THE INFLUENCE OF THE TRANSDUCER BANDWIDTH AND DOUBLE PULSE TRANSMISSION ON THE ENCODED IMAGING ULTRASOUND

IHOR TROTS, ANDRZEJ NOWICKI, MARCIN LEWANDOWSKI,
WOJCIECH SECOMSKI, JERZY LITNIEWSKI

Institute of Fundamental Technological Research, Polish Academy of Sciences
Swietokrzyska 21, 00-049 Warsaw, Poland
igortr@ippt.gov.pl

An influence effect of fractional bandwidth of ultrasound imaging transducer on the gain of compressed echo signal being the complementary Golay sequences (CGS) with different spectral widths is studied in this paper. Also, a new composing transmission method of CGS is discussed together with compression technique applied in order to increase the signal-to-noise ratio (SNR) and penetration.

The CGS with two different bit lengths, one-cycle and two-cycles are investigated. Two transducers with fractional bandwidth of 25% and 80% at centre frequency 6 MHz are used. The experimental results are presented, clearly proofing that increasing of the code length leads to compressed echo amplitude enhancement. The smaller the bandwidth is the larger is this effect; the pulse-echo sensitivity of the echo amplitude increases by 1.88 for 25% fractional bandwidth and 1.47 for 80% while preserving time resolution. The presented results of double transmission of short codes show the penetration and SNR improvement while maintaining dead zone.

INTRODUCTION

Permanent development of the ultrasound technique using the coded excitation signals is related to technological progress – from the methods of the wave generation to computer programs, which facilitate the measurements as well as analysis of the changes and monitoring of the treatment of disease. Nowadays coded transmission in ultrasonography is dynamically developing – from parametric imaging of bone in the range 0.5 – 2 MHz, through imaging in classic ultrasonography (3.5 – 10 MHz) up to imaging in micro ultrasonography (above 20 MHz).

Coded ultrasonography is intensively developed and studied in the last decade. The reason of such interest lies in the properties of the coded transmission: increasing of penetration depth, signal-to-noise ratio improvement, exploring the signal with lower amplitude and improving of the axial resolution moving to the higher frequency range. Nowadays extensively explored coded sequences are: linearly frequency modulated signals (chirp) and phase-modulated signals like Barker codes and Golay complementary sequences (side-lobe canceling codes).

Among the different excitation sequences proposed in ultrasonography, Golay codes evoke more and more interest in comparison to other signals. The reason of that lies in the fact that Golay codes, like no other signals, suppress to zero the amplitude of side-lobes in ideal case. This type of complementary sequences has been introduced by Golay [1]. The principle of construction and properties of the Golay complementary sequences are described in [2].

In contrast to previously published papers [3–4], which examined the factors influencing the spatial resolution of coded Complementary Golay Sequences (CGS), this paper investigates the effect of ultrasound imaging transducer's fractional bandwidth on the gain of the compressed echo signal for different spectral widths of the CGS.

The motivation for this work stems from the fact that in clinical practice it is desirable to limit the peak pressure amplitudes of the ultrasound wave interrogating the tissue while maintaining the depth of field for a given transducer and interrogating frequency. This goal can be achieved by using relatively long wide band transmitting sequences and compression techniques on the receiver side [5].

An aspect of potential clinical ultrasound application by exploring the influence on the limited fractional bandwidth of an imaging transducer on efficiency of pulse compression by adjusting the bit code length of complementary Golay codes is discussed in this paper. CGS was selected because it minimizes the side lobes, which have negative influence on the quality of achievable image [6]. Such data are not available but are of interest as they provide guidance for optimization of pulse-echo sensitivity of bandwidth limited transducers while retaining axial resolution. Although imaging transducers having fractional bandwidth of the order of 80% and higher are becoming gradually available, the majority of the imaging transducers exhibits limited bandwidth, typically in the range 30-50%.

Practical implementation of CGS is not widely available in the literature, for the convenience of the reader a step-by-step procedure for generation and correlation principle of CGS is described in [2].

1. CODED METHOD WITH DIFFERENT BIT LENGTH

The bandwidth of a single, one-cycle CGS bit signal is often exceeding fractional bandwidth of the available imaging transducer. Elongating the CGS code from one-cycle bit to two-cycles narrows the fractional bandwidth of each bit of the code. Hence, the overall signal bandwidth is narrower and, consequently, it can be contained within the bandwidth of the ultrasound transducer. As a result, the transmitted signal energy increases.

Computer simulated CGS with two-cycles 8-bits length and one-cycle 16-bits length at the nominal frequency of 1 MHz and their corresponding spectra are shown in Fig. 1.

