

A New Ultrasonic Pulse Echo Imaging Scheme: Dual Pulse Interrogation Based on Wavelet and Subband Filter Bank

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Abstract

In most ultrasonic pulse-echo imaging, medium reflectivity map is obtained from echoed signal. Its quality depends on the restoration process. Therefore many brilliant techniques are studied and applied to increase its axial resolution. In this study, we proposed another pulse-echo scheme based on the wavelet theory and subband filter banks. Two channel (decomposition) wavelet filters realized themselves at a transducer as a form of short interrogating pulse into scattering medium in place of usual gated sinusoidal wave. Then scattered two-channel echoes are filtered in receiving system by corresponding (reconstruction) wavelet filters. So the medium response is restored by Perfect Reconstruction property of wavelet. Validation of the idea is straightforward according to the wavelet theory. Therefore, its synthetic validity was shown by the simulation result with biologic medium response model, instead of detailed induction of the proposed techniques.

Keywords— Ultrasonic pulse echo imaging, Wavelet, Filter bank, Perfect reconstruction.

I. INTRODUCTION

Modern ultrasonic pulse echo imaging systems, in spite of their merit of being less harmful and easy to use, suffer from its relatively lower image resolution than other imaging modalities, such as Computerized tomography (CT) and Magnetic resonance imaging (MRI). It is mainly because of overlapping among adjacent reflections due to finite duration of the used interrogating pulse. There have been two different approaches to increase the axial resolution of ultrasonogram by compensating for the effect of interrogating pulse itself [Zheng] or by manipulating the

pulse waveform [2].

If we could transmit an ideal impulse, there would be no need for the post signal processing to compensate the interrogating pulse. A pulse-shaping filter technique was proposed to control the transmitted ultrasound pulse shape and frequency [2]. In this study, the ultrasonic transducer driven with a proper excitation signal could transmit a desired pulse shape against its impulse response. The required excitation signal was determined from the desired pulse-shape and the transducer's impulse response.

The critical disadvantages in transmission of impulse-like waveform include overloads to the transducer and driving electronics and difficulties in applying the imaging technique using contrast agent such as air-bubbles because the air-bubbles rapidly explode under the impulsive insonification.

As an alternative approach, a frequency-rich waveform is being searched such as a chirp signal and the Golay code[3]. Even though a time-varying chirp signal is a good example for gathering wide band frequency, since it basically consists of shortened Fourier (sinusoidal) basis, it must result in errors when reconstructing the original reflectivity map using the frequency-modulated echo [4]. The Golay code is more widely used and it is based on the principles of "pseudo-chirp" excitation and equalization filtering. But due to its digital nature, it still leaves the problems of overload to the transducer and driving electronics and erroneous results.

In terms of the above problems, it is more desirable to use an interrogating pulse which is one of the wavelet basis. It is because of not only the fact that the transmitted wave is a kind of short pulse, but also it is an analog signal.

There are studies on using the wavelet transform as image reconstruction algorithm [4,5]. In these studies, a wavelet pulse was transmitted into the medium and the reflected echo was thought to be a combination of translated and dilated versions of the transmitted wavelet scaled by individual reflectivities of medium. Then the wavelet transform of this echoed signal provided expansion coefficients corresponding to the reflectivities. These coefficients reconstructed the medium's reflectivity map

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with an increased resolution.

However, they considered only the simple reflection from the scattering medium. A convolutional interaction between the transmitted pulse and the medium was thought of as a source of error. Although this problem was solved with a modified algorithm to exclude this error, they still used the same assumption about the medium's scattering model [5].

We proposed a new reconstruction method by applying a wavelet and filter bank theory on the design of interrogating short pulses and the interaction model between the pulses and the convolutional scattering medium. The main idea is to replace the commonly used Gaussian-enveloped sinusoidal pulse with two consecutive different short pulses. These pulses match to the wavelet filters satisfying the 2-channel perfect reconstruction (PR) condition [6,7]. The echoes are then considered as their respective subband filtered outputs of impulse response model of convolutional scattering medium. These subband components can reconstruct the original impulse response when filtered by corresponding dual subband wavelet filters.

II. MATERIALS AND METHODS

A. Wavelet basis

Wavelet is a decaying oscillatory signal basis and its main use is for time-frequency representation of signal [6].

