Ultrasound Image Improvement by Code Bit Elongation

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***Abstract*— This paper analyses the influence of the transducer bandwidth on the compression and the axial resolution of an ultrasound image. The distortion of an electrical signal visible in the final image is a major problem in ultrasonography. To solve this problem, the bit length in Golay-complementary sequences was elongated, narrowing the fractional bandwidth of the coded sequences. Therefore, more energy of the burst signal could be transferred through the ultrasound transducer. The experimental results obtained for transmission of the complementary Golay-coded sequences with two different bit lengths – one-cycle and two-cycles – have been compared, and the efficiency of the pulse compression and its influence on the axial resolution for two fractional bandwidths have been discussed. The results are presented for two transducers having a fractional bandwidth of 25% and 80% and operating at a 6-MHz frequency. The results obtained show that the elongation of the Golay single bit length (doubled in our case) compensate for the limited transducer bandwidth. 2D ultrasound images of a tissue-mimicking phantom are presented and demonstrate the benefits of the use of two-cycle bit length.**

***Index Terms*—Coded excitation, Golay sequences, synthetic aperture method, transducer bandwidth, ultrasound imaging.**

I. Introduction

ULTRASONIC imaging continuingly requires improved image quality, *i.e.*, higher resolution and increased penetration depth. Image resolution depends on the signal frequency. However, higher frequencies are attenuated much more. The penetration depth in its turn depends on the transmit power, which is tightly regulated by medical standards[1] .

This paper is motivated by the trade-off between the penetration depth and the image resolution in ultrasound images. This trade-off can be overcome by using long coded sequences and applying compression techniques on the received signal [2]. As a result, high peak pressures of the transmitted signal are no longer required and the gain in signal-to-noise ratio (SNR) results from the compression of the echoes.

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Similar problems of signal compression technique in ultrasound medical diagnostic imaging have been described. Cohen [3] analyzed the principles of pulse compressions in radar system using Barker, pseudorandom and Golay codes. The SNR improvement in medical ultrasound imaging was clearly demonstrated by Haider et al. [4]. The SNR gain was achieved by applying the Barker codes and pseudochirp signals and employment of the modified Wiener filter [5]. O'Donnell compared the pulse and the pseudochirp sequence excitation in a real-time imaging system [6]. It is shown that the improved penetrating power of the coded system in comparison to the conventional pulse excitation preserving image quality parameters. The similar results were obtained and reported by Misaridis et al [7]. Applying a chirp signal, the significant reduction in noise level for depths over 10 cm was achieved.

Our previous studies [8], [9] investigated another aspect of a potential clinical ultrasound application by exploring the influence of the transducer bandwidth on the burst and echo signal. The results of this paper explain why a short pulse does not always improve axial resolution comparing to longer signals transmitted in the same ultrasound transducer.

In [10] we have concentrated on the estimate of the complementary Golay-coded sequences (CGCS). In comparison with other coded excitations, such as chirp, pseudo-random sequences or Barker codes, the CGCS allowed to eliminate side-lobes in the final compressed signal. The estimation of the transducer bandwidth influence on the signal compression in medical diagnostic imaging applying different codded sequences is also discussed in [11], [12].

The aim of this article is to investigate the influence of the bit elongation of the coded transmission on the resolution and penetration depth of a reconstructed ultrasound image applying a commercial 128-element linear transducer array.

II. Complementary Golay-Coded Sequences

The main problem associated with all binary coded sequences is the high side-lobes level in a compressed signal, which can lead to ambiguities in the final ultrasound image. An exception are CGCS, which allow to minimalize the side-lobes level or to avoid side-lobes at all [13].

The CGCS are calculated as follows. Let the variables a_i and b_i (i=1,2,…n) be the elements of two n-long complementary series, which are equal to either '+1'or '-1'

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$$A = a_1, a_2, \ldots, a_n,$$
$$B = b_1, b_2, \ldots, b_n. \tag{1}$$

The ordered pair (*A;B*) are Golay sequences of length *n* if and only if their associated polynomials are:

$$A(x) = a_1 + a_2 x + \ldots + a_n x^{n-1},$$
$$B(x) = b_1 + b_2 x + \ldots + b_n x^{n-1}. \tag{2}$$

and satisfy the identity

$$A(x)A(x^{-1}) + B(x)B(x^{-1}) = 2n \tag{3}$$

in the Laurent polynomial ring $Z[x, x^{-1}]$.