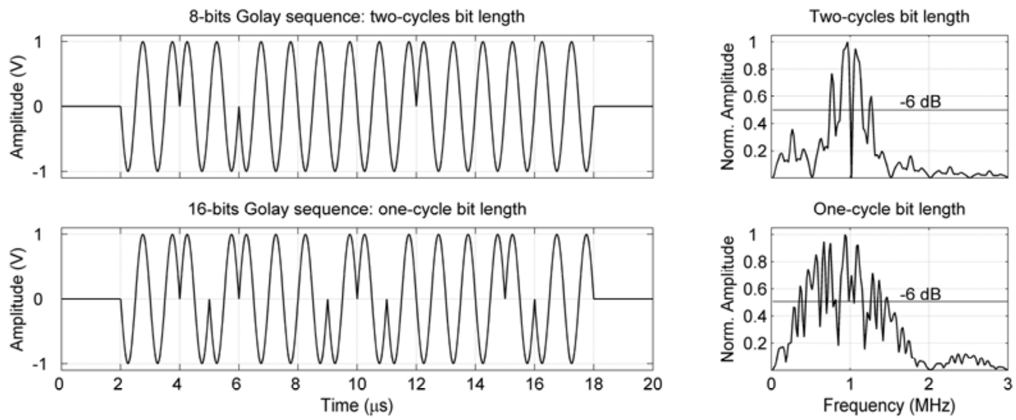

Fig.1 Comparison of two coding methods investigated and the corresponding power spectra of the Golay sequences at nominal frequency 1 MHz: 8-bits code with two-cycles bit length (top) and 16-bits code with one-cycle bit length (bottom)

The plots shown in Fig. 1 demonstrate the advantage of narrowing of the transmitted spectrum. The signal bandwidth for two-cycles bit length, determined at the -6 dB level, is twice as narrow as that of a single cycle. The resulting fractional bandwidth is close to 50%, which is typical to that of available imaging transducers. Hence, the spectrum of two-cycles bit length matches better the bandwidth of typical pulse-echo transducers.

2. INFLUENCE OF ULTRASONIC BANDWIDTH ON PULSE ECHO SIGNAL

As already mentioned, the effective or overall bandwidth, that is the one determined by the overall imaging chain of an ultrasonic transducer, may have an influence on transmitted signal distortion and efficiency of the compression. Therefore, the influence of the overall bandwidth on the amplitude of the compressed signal was computer simulated for different filter bandwidths at the centre frequency of 1 MHz. Fig. 2 shows the simulation results obtained for the compressed Golay complementary coded pairs of length 16-bits with one-cycle bit length and 8-bits with two-cycles bits length for transducer bandwidths ranging from 25% to 100%.

