ANALYSIS OF ACOUSTICAL RESPONSES OF MICROBUBBLES FOR THE OPTIMIZATION OF PHASE- AND AMPLITUDE-CODED PULSE SEQUENCES

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Abstract – We have previously introduced an algorithm for the design of receive filters that are used with coded pulse sequences to enhance the contrast between two media [1], where one filter per pulse in the sequence is derived from training data. Following this approach, we tackled the question of what pulse sequence, considering amplitude and phase coding, is best suited for contrast agent imaging. We also solved the problem that filters of increasing length improve image contrast at the expense of bandwidth by means of non-linear frequency compounding.

INTRODUCTION

Background

To enhance the contrast between two media, a sequence of N pulses $s_{i0}(t)$ is transmitted along the same beam line. For simplicity, we assume all pulses to have the same envelope $g(t)$ and carrier frequency ω_0.

$$\begin{aligned} &s_{i0}(t) = a_i \cdot g_i(t) \cdot \cos(\omega_0 t + \varphi_i), && i = 1 \ldots N, \\ &a_i, \varphi_i \in \mathbb{R}, && g_i(t) \approx g(t) \end{aligned} \tag{1}$$

The corresponding echoes $e_i(t)$ are convolved with N filters $f_i(t)$ and then summed together to form a receive signal $r(t)$.

$$r(t) = \sum_{i=1}^{N} e_i(t) * f_i(t) \tag{2}$$

To differentiate between two media, representative echoes from both media are required to determine the filters according to [1].

Effectiveness of a pulse sequence

Two parameters determine the effectiveness of a sequence with a given number of pulses: the achievable contrast c and the effective bandwidth B, i. e. an indicator of image resolution.

We define the contrast as the energy ratio of the receive signals from the two media:

$$c = \frac{\int_t \left[{}^1r(t) \right] dt}{\int_t \left[{}^2r(t) \right] dt}, \quad {}^1r, {}^2r: \text{ medium 1, medium 2} \tag{3}$$

The effective bandwidth B is defined as the minimal bandwidth, which may be split in an unlimited number of sub-bands, that covers half of the total energy of a signal. To calculate B, we compute the discrete power spectrum of ${}^1r$ and sort the samples in descending order. B is then derived from the K sorted samples p_i, each representing the power within the bandwidth Δf as

$$\sum_{i=1}^{J} p_i \overset{!}{=} \frac{1}{2} \sum_{i=1}^{K} p_i, \qquad B = J \cdot \Delta f . \tag{4}$$

${}^2r$ represents the suppressed signal and is, therefore, not considered with respect to image resolution.

It is also important to note that a pulse compression filter may be required to make use of the resolution in B.

Media Separability

Contrast as defined in (3) is well suited for optimization problems, but it does not necessarily provide an accurate measure of media separability in ultrasound images. In the case of fully developed speckle, echo amplitudes in B-mode images are Rayleigh distributed, where the mean echo amplitude is an indicator of echogeneity. The SNR that is due to the speckles, i. e. the ratio of the mean to the standard deviation of the echo amplitudes, is known to be 1.91. For many reasons, e. g. physical properties of the scatterers, scatterer distribution, nonlinear effects and post-processing, echo amplitudes are not necessarily Rayleigh distributed so that the mean echo amplitudes do not explicitly quantify media separability.

We, therefore, determine the classification error ε. A threshold optimally divides echo amplitudes into two groups (two media). The ratio of misclassified echo amplitudes to all classified echo amplitudes will be referred to as the classification error ε.

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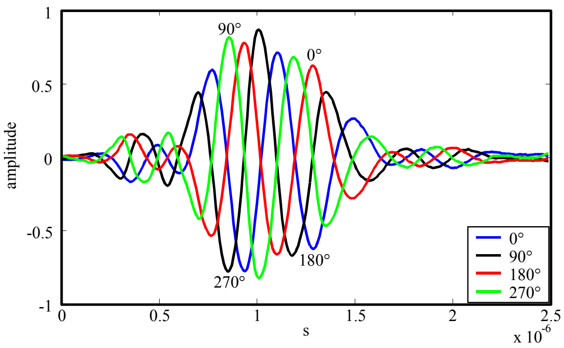

Fig. 1: 3 MHz pulses measured from a glass plate.

