Binary Code Design for High-Frequency Ultrasound

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Abstract—This paper proposes an approach to designing binary codes suitable for high-frequency applications of coded excitation in medical ultrasound. For a high-frequency ultrasound system, transmitting well-designed binary codes with a low sampling ratio (i.e., the bit rate divided by the transducer center frequency) is a practical way to improve the signal-to-noise ratio (SNR) because the challenge of implementing arbitrary-waveform generators for transmitting nonbinary codes increases with the frequency and the switching speed of square-wave pulsers are limited. One conventional approach designs codes using a base sequence that modulates wideband sequences up to the transducer passband. Because a major portion of codes is excluded as a candidate, codes designed using this approach typically need long compression filters for restoring the axial resolution, and they do not improve the SNR efficiently. In contrast, the approach proposed here searches all the codes that match the transducer passband; hence, the resultant codes exhibit better performance. The technique was tested using a bit rate of 50 MHz and a sampling ratio of 2. For a transducer with an ideal Gaussian frequency response with a center frequency of 25 MHz and a -6 dB bandwidth of 15 MHz, the SNR for the same sidelobe extent was 1 to 6 dB higher for the codes designed using the proposed approach compared with those designed using the conventional approach. When a real transducer response with a center frequency of 26.4 MHz and a one-way -6 dB bandwidth of 20.7 MHz was considered, the codes designed using the proposed approach were superior by 0.5 to 5 dB. Therefore, our approach is better than the conventional approach for designing binary codes for high-frequency ultrasound, with the results indicating that the moderate bit rate of 50 MHz will suffice when the ultrasonic center frequency is 25 MHz.

I. INTRODUCTION

A PRIMARY application of coded excitation in medical ultrasound is improving the signal-to-noise ratio (SNR) without increasing the peak acoustic power [1], and the papers on coded waveforms (e.g., [2], [3]) published in this journal describe some of the recent progress and offer extensive references to previous studies in diverse applications. Fig. 1 shows a block diagram of a coded excitation system, in which each channel has a transmitter able to transmit the desired code (which has a wide bandwidth

Fig. 1. Block diagram of a coded excitation system.

and an increased pulse length), and a compression filter whose coefficients and length are strongly influenced by the code is placed after the receive beamformer so as to restore the axial resolution. The performance of pulse compression is generally characterized by the mainlobe width (related to the axial resolution) and the sidelobe level (related to the dynamic range and contrast resolution) of the compressed pulse, and the SNR improvement (i.e., the difference between the SNRs after and before pulse compression).

Codes can be classified according to the required transmitter type. A nonbinary code necessitates an arbitrary-waveform transmitter, and a binary code can be transmitted with a square-wave pulser. Although it is easy to design nonbinary codes with good compression performances, such codes have not been widely used in array systems mainly due to the increased hardware complexity and cost associated with the requirement for multiple arbitrary-waveform transmitters. Furthermore, the challenge of implementing an arbitrary-waveform transmitter increases with the center frequency of the transducer (or the code), and it may still be impractical to use codes other than binary ones for a high-frequency (e.g., 25 MHz) ultrasound system that images using an array of transducers. The difficulty of designing binary codes also increases with frequency due to the limited switching speed of square-wave pulsers and, consequently, the allowable sampling ratio decreases as the center frequency of the transducer increases (where the sampling ratio is the bit rate divided by the transducer center frequency).

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In this paper, we focus on designing single-firing (or single-transmit) binary codes having a low sampling ratio (e.g., 2) and efficiently improving the SNR. Here a code improving SNR efficiently means that it provides a high ratio of SNR improvement to sidelobe duration after pulse compression. Given a certain code length (in units of time), using a lower sampling ratio is equivalent to having fewer tunable bits and fewer degrees of freedom in the code design, which results in worse performance. Note that in order to cover the full bandwidth of the transducer, the sampling ratio is generally at least 2.