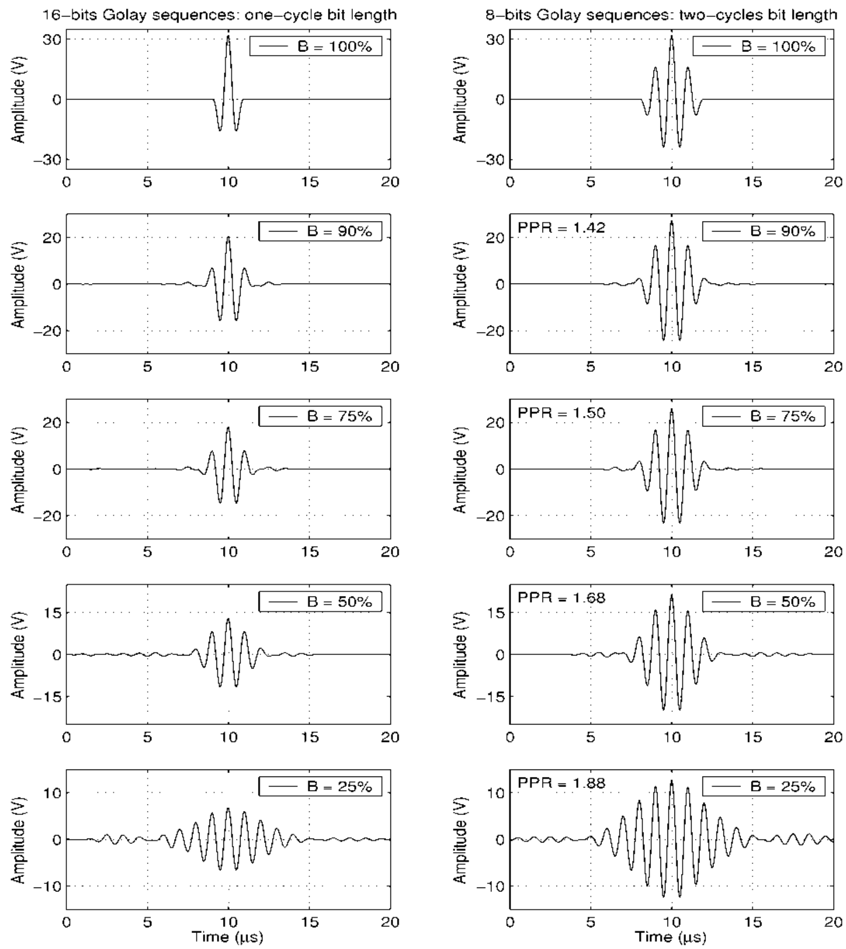

Fig.2 Comparison of the compressed coded sequences at centre frequency 1 MHz: the 16-bits Golay codes with one-cycle bit length (left) and the 8-bits Golay codes with two-cycles bit length (right)

Definition of PPR:

$$PPR = \frac{\text{peak-to-peak compressed signal amplitude with two-cycles bit length}}{\text{peak-to-peak compressed signal amplitude with one-cycle bit length}}.$$

The simulations were performed using the Matlab® software using the following algorithm: first the 8-bits and 16-bits Golay sequences with different bits lengths - one and two periods were numerically synthesized. Next, their Fourier transforms were computed. The band-pass filtering was performed using second order Chebyshev filter. To return to time domain, the results were inverse Fourier transformed and plotted.

In Fig. 2 (top) the compressed signals are shown for the case of 100% fractional transducer bandwidth, i.e. the full coded signal spectrum is transmitted. The time duration T of each coded sequence is equal to 16 μs at the centre frequency of 1 MHz. After filtering, the time duration of the obtained compressed signal is equal to $2T$ [6], here 32 μs. The amplitude of the compressed signals is equal to $2n$, where n is the number of sine-cycles in sequences. In our simulation n was equal to 32 for both cases. This is because for 16-bits Golay sequences one bit is equal to one sine-cycle, whereas in the case of 8-bits Golay sequences one bit consists of two sine-cycles.

To facilitate the comparison with the results of the experiments described in the section 4 obtained under pulse echo conditions, the simulation was performed twice using the Matlab®. The first simulation procedure determined the transmitted signal waveform, the second one determined the received echoes. The obtained power spectra of the echo signals was inverse Fourier transformed into the time domain and correlated with the original signal.

The results of Fig. 2 illustrate that the amplitude of the compressed pulse decreases with narrowing of the fractional transducer bandwidth. This is easily noticeable when comparing 16-bits Golay codes with one-cycle bit length and 8-bits Golay codes with two-cycles bit length. For example, in case of 50% fractional bandwidth the compressed echo duration is almost the same for one and two bits codes whereas the peak-to-peak amplitude of the 'double' code is 68% higher than that of the 'single' one.

3. MATERIALS AND METHOD

Experimental verification of the simulation data presented above was performed in the measurement system described below (Fig. 3). Two ultrasonic sources were used: 6 MHz, focus PZT ceramic transducer having 15 mm diameter and 25% fractional bandwidth and planar, 6MHz, 14 mm diameter PZT composite transducer with fractional bandwidth of 80%.

