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DIRECT AND POST-COMPRESSED SOUND FIELDS FOR DIFFERENT CODED EXCITATIONS – EXPERIMENTAL RESULTS

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Coded ultrasonography is intensively studied in many laboratories due to its remarkable properties: increased depth penetration, signal-to-noise ratio (SNR) gain and improved axial resolution. However, no data concerning the spatial behavior of the pressure field generated by coded bursts transmissions were reported so far. Five different excitation schemes were investigated. Flat, circular transducer with 15 mm diameter, 2 MHz center frequency and 50% bandwidth was used. The experimental data was recorded using the PVDF membrane hydrophone and collected with computerized scanning system developed in our laboratory. The results of measured pressure fields before and after compression were then compared to those recorded using standard ultrasonographic short-pulse excitation. The increase in the SNR of the decoded pressure fields is observed. The modification of the spatial pressure field distribution, especially in the intensity and shape of the sidelobes is apparent. Coded sequences are relatively long and, intuitively, the beam shape could be expected to be very similar to the sound field of long-period sine burst. This is true for non-compressed distributions of examined signals. However, as will be shown, the compressed sound fields, especially for the measured binary sequences, are similar rather to field distributions of short, wideband bursts.

Key words: coded excitation, ultrasonic field distribution, pulse compression, matched filtration, medical imaging.

1. Introduction

Coded transmission is a technique known and widely used in radar systems. The idea of its application in the medical field is about twenty-five years old. Currently the coded transmission in ultrasound techniques is a dynamically developing method that can be used in a wide range of applications such like ultrasonography, Doppler techniques and non-destructive testing. Increasing interest in coded transmission is related to the possibility to overcome the limitation in obtaining fine axial resolution and long-range penetration. Two factors cause this limitation. First of all, attenuation is an increasing function of frequency, but to get a better axial resolution it is necessary to use a higher frequency (shorter wavelength). Secondly, although one can use a higher amplitude impulses when attenuation reduces the echo pulse amplitude, it must not be done without limit, because of undesirable side effects such as cavitation or increase of temperature – these effects in medical applications could be dangerous and damage the tissue. The coded transmission enables to obtain longer range penetration by transmitting long coded pulse and compressing the echo using cross-correlation with the transmitted signal (matched filtration), instad of increasing the amplitude of the impulses. This causes a great signal-to-noise ratio (SNR) gain, so even the signals that were buried in a noise can be detected after compression.

There is an increasing quantity of papers written about the application of coded transmission to ultrasound examinations. POLLAKOWSKI and ERMERT [1] describe the advantages of using nonlinear modulated pseudochirp (square wave) in ultrasonic, non-destructive testing. An increase of the echo amplitude and improvement of the mainlobe-to-sidelobe ratio compared to the ordinary linear chirp can be obtained, and additionally the generating hardware may be simplified with the use of this technique.

NOWICKI *et al*. [2] present experimental results from using pulse compression with Golay's complementary sequences on tissue phantom. These results show deeper penetration preserving axial resolution and improvement of image contrast, in comparison to sine excitation.

MISARIDIS *et al*. [3] present the coded excitation ultrasound system that use linear frequency modulated signals of 20 μs duration. The transducer frequency weighting function is taken into account in the design of the matched filter in this system. This significantly reduces the sidelobe level of the filter output. Phantom and clinical images are presented and show a clear improvement of quality and depth penetration in comparison to an ordinary pulse excitation system.

BEHAR and ADAM [4] investigate and present simulation results of the optimisation of the excitation/compression scheme for the ultrasound linear array system, which transmits linear frequency-modulated pulses. This scheme consists of a choice of window function for tapering the transmitted pulse, a choice of filtering function, an optimisation of chirp-to-transducer bandwidth and a choice of n-bit quantizer. The authors show that with proper parameters of the coding system, benefits of this technique – gain in SNR and the penetration depth – can be obtained with minimised disadvantages – range sidelobes.

Although there are many other papers written about the applications of the coded transmission in ultrasonography, the authors of this work couldn't find any information about spatial field distribution of coded excitation. It is necessary to know the shape of the field to designate possible artefacts connected to the presence of the beam sidelobes. The shape of a beam as well as the quantity and level of the sidelobes are related to the type of transducer and to the excitation signal driving this transducer. Because of the increasing interest in coded transmission and the probable wider application of coded signals in ultrasonic imaging systems, measurements of the spatial field distribution of linear modulation, Barker code and Golay sequences before and after compression have been done.