In medical ultrasound, a typical approach to generating a binary radio-frequency (RF) code with a low sampling ratio is modulating an N_C -bit wideband sequence $c_{WB}(n)$, $n = 0, 1, \dots, N_C - 1$, up to the transducer band using an N_B -bit base sequence $b(n)$, $n = 0, 1, \dots, N_B - 1$. Zeros are inserted into $c_{WB}(n)$ to get:

$$c'_{WB}(n) = \begin{cases} c_{WB}(m) & \text{if } n = N_B m \text{ for } m = 0, 1, \dots, N_C - 1 \\ 0 & \text{elsewhere} \end{cases}, \quad (1)$$

and then $c'_{WB}(n)$ is convolved with $b(n)$ to form the final N -bit RF code $c_{RF}(n)$, $n = 0, 1, \dots, N - 1$, with $N = N_C N_B$ [2]–[4]. Explicitly:

$$\begin{aligned} c_{RF}(p + qN_B) &= b(p)c_{WB}(q), \\ p &= 0, 1, \dots, N_B - 1, \\ q &= 0, 1, \dots, N_C - 1. \end{aligned} \quad (2)$$

The wideband sequence is chosen to have the desired properties such as enabling range sidelobe cancellation [2] or benefiting inverse filtering [3], [4], and the base sequence (together with the bit rate) is used to control the band of the RF code [2]–[4]. We call such an approach the modulation approach. Because it has at most $[(N_C - 1) + (N_B - 1)]$ adjustable bits, a major portion of N -bit codes is excluded as a candidate. This means that some codes with good compression performances are not considered in order to reduce the design effort. Therefore, not all single-firing codes designed using the approach provide a high SNR improvement together with a short sidelobe duration and a short near-field dead zone.

Although the exhaustive-search approach (checking all N -bit codes in order to find the best RF code) is unfeasible in general, there are feasible approaches that are better than the modulation approach. In this study, we developed an indicator-based, random-search approach to finding codes with good compression performance based on a genetic algorithm [5]. This indicator is easy to calculate, and a code with a high-indicator value usually has good compression performance. Hence, the adoption of the indicator makes the proposed approach feasible. As shown in Section IV, the compression performances of codes designed using this approach are superior to those designed using the modulation approach.

This paper is organized as follows. Section II describes the criterion for evaluating the codes that are used to im-

prove the SNR. Section III details the indicator-based, random-search approach to binary code design. The genetic algorithm used for the code search also is presented. Section IV demonstrates the efficacy of the proposed approach and discusses its characteristics, and the paper concludes in Section V.

II. CRITERION FOR EVALUATING CODES

For single-firing codes, restoring the axial resolution by compressing the pulses is achieved by filtering. In order to clarify the criterion for evaluating codes, we must first describe how to design the compression filter used in this study.

A. Design of the Compression Filter

In general, a time-domain compression filter is preferable to a frequency-domain filter because the latter is vulnerable to the presence of incomplete echoes in the near field. In this study, we adopted a previously proposed method [6] providing direct control over the sidelobe level to design time-domain compression filters at baseband. If $h_t(t)$ is the one-way impulse response of the transducer, the digitized echo signal corresponding to an N -bit code $c_{RF}(n)$ from a point target can be modeled as:

$$e(n) = [c_{RF}(t) \otimes h_t(t) \otimes h_t(t)]_{t=n/f_s}, \quad (3)$$

where $\otimes$ denotes convolution,

$$c_{RF}(t) = \sum_{n=0}^{N-1} c_{RF}(n) \Pi\left(f_b t - n + \frac{N}{2}\right), \quad (4)$$

f_b is the bit rate, f_s is the sampling rate of the analog-to-digital converter (ADC) at the receiver, and $\Pi(t) = 1$ if $0 \leq t \leq 1$ and 0 elsewhere. The $e(n)$ is demodulated into a baseband signal:

$$e_b(n) = h_L(n) \otimes [e(n) \cdot \exp(-j2\pi f_0 n / f_s)], \quad (5)$$

where f_0 is the center frequency of the transducer and $h_L(n)$ is a low-pass filter. The $e_b[n]$ then is downsampled by a factor of D to obtain $e_d(n) = e_b(Dn)$. Filtering $e_d(n)$ with a compression filter $h_o(n)$ restores the axial resolution in the output signal.

