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Science Letters:

A new coding scheme in coded ultrasound using staggering repetition interval*

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Abstract: The increase of frame rate, though with the potential in a coded ultrasound system, is generally concomitant with the simultaneous transmission of a number of apertures, and in consequence leads to increased cross-talks between different apertures. In view of this, a new coding scheme using staggering repetition interval was proposed. The transmitting signals were constructed by repeating the two (or more) modulated codes using staggering repetition interval, and then allocated to and transmitted simultaneously among different apertures. The decoding process was based on the subsection-matched filter under the assistance of different matched filters for different apertures. At last the outputs of subsection-matched filtering were added together. Staggering changed the positions of cross-correlation (CC) peaks from coinciding, which resulted in an effective reduction of CC. Our theoretical analysis and simulations showed that, the coding scheme can be used to reduce cross-talk, and a good cross-talk reduction will be achieved if the staggering delay is kept in an appropriate range.

Key words: Coded ultrasound, Frame rate, Cross-correlation (CC), Staggering, Ultrasonic imaging
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INTRODUCTION

Coded signals have been studied for many years in medical ultrasound (Takeuchi, 1979; Chiao and Hao, 2005; O′Donnell and Wang, 2005; Gran and Jensen, 2008). They are primarily used to either improve the signal-to-noise ratio (SNR) or increase the frame rate in ultrasound imaging (Misaridis and Jensen, 2005).

In general, frame rate is increased with the simultaneous transmission of a number of apertures, which will intensify cross-talk between different apertures. The cross-correlation (CC) properties of practical codes that can be used in ultrasound imaging do not suffice for high quality fast imaging. A coding scheme that increases the frame rate in ultrasound imaging without any degradation in image quality is desired. In this letter we propose a new coding scheme using staggering repetition interval to reduce the cross-talk between different apertures. The scheme mainly includes constructing transmitted signals and the special decoding process.

PROPOSED NEW CODING SCHEME

Problem

Frame rate can be increased with the simultaneous transmission of a number of coded signals (Thrush and Hartshorne, 2005), i.e., multiple focused coded beams along different directions or lines, as shown in Fig.1. Separation of the echoes from all excitation signals requires that the CC of any two signals in the set be low for all relative phase shifts.

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The exact lower limit depends on the choice of the code. For practical codes at a length ranging from 30 to 100, which can be used in ultrasound imaging, this corresponds to a cross-talk level of at best 15 dB below the auto-correlation peak for the case of two codes (Misaridis and Jensen, 2005). The dynamic range of ultrasound B-mode images is at least 45 dB for most scanners, and such an interference level will thus significantly degrade the image quality. Imaging strategies have to be sought to minimize acoustic interference among the transmitted signals with a proper code length.

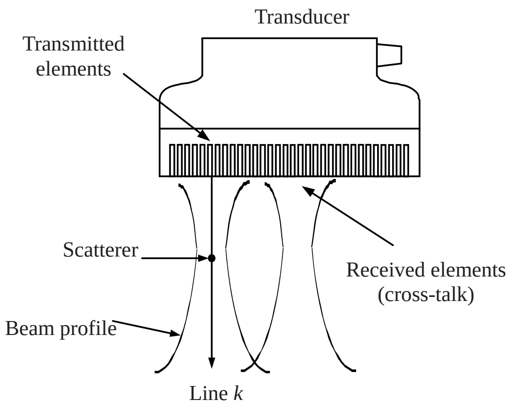

Fig.1 Illustration of simultaneous transmission with coded signals in linear array imaging (Misaridis and Jensen, 2005)

New coding scheme

Given that the UCL-CDMA coding technique (Qin and Turunen, 2004; 2005) sharply reduces CC without using longer codes, we introduce a new coding scheme, modified from UCL-CDMA, by using the principle of unequal coded lengths.

If code lengths of two codes are equal, the transmitting signals, also named as pulse trains, are constructed by repeating the two modulated codes using staggering repetition interval. Fig.2 shows the processing of a transmitting signal created while code lengths of the two codes are equal. $T_d=T_{c2}-T_{c1}$ is the staggering delay between two coded signals, where T_{c1} and T_{c2} represent the constant transmit delays of two transmitting signals from code (pulses) to code (pulses) individually, and the number of repetitions is m=6. Subsequently the constructed signals can be allocated to different apertures and transmitted simultaneously.