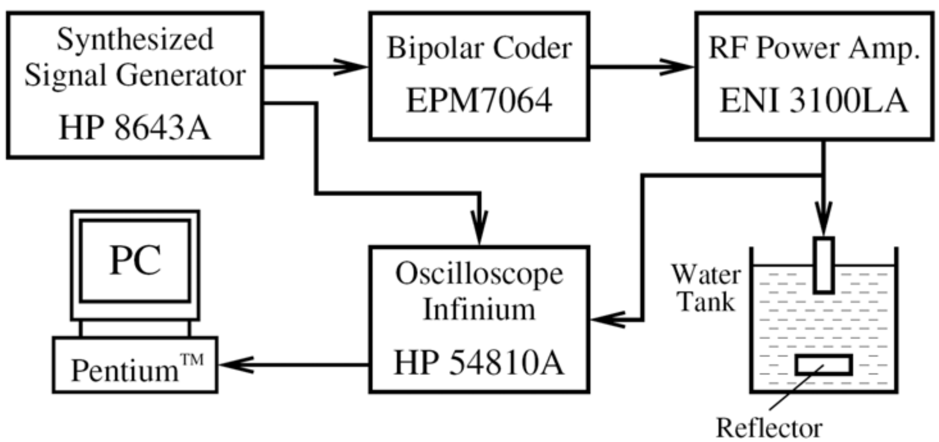

Fig.3 Measurement arrangement

The Golay sequences at frequencies 6 MHz were synthesized in the following way. The Signal Generator (HP8643A, Colorado Springs CO, USA) produced sine wave at 0 dB level at a given frequency. This signal was fed to the bipolar modulator driven by the -1,1 sequences from the custom-designed coder. The coder circuitry based on the programmed logic (EPM7064, AlteraTM, San Jose CA, USA) allowed generating switched pair of 16-bits Golay sequences with one-cycle bit length and 8-bits Golay sequences with two-cycles bit length. The coded signals were then amplified via the power RF amplifier (ENI 3100LA, Rochester NY, USA) and the transmitted coded burst excited the ultrasonic transducer immersed in a water tank. The transmitted signals were first reflected from a brass perfect reflector and then from a finite thickness plexiglas plate. The plate's thickness was 1.3 mm and facilitated to determine the time (axial) resolution of the examined transducer.

The uncompressed RF echoes data were acquired using a digital storage 12-bits oscilloscope (Infinium, HP 54810A, Colorado Springs CO, USA), with a sampling rate of 25MHz. All processing and display were done on the computer using Matlab® routines. The processing included amplification, pulse compression for Golay sequences, and envelope detection and the obtained results were in few seconds displayed on the monitors.

4. EXPERIMENTAL RESULTS

Fig. 4 shows the RF echo signals obtained by two acoustic sources excited by a spike voltage using ultrasonic pulse/receiver unit (DPR300, JSR, Pittsford NY, USA). These echoes were obtained in water using a perfect reflector oriented normally to the transducer surface.

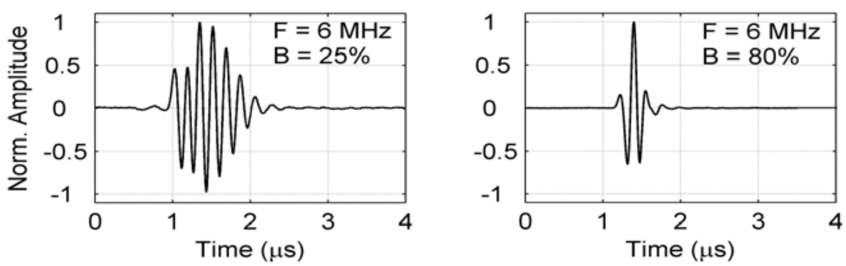

Fig.4 Pulse echo response of two different ultrasonic 6 MHz transducers with fractional bandwidths of 25% and 80%, respectively. The transducers were excited with a short spike voltage

The results of Fig. 4 provide information on the influence of fractional transducer bandwidth on the pulse-echo response. As could be expected they indicate that the echo duration decreases with the increasing of transducer bandwidth.

In Fig. 5 the bandwidths of the two transducers used are compared with the spectra of complementary Golay sequences with one and two cycle bits length where the solid line represents measured transducer bandwidth and the jagged plot corresponds to the spectrum of the coded signal. The jagged plots of the CGS spectra (compressed echoes) can be conveniently explained by considering the results of Fig. 6, where the time domain plots of the compressed echoes obtained from the 1.3 mm plexiglas reflector are shown. Whereas for transducer with the bandwidth of 25% (Fig. 6 a) the pulse separation for both codes (i.e. one and two cycle bits) is almost the same, the amplitude gain of the factor 1.89 is apparent for the double bit length. This gain decreases with bandwidth increasing and is close to 1.6 for 58% transducer bandwidth and 1.47 for 6 MHz composite transducer with transducer bandwidth of 80%.