Given a filter length N_f , $h_o(n)$ is designed to maximize the output SNR under the constraints on the mainlobe width and the sidelobe level. Let m denote the index of the peak position of $e_{d,c}(n)$, I_{sl} denote the index set of the sidelobes, s specify the allowable peak sidelobe level, and $s_{dB} = 20 \log s$, then explicitly:

$$\begin{aligned} h_o(n) &= \arg \min_{h(n)} \sigma_{n_{d,c}}^2(0) \text{ subject to} \\ &\begin{cases} e_{d,c}(m) = 1 \\ |\operatorname{Re}\{e_{d,c}(n)\}| \leq s/\sqrt{2} \text{ for } n \in I_{sl}, \\ |\operatorname{Im}\{e_{d,c}(n)\}| \leq s/\sqrt{2} \text{ for } n \in I_{sl} \end{cases} \end{aligned} \quad (6)$$

where $\sigma_{n_{d,c}}^2$ denotes the power of the thermal noise $n_{d,c}(n)$ after compression, $e_{d,c}(n) = e_d(n) \otimes h(n)$, $h(n)$ has a length of N_f , and $\text{Re}\{\cdot\}$ and $\text{Im}\{\cdot\}$ denote the real and imaginary parts, respectively. The details for solving (6) are available elsewhere [6].

B. Definition of Code Efficiency

The near-field dead zone of a coded excitation system using a code-filter combination $\{c_{\text{RF}}(n; N), h_o(n; N_f)\}$ is $(T_c + T_f)/2$ larger than that of a pulsed excitation system, where $T_c = N/f_b$ and $T_f = N_f D/f_s$ (both in units of time) are the code length and the filter length, respectively. In addition, the sidelobe of a point target spans a duration of $(T_c + T_f)$ for this coded excitation system. Therefore, the value of $(T_c + T_f)$ should be as small as possible, and a given code-filter combination is better than another if it provides the same SNR improvement and has a lower $(T_c + T_f)$. Because the output SNR ideally should be proportional to both T_c and $(T_c + T_f)$, it is reasonable to treat a code-filter combination as better if it has a higher code-filter efficiency:

$$E_{\text{cf}}[c_{\text{RF}}(n; N), h_o(n; N_f)] \equiv \text{SNR}_{\text{dB}} - 10 \log_{10} [(T_c + T_f)/(T_0/2)], \quad (7)$$

where SNR_{dB} is the output SNR in decibels, and $T_0 = f_0^{-1}$. We can use (7) to fairly compare two code-filter combinations even if they provide different SNR improvements.

Note that given a code $c_{\text{RF}}(n; N)$, there is a one-to-one correspondence between N_f and $h_o(n; N_f)$. That is:

$$E_{\text{cf}}[c_{\text{RF}}(n; N), h_o(n; N_f)] = E_{\text{cf}}[c_{\text{RF}}(n; N), N_f], \quad (8)$$

and there exists an N_f (or a T_f) that results in the maximal E_{cf} value for the code. Defining the efficiency E_c of a code $c_{\text{RF}}(n; N)$ as:

$$E_c[c_{\text{RF}}(n; N)] \equiv \max_{N_f} \{E_{\text{cf}}[c_{\text{RF}}(n; N), N_f]\}, \quad (9)$$

means that a code which is easier to compress and/or improves the SNR to a greater extent will have a higher E_c value. Therefore, in this study a code is treated as more efficient at improving the SNR or having better compression performance if its E_c value is higher.