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}} \psi\left(\frac{t-u}{s}\right)$$

u : translation parameter

s : scale (frequency) parameter

(1)

Every signal can be represented by weighted sum of wavelet bases like Eq. (2). $\varphi_{u,s}(t)$ is necessary to represent the residual error component in finite level decomposition. This time, the bases consist of many wavelets i.e., $\psi_{u,s}(t)$ and $\varphi_{u,s}(t)$, covering different frequency and time region.

$$\begin{aligned} f(t) &= \sum_{u,s} \langle f, \psi_{u,s} \rangle \psi_{u,s}(t) \\ &= \sum_{u,s1 \leq s2} \langle f, \psi_{u,s1} \rangle \psi_{u,s1}(t) + \sum_{u,s2} \langle f, \varphi_{u,s2} \rangle \varphi_{u,s2}(t) \end{aligned}$$

$s1, s2$: decomposition level

$\varphi(t)$: scale function

(2)

Where the inner product is defined, so called, wavelet transform,

$$\langle f, \psi_{u,s} \rangle = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{s}} \psi^*\left(\frac{t-u}{s}\right) dt \quad (3)$$

They can be obtained from a mother wavelet function.

Typical mother wavelet is shown in Fig 1.

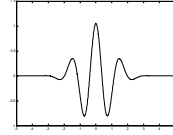


Fig. 1. A typical shape of wavelet: Gaussian example.

B. Multiresolution analysis and filter bank

In practical situation of discrete signal, the wavelet transform in (3), for time-frequency representation is implemented as multi-resolution analysis using sub-band wavelet filters instead of wavelet itself [7]. They decompose the original signal, $x[n]$, into separate wavelet coefficients. The descending tree-like structure in Fig. 2 shows a successive decomposition scheme in dyadic case [7]. The synthesis (reconstruction) of the original signal follows the rules in (2) and there are dual wavelet filters for that use. It is implemented by these dual filters gathered in ascending tree-like structure symmetrical to the decomposing one.

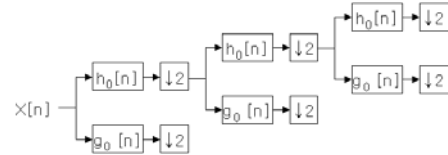


Fig. 2. Multiresolution analysis by wavelet filters.

C. Perfect reconstruction filter bank

These complete decomposition and synthesis of original signal using wavelet filter set can be viewed as a perfect reconstruction (PR) filter bank. Fig 3 shows this filter bank structure. It separate the original signal into two separate convolution results. Afterwards, it gathered them into the original signal by filtering the two results with corresponding dual filters. The two channels are complementary to each other. The reconstruction results has only a time delay, at worst.

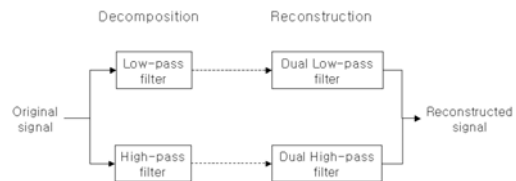


Fig. 3. Perfect reconstruction wavelet filter bank with 2-channel.

D. Modification of ultrasonic short pulse wave

This PR scheme is adopted by pulse echo imaging as in Fig 4. Although the decomposition level can be expanded, however, this would be enough to explain the main idea of

the proposed method. The wavelet filters replace the existing exponentially gated short sinusoidal wave. And the number of transducer is increased to two. The pulses enter the scattering medium (e.g. biologic tissue) separately. Normally the returned echo is expressed by convolution of interrogating pulse and tissue impulse response [1]. Therefore, if these wavelets realize decomposition filters, the echoes from these 2 wavelet filter pulses can be understood as convolution results of the wavelet decomposition filters and the tissue response. This means that two separate echoes returned from respective pulses are wavelet coefficients bearing dissolved and complementary information necessary to restore the original tissue response. At receiver system, these echoed wavelet coefficients are filtered again by 2-channel dual reconstruction filters. Then, theoretically, both filtering outputs can reconstruct the original tissue response without error.

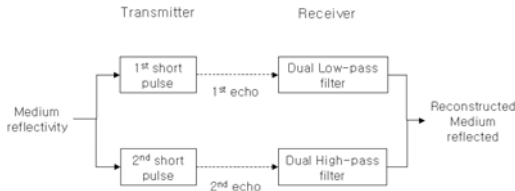


Fig. 4. PR wavelet filters replace the short pulse wave in pulse echo system.

E. Synthetic validation

Verification of this is straightforward according to PR property of wavelet filter pairs [6,7]. A simulation example follows to show its synthetic validity. Therefore, only its synthetic validity was shown by the simulation result with biologic scattering medium model and using specific (*Daubechies'* 10th order) wavelet filter set [6], instead of detailed induction of the proposed techniques. Fig. 5 shows four wavelet filters involved in 2-channel PR. Their frequency band characteristics are shown in Fig. 6 by Fast Fourier Transform result. The medium reflectivity map is generated by Gaussian random number.