Let the auto-correlation functions N_A and N_B corresponding to the sequences *A* and *B* respectively be defined by the following expressions:

$$N_A(j) = \sum_{i \in Z} a_i a_{i+j},$$
$$N_B(j) = \sum_{i \in Z} b_i b_{i+j}. \tag{4}$$

where the set $a_k = 0$ if $k \notin (1, \ldots, n)$. Now the condition (3) can be substituted by the sum $N_A + N_B$, and

$$N_A(j) + N_B(j) = \begin{cases} 2N, & j = 0, \\ 0, & j \neq 0. \end{cases} \tag{5}$$

The sum of both autocorrelation functions is *2N* at *j=0* and zero otherwise.

Fig. 1 shows the principle of the side-lobe-cancelling for a pair of 4-bit Golay codes.

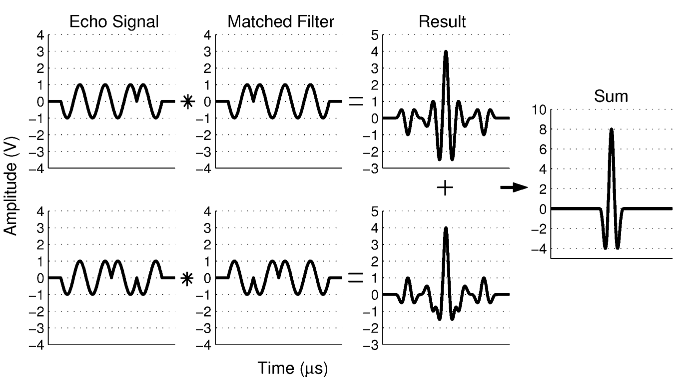

Fig. 1. The principle of the side-lobe-elimination for the CGCS of the length 4-bits, $*$ - represents correlation.

Two echo signals, obtained after transmitting a pair of the Golay-coded sequences, which are correlated with a matched filter, that is individually for every transmitted code. As a result the two compressed signals with side-lobes are obtained. Finally adding these compressed signals one signal with the peak equal to 8 without side-lobes is obtained.

III. Method

In this work we present a novel method which allows to avoid transducer bandwidth limit over code bit elongation. The reason for the elongation of an individual code bit lies in the fact that one cycle has a wider fractional bandwidth (FB) and the energy of this signal is often attenuated by an ultrasound transducer. The coding method consists of elongation of each bit duration to two-cycles and thereby reducing the FB of each bit of the code. The total signal bandwidth is narrower and consequently the average transmitter energy doubles.

Fig. 2 illustrates the comparison of the 8-bit Golay sequence with the two-cycle bit length and 16-bit Golay sequence with one-cycle bit length at a nominal frequency of 6 MHz.

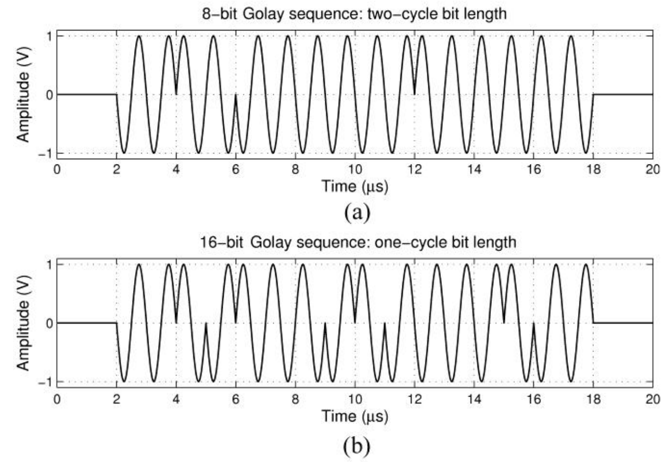

Fig. 2. Coding methods of the CGCS at nominal frequency 6 MHz: 8-bit code with two-cycle bit length (a) and 16-bit code with one-cycle bit length (b).

Fig. 2a shows the 8-bit Golay sequence with elements [+ − + + + − −−]. Every element is presented by two *sine* cycles. Fig. 2b shows the 16-bit Golay sequence with elements [+ + − + − − − + − + + + + − ++] where every element is presented by one *sine* cycle. The sequences length of these codes is the same and equal to 16 µs for frequency 1MHz.

Figure 3 presents the frequency transducer bandwidths and the spectra of the 8-bit and 16-bit Golay sequences with different bit length – two and one cycles, respectively.