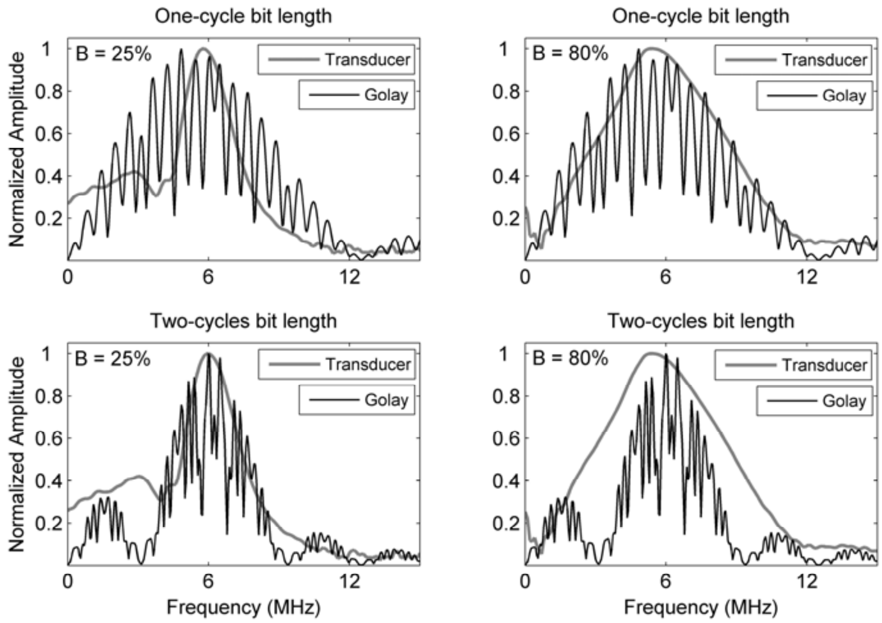

Fig.5 The bandwidths (solid lines) of the investigated transducers [25% (left), and 80% (right)], plotted over the spectra of CGS with one-cycle bit length and two-cycles bit length (thin jagged line)

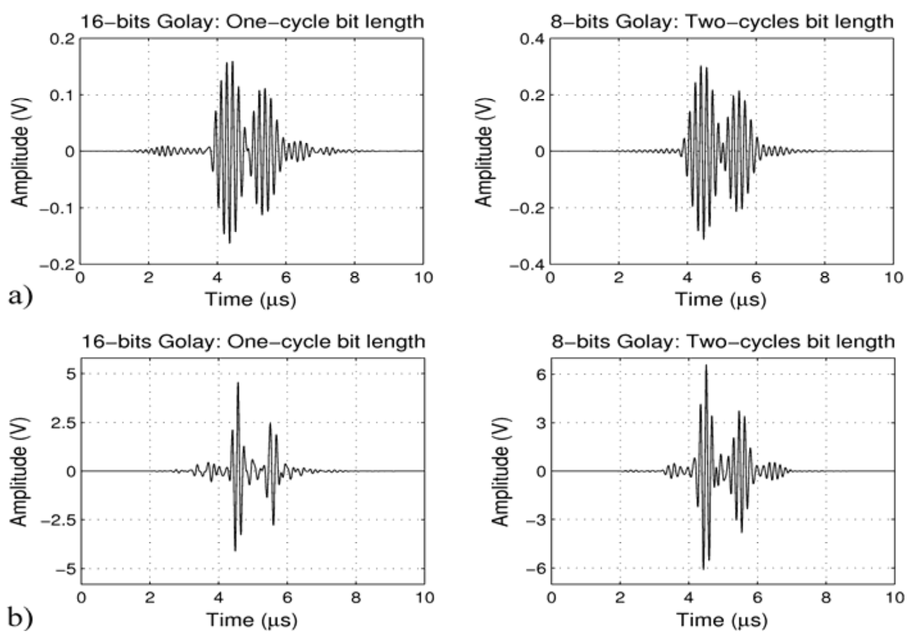

Fig.6 Compressed RF echo signals reflected from the plexiglass plate of thickness 1.3 mm obtained using 6 MHz, 25% fractional bandwidth PZT transducer (a) and 80% fractional bandwidth composite transducer (b)

The results of Fig. 6 indicate that the pulse-echo sensitivity shows a decreasing tendency for the experimental conditions tested here, however, even for a relatively wide bandwidth of 80%, there is a visible gain when using two-cycles bit length code.

To further facilitate the comparison of the axial resolution achievable with the codes tested in this work, the envelopes of the compressed echoes are plotted in time domain in Fig. 7.

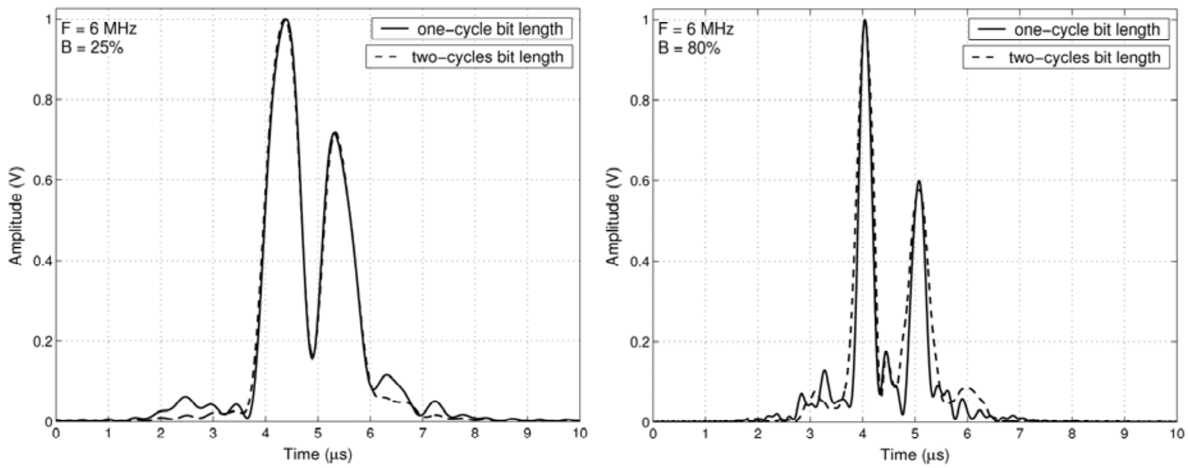

Fig.7 Comparison of the envelopes of the echoes obtained using 6 MHz 25% fractional bandwidth PZT transducer (left) and 6 MHz 80% fractional bandwidth composite transducer (right.