2. Coded transmission

The difference between a standard, short-burst transmission technique and a coded transmission is that in the latter, the emitted signal has a specific signature and has a rather extended time duration. Received echoes $e(t)$ are correlated with the replica of the transmitted signal $s(t)$ using cross-correlation according to Eq. (1).

$$R(\tau) = \int_{-\infty}^{\infty} s(t)e(t-\tau)dt. \tag{1}$$

This so-called matched filtration results in time compression of the received echoes, while restoring a good axial resolution with a considerable increase of SNR. It is possible to differentiate two classes of waveforms depending on their coding algorithm – the amplitude and phase-modulated. Phase modulation can be continuous or a discrete one. Linear frequency-modulated waveform (chirp) belongs to the class of continuous phase modulation. Barker and Golay codes represent the discrete phase modulation. In reality the echoes can be very different from the transmitted signal, because of the overall influence of scattering and frequency-dependent attenuation in tissue, but in an ideal case, neglecting the echoes distortion, the output correlation function can be approximated correlating the transmitted function with itself. Examples of different codes and their autocorrelation functions are shown in Fig. 1, 2 and 3.

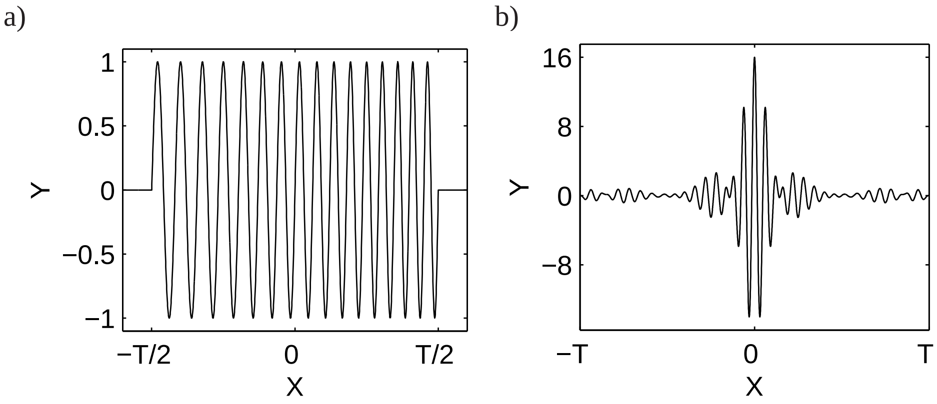

Fig. 1. Linear modulation – chirp signal (a) and its autocorrelation function (b).

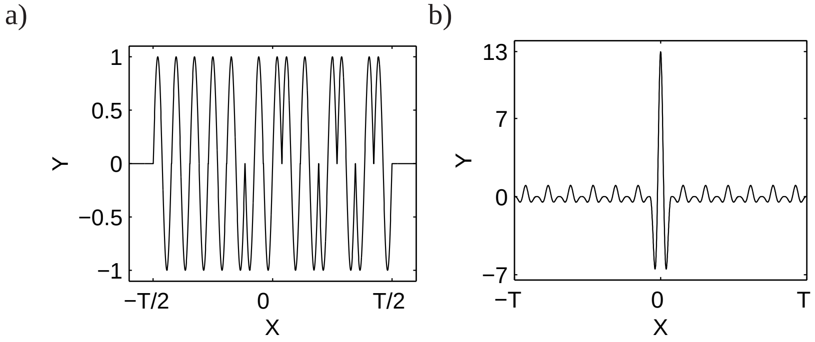

Fig. 2. Barker code (a) and its autocorrelation function (b).