III. THE INDICATOR-BASED SEARCH APPROACH TO BINARY CODE DESIGN

Genetic algorithms may be used to stochastically search a domain that is too large to be searched exhaustively [5]. A genetic algorithm previously was used to design binary codes suitable for being compressed with inverse filtering in the frequency domain [7]. In the present study, we developed a genetic algorithm to design binary codes with high efficiencies. Because given a code, for obtaining its efficiency, typically tens of compression filters corresponding

Fig. 2. Flow diagram of the genetic algorithm used in the proposed search approach.

to different N_f 's need to be designed [see (9)] and designing a compression filter means solving a quadratic programming problem [see (6)] [6], it is evident that directly calculating the efficiency of each code during the search process is computationally expensive. Therefore, in our algorithm the following indicator that is easier to calculate while being closely correlated with the code efficiency was used as the parameter to be optimized during the search process:

$$I_E[c_{\text{RF}}(n; N)] \equiv \left\| \left\{ \frac{R_{c_{\text{RF}}}(t)}{R_{c_{\text{RF}}}(0)} - \frac{R_b(t)}{R_b(0)} \right\} \otimes h_t(t) \right\|^{-1}, \quad (10)$$

where $R_a(t) = a(t) \otimes a^*(-t)$ denotes the autocorrelation function of the signal $a(t)$ [representing $c_{\text{RF}}(t)$ or $b(t)$ here],

$$b(t) = \sum_{n=0}^{N_B-1} b(n) \Pi \left(f_b t - n + \frac{N_B}{2} \right), \quad (11)$$

$R_{c_{\text{RF}}}(0) = (N/f_b)$, and $R_b(0) = (N_B/f_b)$. If the spectrum of an RF code in the transducer band is similar to that of the base sequence (in terms of the normalized amplitude), it will have a large I_E value. Because, in general, the base sequence (such as $\{1, -1\}$ or $\{1, -1, 1, -1\}$) has a smooth spectrum, RF codes with large I_E values tend to have a smooth spectrum. Therefore, they are easy to compress

TABLE I
HEXADECIMAL REPRESENTATIONS OF THE RF CODES DESIGNED USING THE SEARCH APPROACH (SECOND COLUMN)
AND THE MODULATION APPROACH (FIFTH COLUMN) FOR $b(n) = (-1)^n$ AND $N_B = 4$.¹

N	Search approach		Modulation approach	
	RF code	N_C	Wideband sequence	RF code
32	252A5551	8	1A	555AA5A5
36	75558AD4B	9	068	55AA5A555
40	4AD52AAAFB	10	0D0	55AA5A5555
44	5D554BA9529	11	065	5555AA55A5A
48	692952A15555	12	0CA	5555AA55A5A5
52	755552A952969	13	00CA	55555AA55A5A5
56	755556AB54A5A1	14	0195	55555AA55A5A5A
60	7555542A956A5AD	15	0EED	555AAA5AAA5AA5A
64	2D695AA550AAAABB	16	2833	55A5A55555AA55AA

¹The wideband sequences [9] necessary for the modulation approach are listed in the fourth column. The transducer was assumed to have a Gaussian frequency response with a 60% fractional bandwidth, and the additive noise sampled by the ADC was assumed to be white.

and exhibit a high efficiency. That is, the base sequence is used to control the spectrum shape of the RF code in the proposed search approach, as is also the case for the modulation approach.

Fig. 2 shows the flow diagram of the genetic algorithm for RF code design. In the second step, the probability of a code being chosen as a parent code for mating is proportional to its I_E value. A pair of parent codes $\{c_{RF,1}(n), c_{RF,2}(n)\}$ generates two offspring codes $c'_{RF,1}(n)$ and $c'_{RF,2}(n)$ according to the following rule:

$$c'_{RF,k}(n) = \begin{cases} c_{RF,k}(n) & \text{if } u(n) \geq 0.5 \\ c_{RF,3-k}(n) & \text{otherwise} \end{cases}, \quad (12)$$

where $u(n)$, $n = 0, 1, \dots, N-1$, are random numbers generated with a uniform probability density within $[0, 1]$, and k equals to 1 or 2.