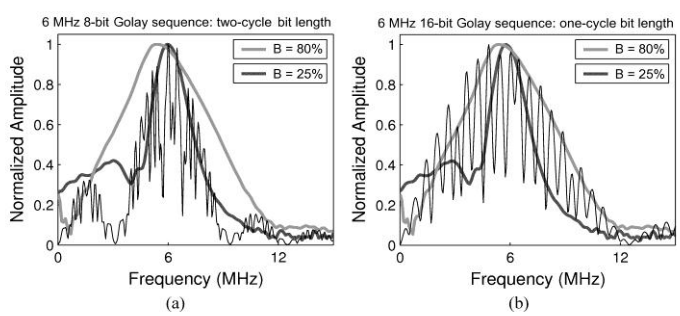

Fig. 3. The power spectra of the CGCS at center frequency 6 MHz with two-cycle bit length (a) and one-cycle bit length (b). Transducer FB for 80% (bright bold line) and for 25% (dark bold line) are shown.

Fig. 3 demonstrates clearly that the FB of the 8-bit CGCS with two-cycle bit length (Fig. 3a) is narrower than the FB of the 16-bit CGCS with one-cycle bit length (Fig. 3b). The FB of the signal is crucial because of the limited FB of transducers. In the first case (Fig. 3a) the bandwidth of the

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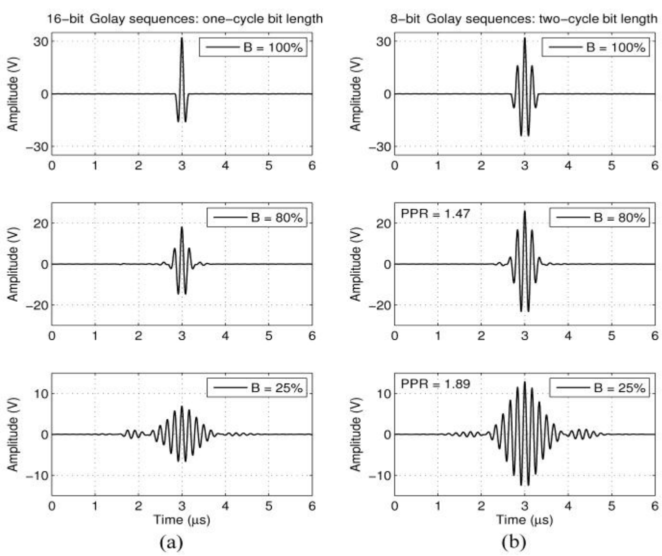
proposed two-cycle bit signal is within the limits of the narrow-band transducer (25%) while in the second case (Fig. 3b) the bandwidth of the one-cycle bit signal exceeds even the limits of the wide-band transducer (80%).

The main purpose of the investigation was to narrow down the bandwidth of the coded transmitted signal to match it with the transducer bandwidth. If the transducer bandwidth is too narrow for the signal, it can lead to negative effects such as signal distortion.

IV. Simulation

The efficient bandwidth of the ultrasound transducer has a potential effect on signal distortion. The influence of the filter bandwidth on the compressed signal amplitude is performed using the Matlab® software. Fig.4 demonstrates the comparison of the compressed CGCS of length 16-bits with one-cycle bit length and 8-bits with two-cycle bit length for different filter bandwidths 100%, 80%, and 25% at center frequency 6 MHz.

The total time duration of these two pairs of coded sequences is the same that allows to the objective estimation of the influence of the transducer bandwidth on the compressed signal from the energetic point of view.



where PPR is the ratio between minimum and maximum amplitude of the compressed signal with two-cycle bit length and minimum and maximum amplitude of the compressed signal with one-cycle bit length.

Fig. 4. Comparison of the compressed CGCS at center frequency 6 MHz: the 16-bit sequences with one-cycle bit length (a) and the 8-bit sequences with two-cycle bit length (b).

In Fig. 4 (top) the compressed signals are shown for the ideal case where full coded signal spectrum is passed. The amplitude of the compressed signals is equal $2N$, and in the given case is equal to 32.

The simulation procedure described above is similar to that used in the experiments, ones when a signal was transmitted and then when a signal was received. The remained power spectrum is transferred into the time domain and correlated with the original signal.