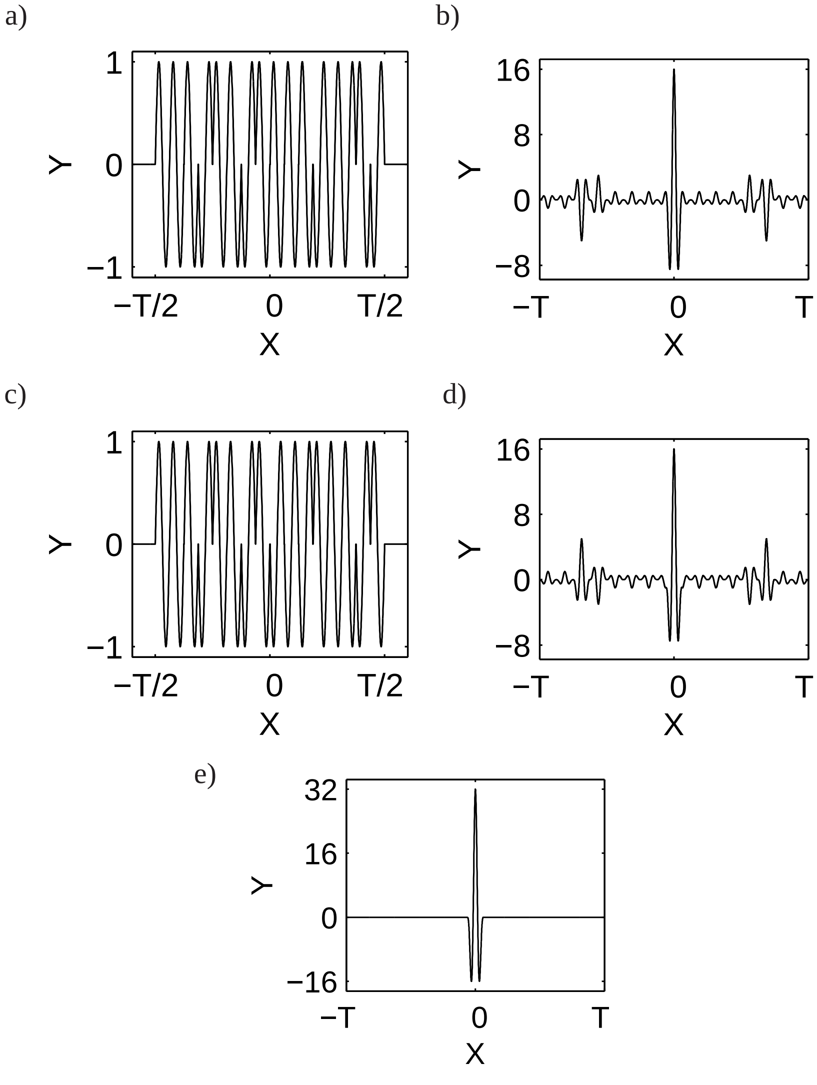

Fig. 3. Golay codes (a, c) its autocorrelation functions (b, d) and the sum of autocorrelation function (e).

As it can be noticed, the important feature of autocorrelation function of these codes is the presence of time (or range) sidelobes. These sidelobes are undesired attributes, because their presence introduces artefacts in the ultrasonic image, affecting its quality. The shape and the peak-sidelobe level depend on the applied signal's type. For linear, non-apodized chirp the sidelobes are 13.2 dB below the main peak, independently of the time-bandwidth product. The only way to obtain a better peak-sidelobe level is weighting in time or in frequency [5]. The most widely used binary codes are the Barker sequences. They are optimum in the sense that the autocorrelation function peak is N and the sidelobe level falls between $+1$ and -1, where N is the number of subpulses (elements). The compression ratio is proportional to the length of the code, however no Barker code larger than 13 elements has been found. The Golay complementary codes, as shown in Fig. 3, have a very interesting property from the ultrasonography point of view. As can be noticed, the sum of autocorrelation functions of Golay codes has no sidelobes. This property comes from the reversed signs of sidelobes amplitude of the compressed output.

This rather well-known behaviour of the three different coding algorithms was shortly discussed before introducing the main goal of this paper, namely what is the shape of the scanning beam for these three codes, after the compression is performed.

3. Measuring system

The measurements were made using a system constructed in IFTR PAS. This system can scan ultrasonic field in line, plane or 3D cube with minimal raster 0.1 mm. Measurements were taken by stationary hydrophone where ultrasonic head was moved by a mechanical scanner controlled by PC computer. The system shown in Fig. 4 consists of:

- mechanical scanner (ISEL)
- arbitrary function generator (LeCroy 9109)
- power amplifier (ENI 3100LA) wideband PVDF hydrophone (Sonic 804-201)
- amplifier (RITEC BR-640)
- sampling oscilloscope (HP 54503A)
- PC computer that controls the scanner arbitrary function generator and sampling oscilloscope.

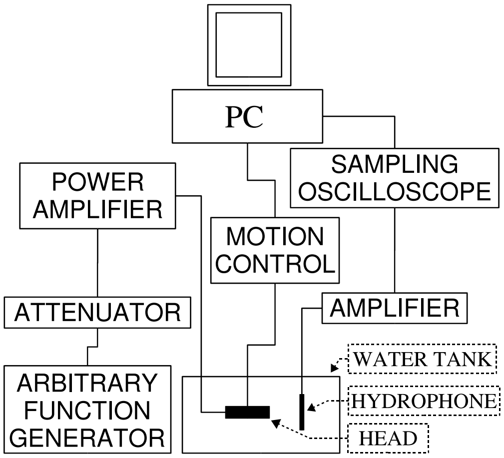

Fig. 4. Scheme of measuring system.