OPTIMAL PULSE SEQUENCES

Simple models for the scattering of microbubble are not accurate enough to predict the performance of pulse sequences. Complex models, however, that comply with broadband excitation over a wide amplitude range require measurements to correctly adjust all parameters and may still not be reliable.

We, therefore, decided not to use models but to measure acoustical responses of scatterers.

Experimental Setup

Scatterers where insonified in a water-filled chamber using two broadband transducers (Panametrics V319, 15 MHz) for transmitting and receiving, respectively. An arbitrary function generator (LeCroy LW 410A) was connected to an ENI A300 amplifier. RF data were collected with a LeCroy 9350AL oscilloscope after pre-amplification and 20 MHz lowpass filtering. The setup was computer controlled to allow the exact acquisition of multiple repetitions of specified sequences.

We investigated a symmetrical 4-pulse sequence (0°, 90°, 180°, 270°) as shown in Fig. 1. In addition to the phase coding, we introduced amplitude coding: full amplitude (H) and half amplitude (L), where the maximum pressure for full amplitude was about 0.7 MPa. To investigate time-variant effects, the total sequence consisted of 16 pulses at a prf of 10 kHz, where all pulses occur twice, denoted by 1 and 2:

270°H1 180°H1 90°H1 0°H1
270°L1 180°L1 90°L1 0°L1
270°H2 270°L2 180°H2 180°L2
90°H2 90°L2 0°H2 0°L2

The complete sequence is repeated four times with pauses of 18.5 ms in between to further investigate decorrelation.

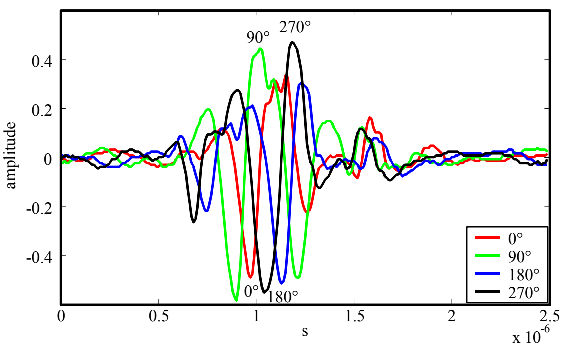

Fig. 2: Echoes from a free gas bubble.

Three types of scatterers and combinations thereof were investigated: linear scatterers, Levovist® microbubbles, and free gas bubbles, produced by breaking the polymer shell of an encapsulated microbubble (experimental agent)

Data Evaluation

All combinations of 2, 3 and 4 out the 16 pulses were analyzed with respect to energy ratio (contrast) c and effective bandwidth. Thus, pure decorrelation sequences (e. g. 270°F1, 270°F2) were also tested. Contrast and effective bandwidth were determined for the following pairs of media:

- Levovist® / linear scatterers
- Free gas bubbles / linear scatterers
- Levovist® / free gas bubbles

For all combinations of pulses and media, optimal receive filters were generated and applied, where 1-tap filters (optimal weighted superposition) and 16-tap filters were considered.

Results

Fig. 2 shows typical echoes from a free gas bubble. Repeated measurements confirm that the distortion of the echoes is due to non-linear effects and not to bubble destruction.

The following tables provide an excerpt of the vast amount of data. In brief it can be stated that

- contrast increases with sequence length (2, 3, 4),
- 90°, 270° pulses outperform 0°, 180° pulses,
- 2-pulse sequences require full amplitudes for acceptable contrast,
- longer sequences require full amplitudes or amplitude modulation (full/half, less contrast),
- longer filters emphasize higher harmonics and improve contrast by about 10 dB,
- energy ratios of about 31 dB can be achieved with 4-pulse sequences and 16-tap filters.

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Table 1: Levovist® / Linear scatterers, 1-tap filter

Pulses				c/dB	B/MHz
		90H1	270H1	22.9	3.31
		90H2	270H2	21.5	4.44
		0H1	180H1	20.6	6.4
	0H1	90H1	270H1	24.8	3.27
	90H1	270H1	0L1	24.8	3.27
	90H1	270H1	0H2	24.7	3.22
90H1	270H1	0H2	180H2	25.1	2.83
0H1	90H1	180H1	270H1	25.1	2.88
0H1	90H1	270H1	180H2	25.1	2.98