The data presented in Fig. 7 show that for a narrow, 25% bandwidth transducer the resolution is almost identical (Fig. 7 left). The width of the compressed pulses is equal to 0.71 µs for one-cycle bit length and 0.73 µs for two-cycles bit length at the level of -6 dB. For the composite 6 MHz transducer with 80% fractional bandwidth the pulse widths are equal 0.28 µs and 0.37 µs (Fig. 7 right).

The experimental results verified the simulation data and indicate that axial resolution is only slightly worse for longer (two-cycles) bit length. The difference in pulse duration at -6 dB level of compressed pulses varied from about 3% for 25% transducer bandwidth to less than 30% for the wide (80%) transducer bandwidth. However, the amplitudes of the obtained compressed pulse-echo signals in the case of coded sequences with two-cycles bit length ranged from 1.47 to 1.89 times higher than those obtained with one-cycle bit length depending on fractional bandwidth of the ultrasonic transducer used.

5. DOUBLE CODED TRANSMISSION

Within the last few years, the increasing interest in visualization of tissue surface [7] as well as vessel wall research using ultrasound technique can be observed among clinicians. Development of coded transmission is directed to a new region of application in dermatology and diagnostics of the skin disease as well as lesion treatment [8]. Ultrasonography methods are applied to examine three main skin layers: epidermis, cutis vera and hypodermis. Also, the application of ultrasound diagnostics in ophthalmology is very important as it allows to examine and to diagnose the pathological changes of benign and malicious tumours, cysts, cornea, iris, and other parts of the eye. The one more advantage is that ultrasound allows penetrating into the structure of the atherosclerosis changes in blood vessels.

By now the usage of Golay complementary codes was limited by transmitting single complementary pair with later processing (correlation and summing) as shown in Fig. 8.

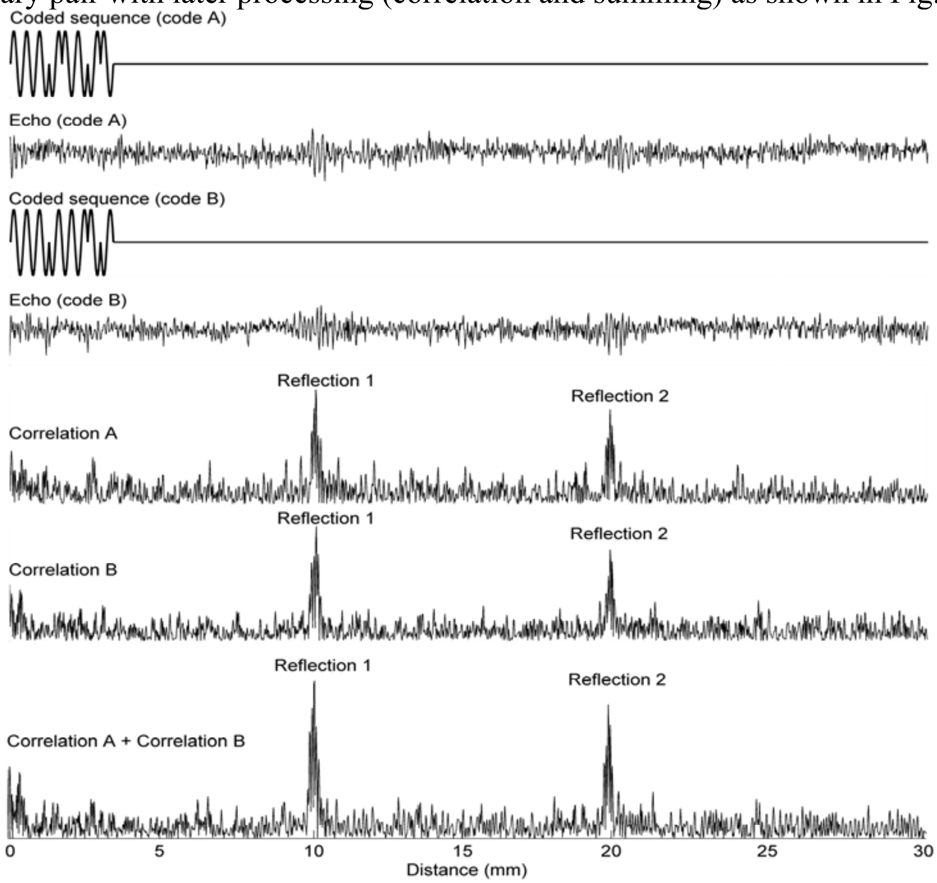

Fig.8 Correlation and summing of the received echo signals in case of using Golay complementary sequences