There was a 2 MHz head with 15 mm diameter and 50% bandwidth used in measurements. The near-field distance for the transducer was 75.5 mm. The head was excited by one of the four signal types:

- 2 or 16 periods of sinus of frequency 2 MHz (as reference singnals),
- the chirp signal with center frequency 2 MHz and bandwidth 1 MHz,
- the Barker code, 13 bits long with carrier frequency 2 MHz,
- complementary pair of Golay codes, 16 bits long, with carrier frequency 2 MHz and signatures:
- $\{1, 1, 1, -1, 1, 1, -1, 1, 1, 1, 1, -1, -1, -1, 1, -1\}$ and
- $\{1, 1, 1, -1, 1, 1, -1, 1, -1, -1, -1, 1, 1, 1, -1, 1\}$.

The ultrasonic field was scanned in rectangle 6 by 10 cm that lied on a longitudinal axis of the head with the raster of 1 mm across, and 5 mm along the beam. In all points the pressure variation was measured, and the maximum peak-to-peak value was specified. In case of coded signals the maximal value after compression was specified as well, so the field distribution before and after compression was obtained. The maximal pressures obtained in the experiment reached ca. 1.5 MPa.

4. Results

The compression process results in SNR gain – about 15 dB for Barker code, 19 dB for chirp and 20 for Golay codes. There is a small but visible narrowing of the beam too – about 1 mm at -6 dB, and 5 mm at -20 dB from a distance of 50 mm away from the transducer (Fig. 5). The field distributions are presented in Fig. 6–11. The isobars on images are placed every 6 dB. As one can notice, there are some sidelobes in the spatial field distributions of uncompressed codes (Fig. 8, 10, 12), while in the fields of compressed signals (Fig. 9, 11, 13) the sidelobes are much smaller, as for chirp, or there are almost no sidelobes, as for binary sequences. In comparison to reference signals of long 16 periods and short two periods of sine (Fig. 6, 7) it is clear, that the field distribution of code after compression became similar to the field distribution of a short-pulse, while before compression it used to be rather similar to the field distribution of a long signal.

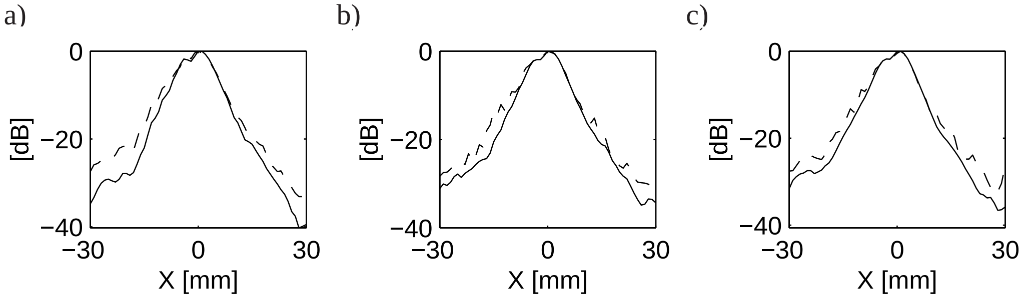

Fig. 5. Changes of pressure on line sheer to the beam, 50 mm away from the transducer for chirp (a), Barker code (b) and Golay code (c). Solid and dashed line denotes the compressed and non-compressed beam respectively.

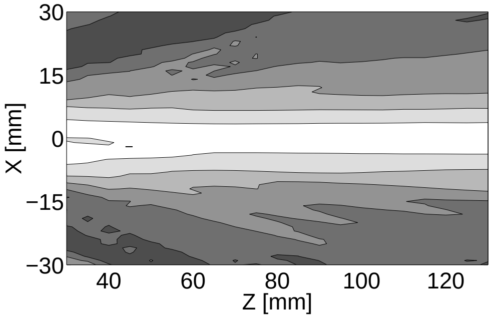

Fig. 6. 16 periods of sine.

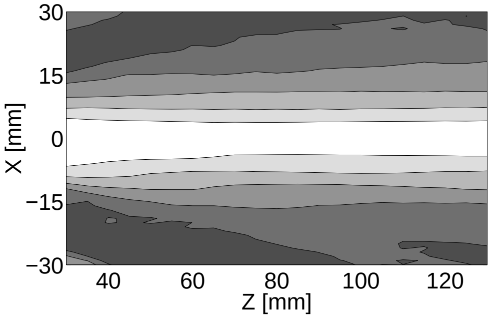

Fig. 7. 2 periods of sine.