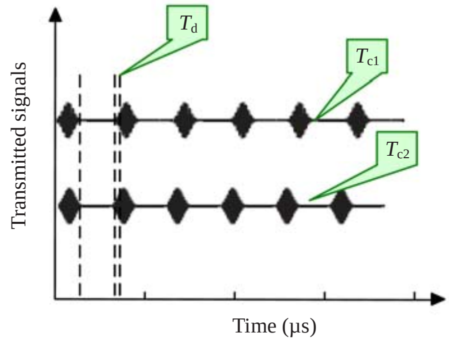

Fig.2 Illustration of staggering transmitted signals

The decoding process is based on the subsection-matched filter, assisted by using different matched filters for different apertures (Fig.3). It necessitates the setting of individual matched filters on individual apertures and the sub-sample delays are introduced to divide the received signal into m contiguous subsections. The outputs of matched filtering of m subsections are S_0, S_1, …, S_{m-1}. At last by adding together ($S_0+S_1+\ldots+S_{m-1}$), the CC is suppressed and the cross-talk is reduced. Of course, according to the distribution law for the convolution transform, it is also possible to change the order of the matched filtering and summation processing.

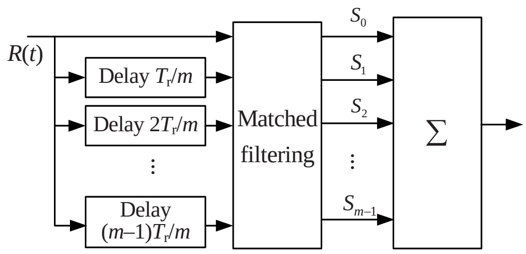

Fig.3 Processing of subsection filtering when the number of repetitions is m. T_r represents the total delay during the whole transmitting process

Theoretical analysis of the coding scheme

We denote the coded signal of two pulse trains by

$$s_x(t)=\sum_{i=0}^{L-1} x_i f(t-iT_c), \quad (1)$$

$$s_y(t)=\sum_{i=0}^{L-1} y_i f(t-iT_c), \quad (2)$$

where T_c is the chip length, f is a baseband pulse waveform, x_i and y_i indicate a sequence of chips belonging to the alphabet $\{-1, 1\}$, and L is the length of the sequence x and y.

The signals of $s_x(t)$ and $s_y(t)$ received from the first aperture can then be expressed as $g_x(t)$ and $g_y^l(t)$, respectively. $g_y^l(t)$ denotes the interference, and l is the length of staggering between y and x, $l\in[-L+1, L-1]$. It is assumed that the effects of code Doppler can be neglected. We define continuous time CC functions as

$$R_{x,y}(t)=\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2}g_x^*(u)g_y^l(u+t)\mathrm{d}u. \tag{3}$$

We can express Eq.(3) at discrete time events:

$$\theta_{x,y}(n)=\sum_{i=0}^{L-1}x_{n-i}y_{i-l}^l. \tag{4}$$

When $i<0$, $y_i=0$, for $l\in[-L+1, L-1]$,

$$\sum_{l=-L+1}^{L-1}\theta_{x,y}(n)=\sum_{l=-L+1}^{L-1}\sum_{i=0}^{L-1}x_{n-i}y_{i-l}^l, \tag{5}$$

$$\sum_{l=-L+1}^{L-1}\theta_{x,y}(n)=\sum_{i=0}^{L-1}\left(x_{n-i}\sum_{l=-L+1}^{L-1}y_{i-l}^l\right). \tag{6}$$

For each i there exists $\sum_{l=-L+1}^{L-1}y_{i-l}^l=\sum_{k=0}^{L-1}y_k$, and all values of y are traversed. We use the term balanced to indicate that the sum of code elements is zero or, when the code length is odd, it differs from zero by one; i.e.,

$$\sum_{k=0}^{L-1}y_k=\begin{cases}0, & L \text{ is even},\\ \pm 1, & L \text{ is odd}.\end{cases} \tag{7}$$

When L is even, $\sum_{l=-L+1}^{L-1}y_{i-l}^l=0$, and $\sum_{l=-L+1}^{L-1}\theta_{x,y}(n)=0$. This means that there is almost no interference between the two sub-pulses if the staggering for all $l\in[-L+1, L-1]$. The same is true for any multiple of the staggering cycle. If the code lengths are not even, the above conclusion does not hold.

In addition, the changes in the pattern appear as if the CC peaks were sliding by comparing $\theta_{x,y}(n)|_{l=i}$ with $\theta_{x,y}(n)|_{l=i+1}$. The staggering makes the CC patterns non-stationary with respect to the pulse trains profile so that CC can be eliminated by averaging when the results of repeated correlations are combined.

Matlab analysis of the coding scheme

Using Matlab, we have chosen randomly balanced codes:

$x=\{-1, 1, 1, 1, -1, 1, 1, -1, -1, 1, -1, 1, -1, -1, -1\}$,
$y=\{-1, -1, -1, -1, 1, 1, 1, -1, 1, 1, -1, -1, 1, -1, 1\}$.