Figure 8 shows the practical realization of the transmitting Golay coded sequences. As can be easily seen in practice even for coded transmission the different artefacts are present and because of that the noise elimination and efficient side-lobe cancellation cannot be obtained. And the noise level can lead to wrong visualization of the examined organs and range ambiguity. The nice method, which can decrease the noise level is using the longer Golay coded sequences i.e. 128 or even 512 bit lengths. Using longer coded sequences is welcome in radar technique or hydrolocation – where information located closely to transducer is not important. In ultrasonography the usage of longer coded sequences is rather limited since it leads to increase of the dead zone that is not accepted in some diagnostic application. Theoretically, the dead zone area is equal to the half burst pulse time duration. But in practice the time duration of the burst pulse is calculated from the beginning to the moment when power drops to the -3 dB level, so the dead zone area is assumed to be equal to burst pulse time duration.

Increase of the echo detection using CGS in comparison to short pulse is evident. Previously reported experiments showed the two echoes received from reflectors distanced one from other by 1 cm. SNR improving in compressed signal in comparison to direct echoes is about 15 dB [9].

The idea of double transmission method lies in an assumption of mutually noise cancellation, where noise in the resulted RF signal is averaged by summing two compressed echo signals obtained by single transmissions. Such solving allows to obtain a relatively high SNR using shorter coded Golay sequences.

Figure 9 shows the comparison of transmitting 32-bits Golay coded sequences at nominal frequency 6 MHz and time duration 5.33 μs and proposed method of the double transmission of 16-bits Golay coded sequences with shorter time duration that is equal 2.66 μs. The start time of the second sequence depends on penetration depth that is examined. In the given case, the plot illustrates the examined environment on penetration depth up to 2.4 cm. The starting time of the second sequence can be calculated from:

$$t = \frac{2d}{v} = 30\mu s ,$$

where d is the depth, and v is speed of the ultrasound wave in examined environment (1540 m/s).

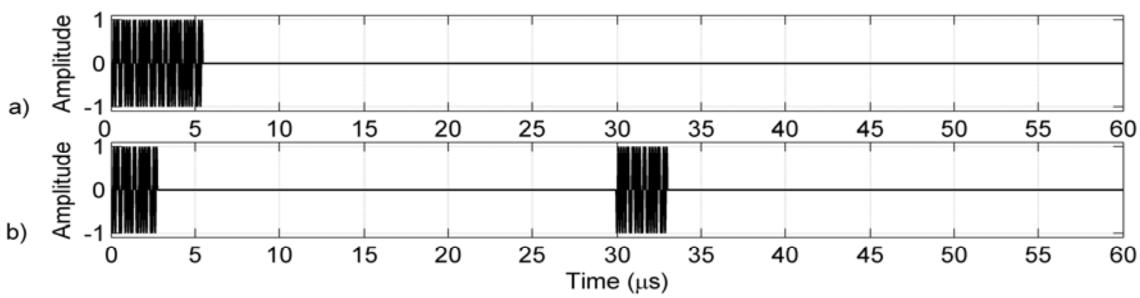

Fig.9 Transmission of the 32-bits Golay sequence with time duration 5.33 μs (a), and double transmission of the 16-bits Golay sequence with time duration 2.66 μs (b)

Fig. 10 shows resulted (filtered and summed) RF echo signals obtained from the tissue mimicking phantom RMI 405GSX.

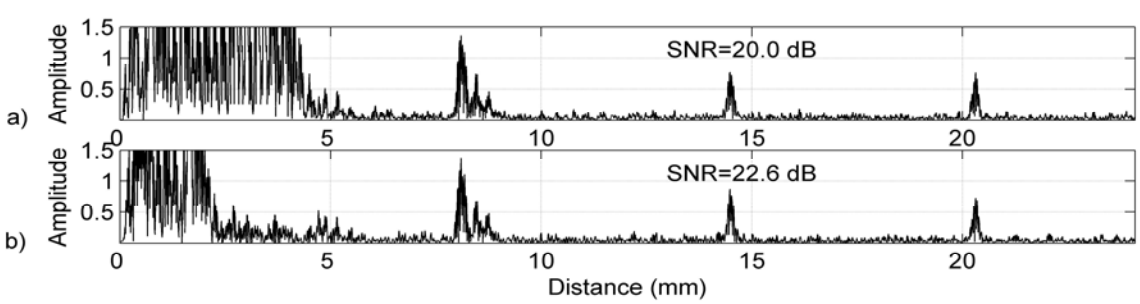

Fig.10 The resulted RF signals obtained using 32-bits Golay sequences (a) and double transmission 16-bits Golay sequences (b)