Fig. 4 clearly illustrates the advantages of the coding method with two-cycle bit length over that with one-cycle bit length. It is related to the fact that the elongation of the Golay single bit length, compensates the limited transducer bandwidth. In the case of 6 MHz 80% FB the amplitude of the compressed signal increased in 1.47 times. For 25% FB the compressed signal amplitude increased in 1.89 times.

V. Experimental Setup

Experiments were performed using the Sonix-TOUCH Research system (Ultrasonix Medical Corporation) equipped with the 128 element linear transducer L14-5/38 [14]. The block diagram of the experimental setup is shown in Fig. 5.

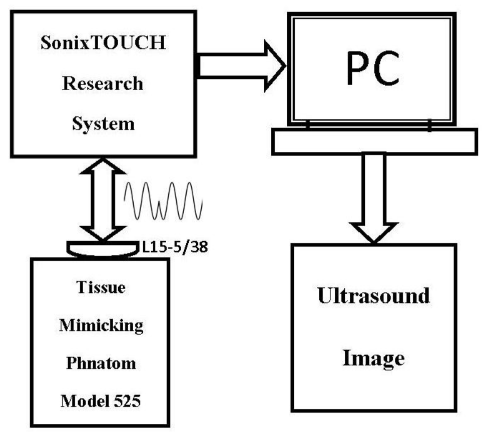


Fig. 5. The experimental setup.

The 8-bit and 16-bit CGCS with different bit lengths at a frequency of 6 MHz were generated by the SonixTOUCH Research system. These coded bursts excited the linear ultrasound transducer L15-5/38 that was pressed to the tissue mimicking phantom (model 525 Danish Phantom Design). Uncompressed RF echo data were acquired with a sampling rate of 40 MHz and were transferred to a personal computer. All processing with collected RF echoes was done on the computer using Matlab® routines. The processing included pulse compression, envelope detection, and image reconstruction, and the obtained results were immediately displayed on the monitor.

VI. Results and Discussion

In Figure 6, a computer simulation of a multi-scatterer phantom is shown. Here, a 128-element linear transducer array with 0.3 mm inter-element spacing and bandwidth 80% had been applied. The 16-bit Golay-coded sequences with one-cycle bit length and 8-bit Golay-coded sequences with two-cycle bit length at nominal frequency 6 MHz had been used.

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The phantom attenuation is equal to 0.5 dB/[MHz×cm].

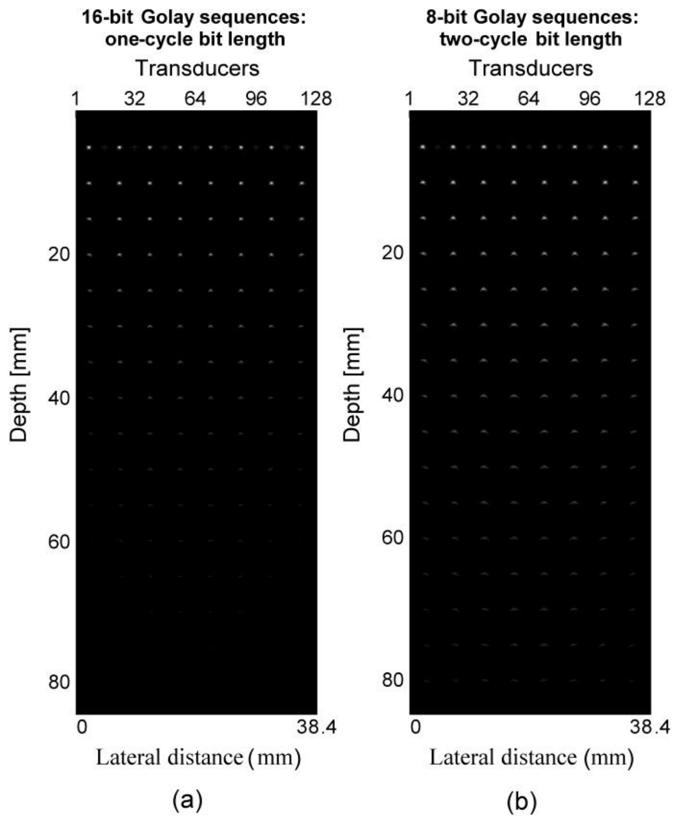

Fig. 6. Comparison of the 2D ultrasound images obtained by computer simulation for 128-element linear transducer array with bandwidth 80% using: a) 16-bit Golay sequences with one-cycle bit length; b) 8-bit Golay sequences with two-cycles bit length. The phantom attenuation is equal to 0.5 dB/[MHz×cm].