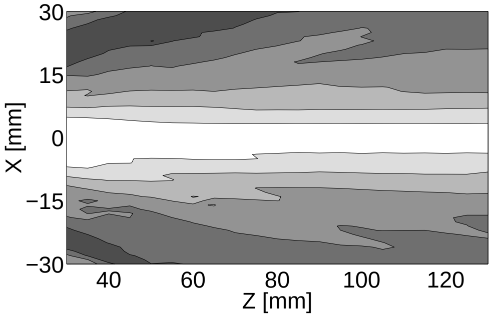

Fig. 8. Non-compressed chirp.

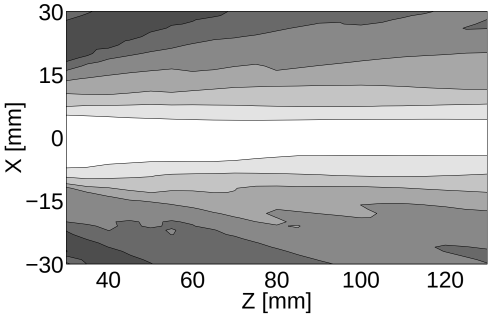

Fig. 9. Compressed chirp.

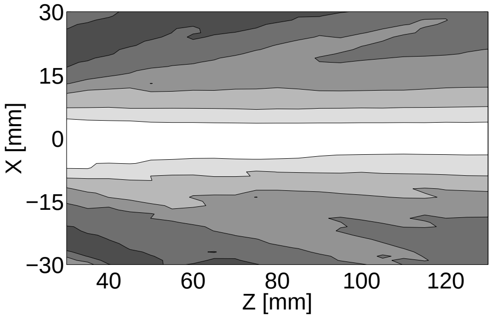

Fig. 10. Non-compressed Baker code.

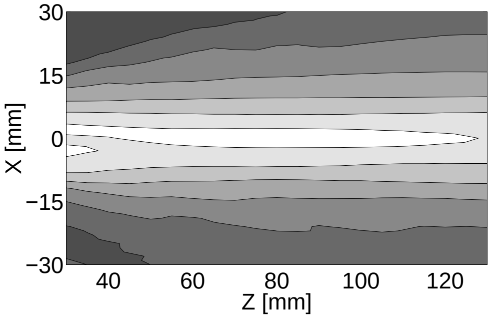

Fig. 11. Compressed Baker code.

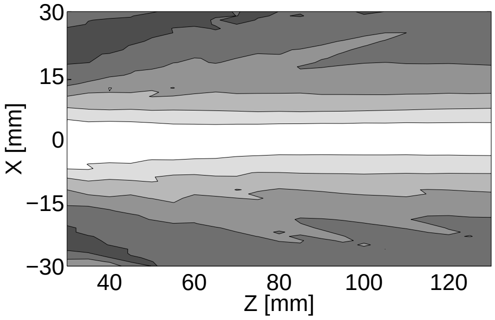

Fig. 12. Non-compressed Golay's pair element.

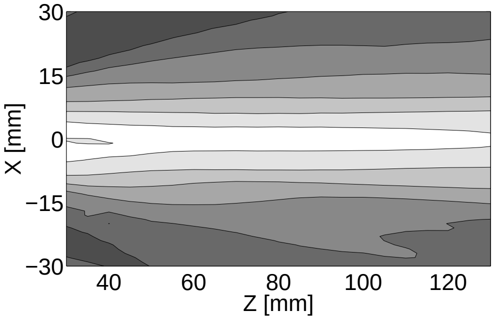

Fig. 13. Sum of compressed Golay's pair elements.

5. Conclusions

Presence of the spatial sidelobes in ultrasonic field distribution is characteristic for long or continuous excitation with narrow bandwidth, while for short signals with wide bandwidth the sidelobes tend to disappear. The results of measurements show that the field distributions of uncompressed coded signals are similar to the field distribution of comparable longsine excitation, but after compression it becomes more similar to the distribution of short, wideband signal. Therefore, not only does the matched filtration of proper coded signals significantly increase the SNR, but it also results in a strong reduction of spatial sidelobes of the beam. Thus, transmissions of long, but coded sequences, with the use of matched filtration will not introduce the artifacts connected with the presence of spatial sidelobes of the beam to ultrasonic image.

References

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