Using longer coded sequences results in increasing of the dead zone area (Fig. 10a) that increases proportionally to the coded sequences length and inversely to frequency. In the second case (Fig. 10b) the RF echo signal splits into two sequences, next compressed and summed. For objective comparison the SNR is calculated.

Fig. 10 shows advantages of the double transmission of the Golay coded sequences (Fig. 10b) in comparison to single Golay coded transmission used heretofore (Fig. 10a). In double transmission case the SNR improves by 2.6 dB. It has to be noted that the coded sequence in double transmission case is 2 times shorter. According to the assumption [2] for getting the SNR equal to 22.6 dB the coded sequence length in method used by now must be not less than 64 bits. In that case and for the nominal frequency 6 MHz the dead zone area would be 8.5 mm!

CONCLUSIONS

This work examined the relationship between fractional bandwidth of ultrasound transducers and the CGS code bit lengths and its effect on the pulse-echoes sensitivity while retaining the axial resolution. As anticipated, the results of this work support the notion that the narrower fractional bandwidth of the coded excitation provides deeper penetration in a given medium. Consequently, CGS coded excitation can be successfully implemented using relatively narrowband imaging transducer without sacrificing axial resolution and taking advantage of the increased gain due to coded excitation. It is of importance, especially in diagnostic imaging, where the strongest possible suppression of peak pressure amplitudes is essential.

In closing it should be pointed out that the CGS theoretically provide the most attractive solution to the side-lobe suppression problem. However, in clinical practice tissue and blood movement between two consecutive pulse transmits will impede the perfect side-lobe cancellation and the influence of this deficiency on image quality has to be accounted for.

The results obtained by using proposed coded method of double transmission can also be applied in standard ultrasonography. This method shows the effectiveness of the double transmission and its resistance to the refraction, attenuation, and reflection of ultrasound waves. Introduction of this proposed coded method in medical ultrasound equipment can increase the effectiveness and quality of the ultrasound diagnostic.

ACKNOWLEDGMENTS

This work was supported by the Polish Ministry of Science and Higher Education (Grant N51502732/1964 and N51804432/3434).

REFERENCES

1. M. J. R. Golay, Complementary series, IRE Trans. Inf. Theory, IT-7, 82 – 87, 1961.
2. I. Trots, A. Nowicki, W. Secomski, J. Litniewski, Golay sequences – side-lobe - canceling codes for ultrasonography, Archives of Acoustics, Vol. 29(1), 87 – 97, 2004.
3. A. Nowicki, Z. Klimonda, M. Lewandowski, J. Litniewski, P. A. Lewin, I. Trots, Comparison of sound fields generated by different coded excitations - Experimental results, Ultrasonics, Vol. 44(1), 121–129, 2006.

4. J. Litniewski, A. Nowicki, Z. Klimonda, and M. Lewandowski, Sound fields for coded excitations in water and tissue: experimental approach, Ultrasound in Med. & Biol., Vol. 33(4), 601–607, 2007.
5. E. S. Furgason, V. L. Newhouse, N. M. Bilgutay, G. R. Cooper, Application of random signal correlation techniques to ultrasonic flow detection, Ultrasonics, Vol. 13, 11–17, 1975.
6. N. M. Cohen, Pulse compression in pulse-Doppler radar systems, Airbone pulsed Doppler radar, G. Morris, L. Harkness [Eds.], Ch. 9, Artech House, 173–214, Boston 1996.
7. Monika-Hildegard Schmid-Wendtner, W. Burgdorf, Ultrasound scanning in dermatology, Arch. Dermatol., Vol. 141, 217 – 224, 2005.
8. Z. Kielbasa, H. Gawda, B. Wach, Ultrasonography as a method of diagnosis and treatment monitoring in dermatology, Vol. LXII, no. 1, 46, 242 – 247, Annales Universitatis Mariae Curie-Sklodowska, Lublin – Polonia 2007.
9. A. Nowicki, W. Secomski, I. Trots, J. Litniewski, Extending penetration depth using coded ultrasonography, Bulletin of the Polish Academy of Sciences Techical Scien., Vol. 52(3), 2004.