IV. RESULTS AND DISCUSSION

A bit rate of 50 MHz was used in this study, except where stated otherwise. Given a fixed bit rate, the efficiency of a code relative to other codes is dominated by the transducer response and the noise characteristics, and it is less dependent on the parameters related to the design of the compression filter, including those of the filter $h_L(n)$, the sampling rate of the ADC ($f_s = 200$ MHz), the down-sampling ratio ($D = 5$), the mainlobe width (defined as the central nine points of the compressed signal), and the allowable peak sidelobe level ($s = 0.01$ or $s_{dB} = -40$ dB). Here $h_L(n)$ was a Kaiser-windowed finite impulse response low-pass filter with filter length $(M+1) = 19$, shape parameter $\beta = 3.7$, and -6 dB cutoff frequency $f_c = 0.1125$ [6], [8].

We designed RF codes using the search approach described in Section III and compared their efficiencies with those of the codes designed using the modulation approach. The additive noise sampled by the ADC was assumed to be a white noise. Furthermore, we assumed that

the SNR defined as the ratio of the peak signal power to the average noise power at baseband was 1 when transmitting a single-bit signal. Section IV-A describes the RF codes corresponding to an assumed transducer response. Section IV-B presents the impulse response of a transducer and the consequent designs of the matching RF codes. The effects of quantizing filter coefficients on compression performance are discussed in Section IV-C.

A. Results for a Gaussian-Shaped Transducer Response

Codes were designed assuming that the transducer has a Gaussian frequency response with a center frequency f_0 of 25 MHz and a -6 dB bandwidth of 15 MHz. The parameters of the genetic algorithm were $N_1 = 200$, $N_2 = 100$, $p = 1/N$, and $N_{iter} = 1000$. Given a specific code length and a base sequence, we realized $N_3 = 200$ trials and calculated the efficiencies of the 10 RF codes with the largest I_E values, in which the code with the highest efficiency was chosen to be the final RF code. Twenty-six codes were designed in this way, nine of which correspond to $N = 32$ to 64 with a step size of 4 using a two-cycle square wave [i.e., $b(n) = (-1)^n$ and $N_B = 4$] as the base sequence (Table I), with the others corresponding to $N = 32$ to 64 with a step size of 2 using a one-cycle square wave [i.e., $b(n) = (-1)^n$ and $N_B = 2$] as the base sequence (Table II). Note that, before transforming a code into its hexadecimal representation, all the bits equal to -1 were replaced with 0. Tables I and II also list the codes designed using the modulation approach, which were used as the references. The wideband sequences for the modulation approach were the sequences minimizing the noise enhancement factor [9]. That is, the output SNR will be well maintained if inverse filtering is applied to compress such a sequence (or code) and the noise is white. Note that the above statement neglects the transducer frequency response; a base sequence is necessary for pulse shaping (i.e., controlling the band of the RF code) if the transducer is taken into account. RF codes have been designed [3], [4] using the modulation approach with previously listed sequences [9].

TABLE II
HEXADECIMAL REPRESENTATIONS OF THE RF CODES DESIGNED USING THE SEARCH APPROACH (SECOND COLUMN)
AND THE MODULATION APPROACH (FIFTH COLUMN) FOR $b(n) = (-1)^n$ AND $N_B = 2$.¹

N	Search approach		Modulation approach	
	RF code	N_C	Wideband sequence	RF code
32	3AAB5A4C	16	2833	59955A5A
34	03AAB5A4C	17	04C2B	165A5599A
36	3C96A5577	18	0B477	59A656A6A
38	1A56AA9B0C	19	17421	166A655956
40	25AD72AA0C	20	05D39	5566A65A96
42	1D755AB4F6C	21	07C452	16AA5656659
44	02494A95457	22	0F88A4	5AA95959965
46	0906B5AAAF04	23	00E6D5	1555A969A666
48	0E952AEADA4F	24	111E2D	565656A959A6
50	0C17455AA525B	25	073F536	16A5AAA665A69
52	6214A5556C24F	26	063F56D	5695AAA6669A6
54	0DED2B562ABA6C	27	0F1112D	15AA56565659A6
56	65DD5252A8567B	28	38FEA4D	5A95AAA99965A6
58	07641556AB4A53C	29	031FD5B2	15A56AAA6669A59
60	6964AD6AAAF04C0	30	09BF8EB5	5969AAA95A99A66
62	032CAAA456A521CC	31	1CEADBFO	16A5A999A69AAA55
64	06B56AD352EAAE80	32	00F2D533	5555AA59A6665A5A

¹The wideband sequences [9] necessary for the modulation approach are listed in the fourth column. The transducer was assumed to have a Gaussian frequency response with a 60% fractional bandwidth, and the additive noise sampled by the ADC was assumed to be white.