The 2D ultrasound images obtained clearly demonstrate the advantage of using the Golay-coded sequences with double bit length in comparison to single bit one. With the elongation of the bit length the signal bandwidth is covered by the transducer bandwidth and the acoustical power increases yielding higher SNR, that leads to an increase in the penetration depth while maintaining both axial and lateral resolution. The last resolution depends on the transducer acoustic field and is discussed in [15]. The visualization depth when the 16-bit Golay code with one-cycle was applied is equal to 4 cm (Fig. 6a), while in the case of applying 8-bit Golay codes with two-cycle bit length this depth increases up to 6 cm (Fig. 6b).

Fig. 7 presents 2D ultrasound images of a tissue mimicking phantom (model 525 Danish Phantom Design with attenuation of background material 0.5 dB/[MHz×cm]). The measurements were done using the SonixTOUCH Research system equipped with a 6 MHz 128 element linear transducer L14-5/38 with a 0.3 mm element pitch, 0.28 mm element width and 70% FB.

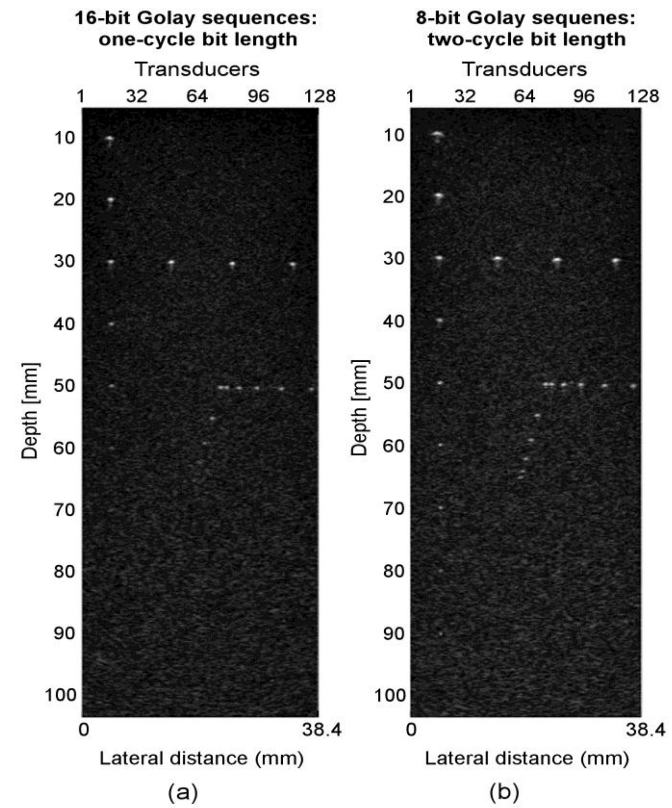

Fig. 7. 2D ultrasound images of tissue mimicking phantom applying: a) 16-bit Golay sequences with one-cycle bit length; b) 8-bit Golay sequences with two-cycle bit length.

As seen from Fig. 7, 8-bit Golay-coded sequences with two-cycle bit length provide better penetration depth without decreasing resolution. In this case the penetration depth increases up to 9 cm (Fig. 7b) in comparison when the 16-bit Golay-coded sequences with one-cycle bit length were used were penetration depth is equal only to 6 cm (Fig. 7a). With the bit-length elongation of the Golay single bit length the acoustical energy of the transmitted signal allows to overcome the problem of limited commercial transducer bandwidth. Note, that the axial and lateral resolution are similar.

VII. Conclusion

The obtained results proved that bit elongation in CGCS allows for the minimizing of the influence of the narrow ultrasound transducer bandwidth without deteriorating axial resolution in medical ultrasound imaging. 2D ultrasound images of the tissue mimicking phantom obtained using the CGCS with different bit lengths are presented and demonstrate the benefits of the use of two-cycle bit length. The penetration depth in case a two-cycle bit length is used increases in about 50% from 6 cm to 9 cm. Hence, narrower FB of the coded sequences allow for deeper penetration into abdominal tissue.

These results indicate that two-cycle bit length coded excitation is more suitable for use with commercially available narrowband transducers. Also, for such bandwidth-limited transducers, two-cycle bit-length phased coded excitation would not decrease the axial resolution, obtained with the conventional short pulse.

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