Table 2: Levovist® / Linear scatterers, 16-tap filter

Pulses				c/dB	B/MHz
		90H1	270H1	29.8	1.66
		90H1	180H1	29.2	2.2
		90H2	180H2	28.0	2.93
	90H1	180H1	270H1	31.3	1.66
	90H1	270H1	90H2	30.0	1.66
	90H1	270H1	0H2	30.0	1.66
90H1	180H1	270H1	90H2	31.5	1.66
0H1	90H1	180H1	270H1	31.4	1.71
90H1	180H1	270H1	180H2	31.4	1.71

Table 3: Free bubble / Linear scatterers, 1-tap filter

Pulses				c/dB	B/MHz
		90H2	270H2	21.1	2.34
		90L1	90H2	20.7	3.56
		90H1	270H1	20.5	1.71
	0L2	90H2	270H2	22.8	2.34
	0H2	90H2	270H2	22.7	2.29
	0L1	90H2	270H2	22.7	2.34
0H2	90H2	180H2	270H2	24.4	2.15
90H1	270H1	90H2	270H2	23.9	2.00
90H2	180H2	270H2	0L2	23.6	2.15

Table 4: Free bubble / Linear scatterers, 16-tap filter

Pulses				c/dB	B/MHz
		90H2	270H2	28.7	1.56
		90H2	180H2	28.4	1.61
		90H1	180H1	28.1	1.37
	90H2	180H2	270H2	30.5	1.37
	90H1	180H1	270H1	29.9	1.22
	90L1	90H2	180H2	29.5	1.76
90H1	270H1	90H2	270H2	31.4	1.27
90H1	270H1	90H2	180H2	31.3	1.32
90H1	180H1	90H2	180H2	31.1	1.42

NONLINEAR FREQUENCY COMPOUNDING

Frequency compounding improves the SNR of B-mode images by averaging images taken from different frequency bands of the receive spectrum, thus showing decorrelated speckle. In the case of nonlinear imaging, partly decorrelated images can even be generated from the same frequency range, because different spectral features (e. g. harmonics) share frequency bands but are separable due to their amplitude and phase response to multiple coded transmit pulses.

The filter optimization discussed in [1] yields $N \cdot J$ complete sets of filters for a sequence with N pulses per sequence and J-tap FIR filters. Each set of filters represent a global or local maximum with respect to the optimization of c. The best maxima may give images of comparable contrast c and effective bandwidth but with partly decorrelated speckle, so that averaging these images improves the SNR and, hence, improves media separability.

Data Acquisition

Data were acquired from a contrast agent phantom using a 3.5 MHz probe (see [1]). A 4-pulse sequence with $\varphi_i = [0°,120°,180°,240°]$ at $\omega_0 = 2.0\ \text{MHz}$ was used. Echoes from the contrast agent Definity® and tissue were taken from a depth range of 6.25 – 7.25 cm covering a lateral span of 1 cm.

Results

Fig. 3 – Fig. 6 show normalized histograms, segmentation images based on optimal thresholding, and gray scale images (55 dB dynamic range) for different processing techniques.

Fig. 3 reveals that contrast agent and tissue cannot be distinguished in B-mode. Optimal receive filtering with a 16-tap filter clearly improves media separability (classification error $\varepsilon = 19\%$, effective bandwidth $B = 0.71\ \text{MHz}$), Fig. 4. Averaging the best four images based on 16-tap filtering substantially improve image separability ($\varepsilon = 8.2\%$, $B = 0.64\ \text{MHz}$) by reducing speckle, i. e. by narrowing the histograms of the two media, Fig. 6. In comparison, a single 64-tap filter provides a somewhat better separability but substantially reduces the effective bandwidth ($\varepsilon = 6\%$, $B = 0.4\ \text{MHz}$), Fig. 5.

CONCLUSIONS

The absolute phase is an important parameter in the design of pulse sequences, especially for short and low MI (mechanical index) sequences. Mean image brightness is not useful to quantify image contrast. Nonlinear frequency compounding, for example, significantly improves media separability but leave the mean brightness unchanged.