Fig. 3. (a) 36-bit RF codes designed using the modulation and search approaches using a two-cycle square wave as the base sequence. (b) The normalized spectra of the base sequence, the wideband sequence for the modulation approach, and the RF codes.

As an example, the results from designing a 36-bit RF code using the modulation and search approaches with the two-cycle base sequence (i.e., $\{1, -1, 1, -1\}$) are shown in Fig. 3. Fig. 3(a) shows the RF codes designed using the two approaches, and Fig. 3(b) shows the normalized spectra of the base sequence, the wideband sequence for the modulation approach, and the RF codes. The spectrum in the transducer passband of the RF code designed using the search approach is smoother and thus easier to equalize than that designed using the modulation approach, resulting in a better compression performance and a higher efficiency. Note that Fig. 3(b) also illustrates that the base sequence controls the sampling ratio. If the base sequence $\{1, 1, -1, -1, 1, 1, -1, -1\}$ is used instead of $\{1, -1, 1, -1\}$, the sampling ratio will be 4 instead of 2.

Given a code length T_c , N will increase by a factor of 2. Because there are more adjustable bits, the code designed using the search approach will have a higher efficiency traded with a higher bit rate. For example, the 72-bit code “1CE73988CCCCDD936” operating at a bit rate of 100 MHz has an efficiency of 1.11 dB (resulting from an SNR of 21.31 dB at a filter length of $1.375 \mu\text{s}$), which is 0.81 dB higher than that of its corresponding 36-bit code operating at 50 MHz.

Fig. 4(a) shows the efficiencies of codes as functions of their lengths. Each code designed using the search approach has a higher efficiency than its corresponding code designed using the modulation approach with the same base sequence, with the difference ranging between 1 and 6 dB. In addition, the efficiencies of codes designed using

Fig. 4. Results for a Gaussian-shaped transducer response with a center frequency of 25 MHz and a -6 dB bandwidth of 15 MHz. (a) The efficiencies of codes as functions of their lengths. (b) The filter lengths that resulted in the maximal E_{cf} values equal to the code efficiencies. (c) The output SNRs corresponding to the filter lengths shown in (b).

the search approach are more independent of their lengths. Fig. 4(b) shows the filter lengths that resulted in the maximal E_{cf} values (i.e., the code efficiencies); the filter length is roughly proportional to the code length for the search approach. The ratios of the filter length to the code length range over [1.9, 2.3] and [1.5, 2.1] with the two- and one-cycle base sequences, respectively. In contrast, the filter length fluctuates markedly as the code length increases for the modulation approach; the ratios of the filter length to the code length range over [3.1, 8.4] and [2.8, 6.1] with the two- and one-cycle base sequences, respectively. Fig. 4(c) shows the output SNRs corresponding to the filter lengths

Fig. 5. Block diagram of the experimental setup used to measure the impulse response of a real transducer.

that resulted in the maximal E_{cf} values. Because the search approach tends to maximize the code efficiency instead of the SNR, some codes designed using this approach have SNRs that are lower than those of the corresponding codes designed using the modulation approach. In general, for a given code length, the SNR differs little between the codes designed using the two approaches; that is, the improvement in code efficiency using the search approach is mainly attributable to the reduction in the filter length. Furthermore, using a two-cycle square wave instead of a one-cycle square wave as the base sequence results in higher SNRs [Fig. 4(c)] due to the better match between the spectrum of the former base sequence and the transducer frequency response. This explains why the codes designed using the two-cycle base sequence have higher efficiencies, as shown in Fig. 4(a).

