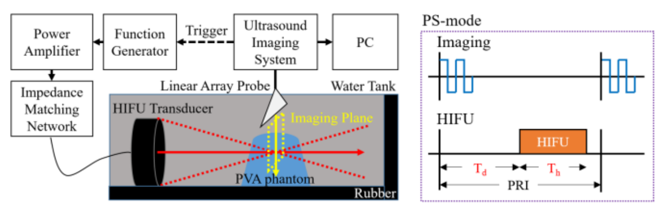


Fig. 3. Experimental setup and the timing of system synchronization

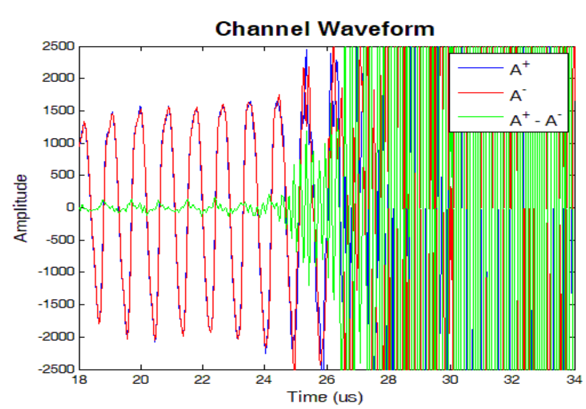


Fig. 4 Experimentally received channel waveform of 4-bit Golay transmit

## IV. RESULTS

Fig. 4 shows the temporal waveforms of experimentally acquired channel data from the PVA phantom. Note that the time segment before 24 μs corresponds to water. It can be seen that the PIS technique effectively suppresses the strong HIFU interference to a lower level. Fig. 5 demonstrates the experimental B-mode image of *ex-vivo* liver when HIFU has been turned on for 30 seconds. The baseline image is also provided for reference. In this study, the SIR is evaluated by subtracting the baseline image (i.e., HIFU off) from the image acquired during HIFU treatment to extract the interference pattern in the green box. In the presence of HIFU transmission. the un-coded image is severely interfered by the HIFU patterns and the underlying structure of liver tissue can be barely identified. When the transmit waveform is switched from un-coded to Golay, the HIFU interference pattern is significantly suppressed so that the underlying tissue becomes partially recognized. The corresponding SIR increases from -15 dB of the un-coded to 3.5 dB of the Golay transmit. Note that the improvement of SIR is consistent to $20\log_{10}(2N)$ in the case of 4-bit Golay. Nonetheless, it is noted that the HIFU interference pattern remains visible when Golay transmit is performed without PIS sequence.

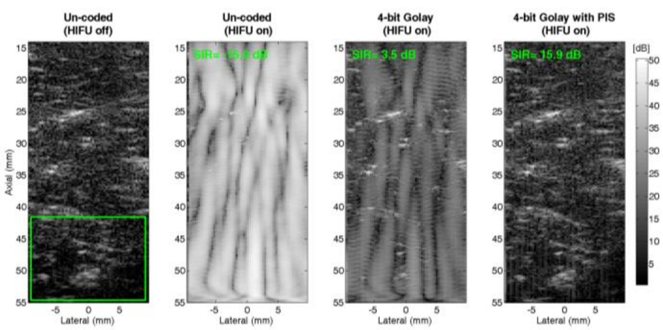


Fig. 5 B-mode images of *ex-vivo* liver tissue during HIFU ablation (30 s)

To further improve the SIR, PIS technique is integrated with Golay transmit to remove the HIFU interference by pulse subtraction. The resultant SIR improves to 15.9 dB in Golay-encoded PIS sequence while the corresponding B-mode image also shows that the HIFU interference pattern is mostly eliminated. Though the change of liver tissue can now be monitored in real-time during HIFU treatment, it is noticeable that the B-mode image with Golay-encoded PIS sequence still suffers from minor residual HIFU pattern. The residual HIFU interference appears as vertical stripes on random scanlines in the B-mode image, which might result from clock jitter between the imaging system and the HIFU system.

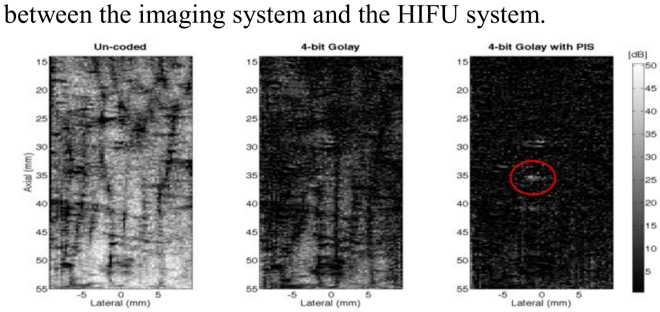


Fig. 6 Difference image of *ex-vivo* liver tissue during HIFU ablation (300 s)

Difference image is also constructed to better highlight the change of liver tissue during HIFU ablation. As shown in Figure 6, when the HIFU has been turned on for 300 seconds, a bright spot can be visually identified within the red circle in the difference image at depth of 35 mm, which is exactly the location of HIFU focus in our experimental setup.

## V. DISCUSSION

Since the proposed Golay-encoded PIS sequence demands for four transmits in each scanline, it may suffer from potential motion artifacts of the imaged object due to breathing or other physiological motion [13] and thus compromise the achievable HIFU suppression and US image quality. A separate experiment was performed by moving the imaging probe relative to the imaged object to simulate the respiration-induced motion. The tissue velocity is assumed to be 20 mm/s [14] and the imaging probe is displaced by a motor in either axial or lateral direction according to different PRIs. Fig. 7 demonstrates that the time shift between the received echoes of PIS sequence is more pronounced in the case of axial motion. Therefore, in the following discussion, only the axial motion is considered since it dominates the motion artifacts in Golay-encoded PIS sequence.