T_d is equal to the chip length. In Fig.4, the solid line is the auto-correlation of x and the dashed one is the CC. In Fig.4a the dashed line shows the CC of x and y. Fig.4b reports the result at the staggering cycle of $[0, L-1]$ (i.e., $m=L$), where the maximum CC peak is only 26 dB below the CC value of Fig.4a. Fig.4c presents the result at the staggering cycle of $[-L+1, L-1]$, where the CC can be eliminated completely.

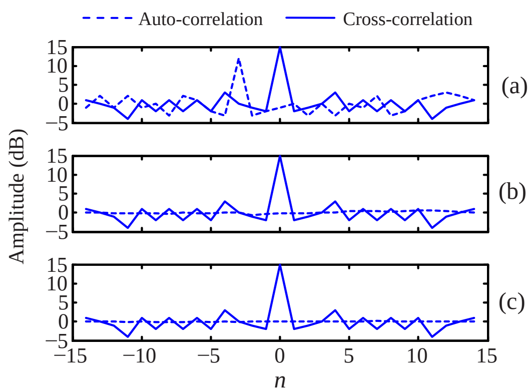

Fig.4 Simulation results using Matlab
(a) $m=1$; (b) $m=L$; (c) $m=2L-1$

The values in Table 1 indicate the maximum CC below the CC value of x and y, and the following conclusions will be made:

(1) With appropriate staggering (T_d) a good reduction of CC can be achieved.

(2) The CC reduction is proportional to the size of m.

Table 1 Simulation results with parameters of m and T_d

m	Reduction in maximum cross-correlation (dB)				
	$T_d=T_c$	$T_d=2T_c$	$T_d=3T_c$	$T_d=4T_c$	$T_d=5T_c$
1	0.00	0.00	0.00	0.00	0.00
2	7.60	7.60	6.02	6.78	9.54
3	13.06	12.04	10.30	9.54	10.30
4	15.56	13.62	12.80		
5	16.48	14.74	15.56		
6	18.82	15.56			
7	19.08	17.66			
8	20.76				

COMPUTER SIMULATION AND DISCUSSION

It is necessary to investigate the cross-talk reduction and its related factors. The factors mainly include the staggering delay (T_d) and the number of repetitions (m).

Simulation conditions

The simulation program Field II (Jensen, 2004) was used to simulate a linear array system with a 128-element transducer. The transducer center frequency was 5 MHz with a kerf of 0.051 mm, the height of an element was 10 mm, and the width of an element was equal to the wavelength. The size of transmit apertures was 22 elements and a fixed transmit focus was 80 mm. The target was a single scatterer located at 60 mm along line k. The size of receive sub-apertures was 48 elements and the distance between the two receive apertures was 50 elements. Fig.1 shows the processing of a linear array transducer with two sub-apertures that transmit simultaneously.

Simulation results

In order to prove that this encoding scheme can reduce cross-talk, we have chosen heuristically the following phase-coded waveform of the length-15 PN code:

$$x=\{-1, 1, 1, 1, -1, 1, 1, -1, -1, 1, -1, 1, -1, -1, -1\},$$
$$y=\{-1, -1, -1, -1, 1, 1, 1, -1, 1, 1, -1, -1, 1, -1, 1\}.$$

And the duty cycle was assumed as 0.5.

Results in Table 2 show that the maximum CC peak of the receive aperture is smaller than the CC value of the receive aperture when the simultaneous transmission was conducted using x and y.

Table 2 Ultrasound simulation results with parameters of m and T_d

m	Reduction in maximum cross-correlation (dB)				
	$T_d=T_c/2$	$T_d=T_c$	$T_d=2T_c$	$T_d=3T_c$	$T_d=4T_c$
1	0.03	0.03	0.03	0.03	0.03
2	5.98	5.95	5.96	6.02	5.95
3	7.66	8.34	9.68	8.61	9.74
4	15.86	17.12	13.05	9.65	10.27
5	22.49	14.53	13.19	11.71	
6	21.46	15.55	15.02	13.77	
7	23.92	17.12	16.21		
8	27.39	18.49	17.53		

Thus, from a number of ultrasound simulation results in Table 2, we can make a summary:

(1) The coding scheme can be used to reduce cross-talk.

(2) The CC reduction is proportional to the size of m if $mT_d<LT_c$.

(3) If the staggering delay is in an appropriate range, a good cross-talk reduction will be achieved.

CONCLUSION

In order to increase the frame rate in ultrasound imaging without any degradation of image quality, a new coding scheme using staggering repetition interval was proposed. Generally speaking, staggering changes the positions of CC peaks from coinciding, leading to an effective reduction of CC.

Only a preliminary investigation of the coding scheme was carried out in this letter. Many other issues with this coding scheme, such as robustness to Doppler shift and effect on resolution, will be investigated systematically later.

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