B. Results for a Measured Transducer Response

Fig. 5 shows the experimental setup used to measure the impulse response of a real transducer, which had a diameter of 6.35 mm and a focal length of 12.7 mm (V324, Panametrics, Waltham, MA). A pulser/receiver (5910PR, Panametrics) operating in pulse-echo mode was used to drive the transducer with a negative impulse, to receive and provide a noninverting 66 dB gain with -3 dB bandwidth between 5 and 400 MHz to the echo signal from a metal wire, and to synchronize an oscilloscope (WaveSurfer 432, LeCroy, Chestnut Ridge, NY) at a pulse repetition frequency of 200 Hz. The wire was measured to have a diameter of 32 μm and was placed 12.4 mm from the transducer. The amplified echo was digitized by the oscilloscope at a sampling rate of 2 GHz with an amplitude resolution of 8 bits.

Assuming that the effects of the finite bandwidths of the transmitted impulse and the amplifier in the receiver were negligible—although a thin wire was used instead of a small sphere—we treated the minus of the recorded echo e_{pulse} as a scaled approximation of the two-way impulse response of the transducer near the focus. Therefore, the

Fig. 6. (a) The averaged echo signal reflected from a wire. (b) The spectrum of the echo signal. (c) The one-way impulse response derived from the echo signal.

normalized transducer response can be estimated using the following relation: $h_t(t) \propto \mathbf{F}^{-1} \left[(\mathbf{F}[-e_{\text{pulse}}(t)])^{1/2} \right]$, where $\mathbf{F}$ and $\mathbf{F}^{-1}$ denote forward and inverse Fourier transforms, respectively.

Figs. 6(a) and (b) show the echo signal e_{pulse} from the wire (which is the average of 2000 records) and its spectrum, respectively. The estimated center frequency and one-way -6 dB bandwidth were 26.4 and 20.7 MHz, respectively. The estimated transducer impulse response is shown in Fig. 6(c).

Twenty-six RF codes corresponding to the measured transducer response were designed using the search approach with the same parameters as used in Section IV-A for the genetic algorithm, nine of which correspond to

Fig. 7. Results for the measured transducer response shown in Fig. 6. (a) The efficiencies of codes as functions of their lengths. (b) The filter lengths that resulted in the maximal E_{cf} values equal to the code efficiencies. (c) The output SNRs corresponding to the filter lengths shown in (b).

$N = 32$ to 64 with a step size of 4 using a two-cycle square wave as the base sequence, with the others corresponding to $N = 32$ to 64 with a step size of 2 using a one-cycle square wave as the base sequence (Table III). Fig. 7(a) shows the efficiencies of codes as functions of their lengths, and Figs. 7(b) and (c) show the filter lengths that resulted in the maximal E_{cf} values (that equal the code efficiencies) and the corresponding output SNRs, respectively. These results are consistent with those given in Section IV-A. Each code designed using the search approach has a higher efficiency than its corresponding code designed using the modulation approach with the same base sequence, with the difference ranging between 0.5 and 5 dB. The higher

Fig. 8. Effects of amplitude quantization. (a) Δ SNRs (differences between SNR improvements with and without amplitude quantization) for the Gaussian-shaped transducer response. (b) Δ SNRs for the measured transducer response. (c) The peak sidelobe levels for the Gaussian-shaped transducer response. (d) The peak sidelobe levels for the measured transducer response.