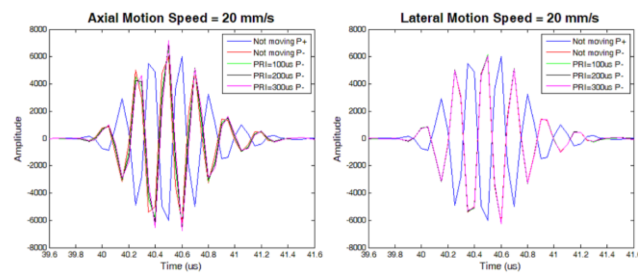


Fig. 7 Experimentally received channel waveform of PIS sequence with axial motion and lateral motion

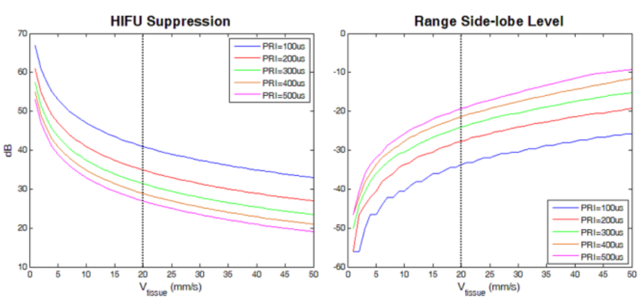


Fig. 8 HIFU suppression and range side-lobe level after Golay decoding as a function of the velocity of axial motion and PRI.

In the presence of axial motion, the HIFU suppression is estimated as a function of motion velocity (0 to 50 mm/s) and PRI (100 to 500 μs). Here, the HIFU waveform is assumed to be in the form of time-shifted sinusoid with a constant amplitude. In Fig. 8, the HIFU suppression is shown to gradually decrease with the motion velocity and the PRI. Nonetheless, 20 dB of HIFU suppression is still achievable even at a high motion velocity of 50 mm/s and a large PRI of 500 μs. When the velocity of 20 mm/s is considered for respiration motion, the achievable HIFU suppression further increases to 27 dB and 35 dB, respectively for PRI of 500 and 200 µs. On the other hand, the range side-lobe level would inevitably increase with the motion velocity and the PRI due to incomplete cancellation of range side lobe in the complementary sum of Golay pair. At the axial motion of 20 mm/s, Fig. 8 also shows that the range side-lobe level is elevated to -19 dB and -28 dB by axial motion, respectively for PRI of 500 and 200 µs.

B-mode images of phantom are also constructed with PRI = 300 µs in the presence of axial motion for comparison of image quality. Fig. 9 shows the axial profile of the wire phantom in the B-mode image using 4-bit Golay transmit with different PRIs at the axial velocity of 20 mm/s. Results indicate that, compared to the case of no motion, the axial motion results in negligible change of axial resolution in terms of -6-dB width but higher range side-lobe level. It should be noted that, however, the B-mode images remains visually comparable in the speckle background with and without axial motion. It is concluded that the motion artifacts in Golay-encoded PIS sequence would not compromise the US monitoring of HIFU treatment.

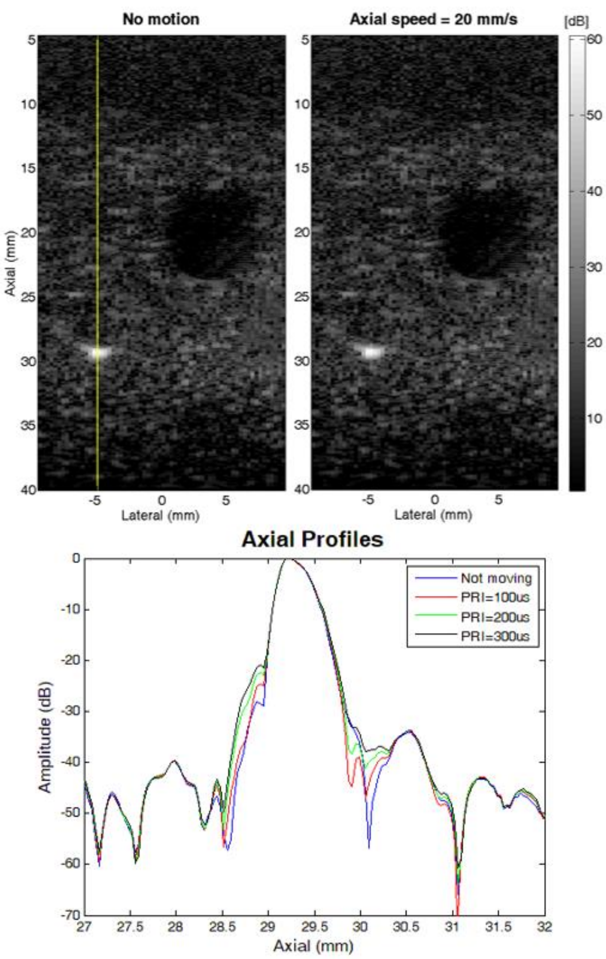


Fig. 9 B-mode images and corresponding axial profiles of wire phantom using 4-bit Golay transmit

## VI. Conclusion

In this study, Golay-encoded PIS sequence is proposed to facilitate the real-time US monitoring of HIFU treatment. The HIFU interference is effectively suppressed by Golay-encoded transmit to boost the imaging echo and by pulse subtraction to remove the HIFU component. The achievable image SIR will increase with the bit length of Golay excitation while the number of transmit on each scanline remains fixed to four. Potential motion artifacts due to breathing are also considered and it is shown that the level of HIFU suppression is sufficient with negligible change of image quality.

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