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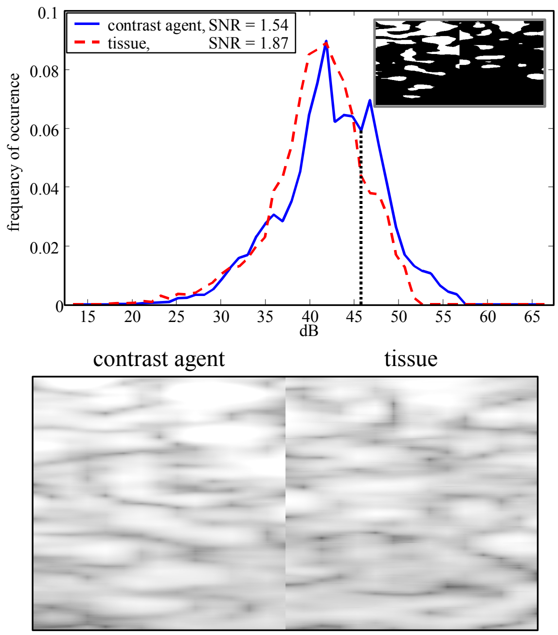

Fig. 3: B-mode processing.

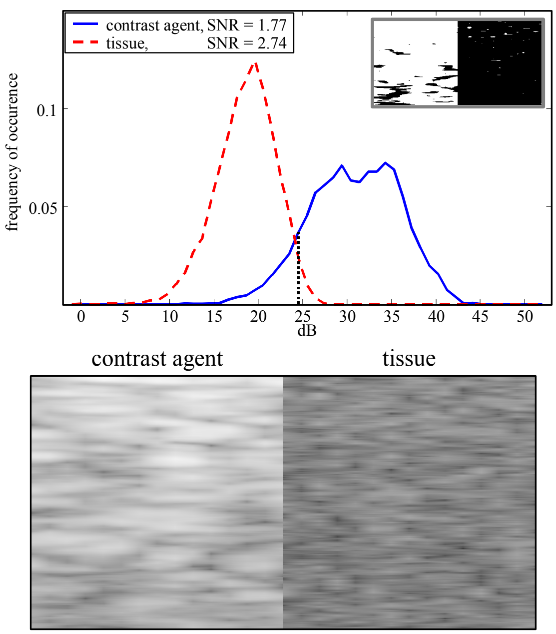

Fig. 6: Nonlinear frequency compounding, 16 taps.

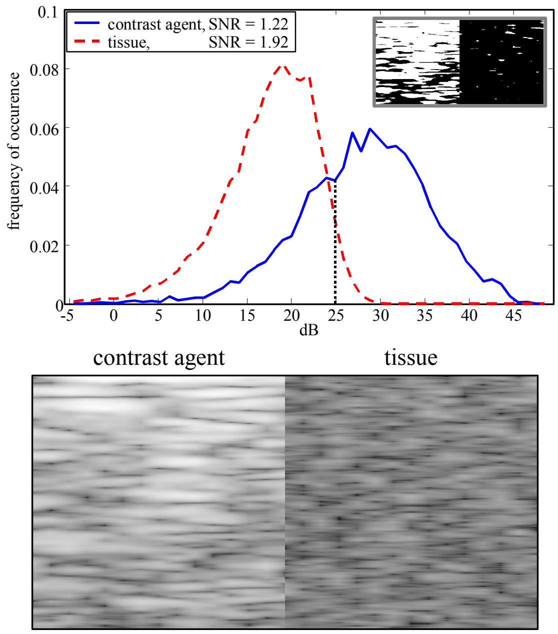

Fig. 4: 16-tap optimal filtering.

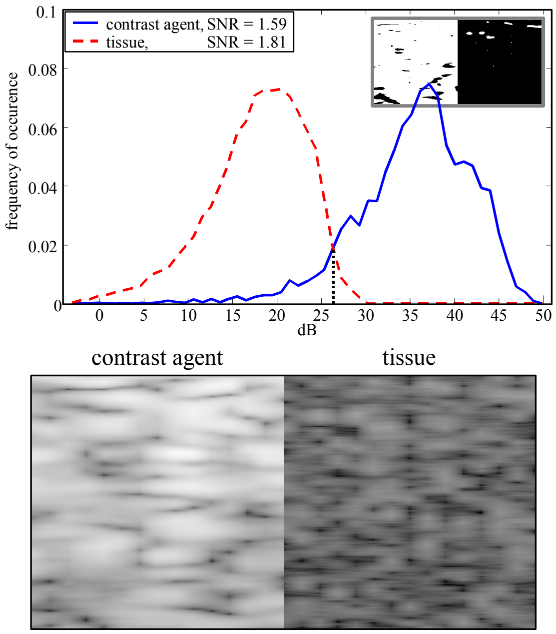

Fig. 5: 64-tap optimal filtering.

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