TABLE III

HEXADECIMAL REPRESENTATIONS OF THE RF CODES DESIGNED USING THE SEARCH APPROACH FOR $b(n) = (-1)^n$ AND $N_B = 4$ (SECOND COLUMN), AND FOR $b(n) = (-1)^n$ AND $N_B = 2$ (THIRD COLUMN).¹

N	Search approach	
	$N_B = 4$	$N_B = 2$
32	252A5551	0C96B557
34		03AAB5A4C
36	2D4A85551	7A52AAC93
38		096D2A55DD
40	5555AB52DB	3F555AD6C9
42		0DD55EA52DB
44	55552AD4B09	22AAD4A436C
46		027B5AB5574C
48	692952A15555	2484D554AD78
50		02254AA2A7B49
52	696B56AB55551	32E8AA950B4B4
54		18F5A9555B693F
56	755556AB54A5AD	09252B52AABB67
58		092127AAAB56B76
60	155556AB54AD2D6	212D4ABD4514D9F
62		1B68FB5556B57A73
64	0B5A56A955AAAAA8	0745145AAD4B4A67

¹The transducer response measured with the setup shown in Fig. 5 is shown in Fig. 6, and the additive noise sampled by the ADC was assumed to be white.

code efficiency for the search approach relative to the modulation approach is mainly attributable to the reduction in filter length. With the two- and one-cycle base sequences, the ratios of the filter length to the code length range over [1.4, 2.3] and [1.5, 2.2] for the search approach, respectively, and over [2.9, 7.4] and [2.4, 4.8] for the modulation approach. Note that, in general, the code efficiencies are lower than those obtained in Section IV-A. This is due to the definition of SNR reference given at the beginning of this section. Because the transducer considered in the subsection has a wider bandwidth, a higher echo signal level will be obtained when a single-bit signal is transmitted. Therefore, setting the SNR corresponding to a single-bit firing signal to 1 equivalently assumes more noise. Also note that the codes designed using the modulation approach with the one-cycle base sequence adapt to the increased transducer bandwidth better than the other three groups of codes. Nonetheless, in terms of improving the SNR, those codes are worse than the others.

C. Quantization Effects

All the above results were obtained based on floating-point operations. In practical situations, filter coefficients may be quantized to fixed-point numbers. To evaluate the effects of amplitude quantization on pulse compression performance, for each code we quantized the real

and imaginary parts of the compression filter $h_o(n)$ to 8 bits, repeated the pulse compression procedure, and compared the resultant SNR, $\text{SNR}_{\text{dB},q}$, with the SNR corresponding to the ideal filter, $\text{SNR}_{\text{dB},i}$. Define ΔSNR as $\text{SNR}_{\text{dB},q} - \text{SNR}_{\text{dB},i}$. Figs. 8(a) and (b) show the ΔSNRs as functions of the code length for the Gaussian-shaped and measured transducer responses, respectively. All the ΔSNR values are small. Note that ΔSNR is equal to the difference between code efficiencies with and without amplitude quantization. Figs. 8(c) and (d) shows the peak sidelobe levels for the Gaussian-shaped and measured transducer responses, respectively. The results show that amplitude quantization only slightly degraded the pulse compression performance.

V. CONCLUSIONS

This paper proposes an approach to designing binary codes having a low sampling ratio and providing efficient SNR improvements. Unlike the conventional modulation approach in which a base sequence is used to modulate wideband sequences up to the transducer passband, which thereby excludes a major portion of the codes as possible RF codes, the proposed search approach uses a genetic algorithm to search all the codes that match the transducer passband; hence, the resultant codes can improve the SNR more efficiently. In the study, the bit rate was set to 50 MHz in order to keep the sampling ratios about 2, and two transducer responses were considered in order to demonstrate the adaptability of the proposed approach. Assuming that the transducer has an ideal Gaussian frequency response with a center frequency of 25 MHz and a -6 dB bandwidth of 15 MHz, the codes designed using the proposed approach outperformed those designed using the modulation approach by 1 to 6 dB in terms of code efficiency (i.e., in terms of the capacity for improving the SNR normalized by the total length of the code and the filter). When a real transducer with a center frequency of 26.4 MHz and a one-way -6 dB bandwidth of 20.7 MHz was considered, the codes designed using the proposed approach were superior by 0.5 to 5 dB. Our approach can be applied to designing binary codes with SNR improvements in high-frequency ultrasound systems, for which using arbitrary-waveform transmitters may be infeasible. A reasonable bit rate of 50 MHz will suffice if the ultrasonic center frequency is 25 MHz.

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