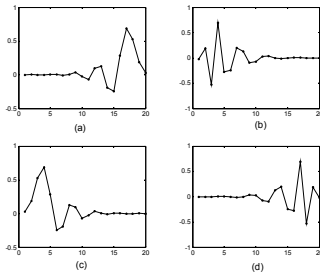


Fig. 5. Time domain appearance of wavelet filters. a) decomposition low-pass filter. b) decomposition high-pass filter. c) reconstruction low-pass filter. d) reconstruction high-pass filter.

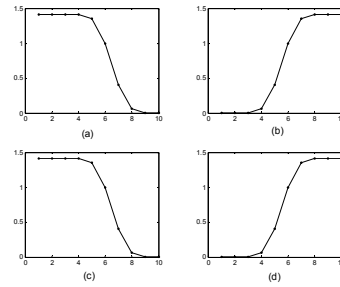


Fig. 6. Frequency domain appearances (FFT results) of the wavelet filters. a) decomposition low-pass filter, b) decomposition high-pass filter, c) reconstruction low-pass filter, d) reconstruction high-pass filter.

Furthermore, the medium model includes convolutional scattering effect, that is, frequency-dependent attenuation and backscattering effects [8]. Therefore, it may as well be called medium response in Fig. 7.

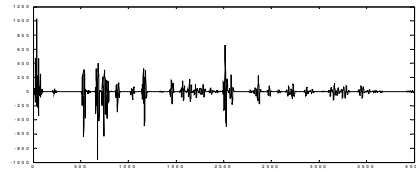


Fig. 7. Original tissue response model in time domain including random reflectivities, and frequency-dependent attenuation and backscattering.

III. RESULTS

The medium response is convolved with two interrogating short pulses (wavelet filters) to generate respective echoes in Fig. 8. The high-pass echo in Fig. 8 – (b) shows more serious attenuation than low-pass echo in (a), because it experienced more attenuation than (a). However, we didn't compensate the attenuation separately but left it to the reconstruction stage as it is.

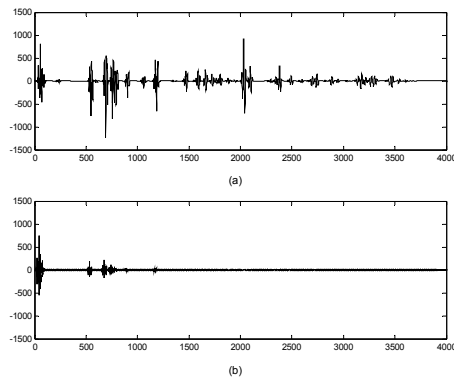


Fig. 8. Two-channel echoes imply the the filtered coefficients for the two sub-band wavelet filters in Fig 3. a) returned from 1st (low-pass) short pulse. b) returned from

2nd (high-pass) short pulse.

After the reconstruction appearing in Fig. 9-(b), the performance was evaluated with correlation coefficient between the original medium response and the reconstructed one with delay adjustment. It yields accurate 1, as is clear from PR property. Fig. 9 compares them.

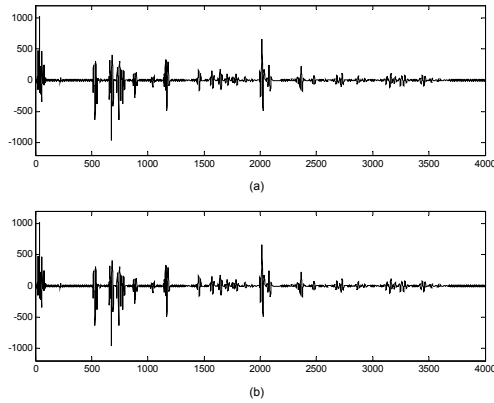


Fig 9. Reconstruction result. a) original response, b) reconstructed response by summing up the dual filters' output.

IV. CONCLUSIONS AND DISCUSSIONS

The proposed reconstruction technique using modified-short-pulse-wave based on PR wavelet filters is proved straightforwardly by Wavelet theory [6], and its synthetic validation is illustrated with *Daubechies'* wavelet filters. Any wavelet filters can be recruited as the interrogation pulses if they satisfy the PR condition and additional requirement of compact (finite) support considering practical issues. This scheme is theoretically clear and it is interesting to note that the short-pulse nature is shared in wavelet theory and pulse-echo imaging system. This will encourage their partnership in ultrasonic systems.

To accomplish the technique in real situation, the transducer can provide wider band characteristic than that of normal transducer. Fortunately, the advances in recent transducer technique will help us to use slightly wider band transducer. In Fig. 5, their time domain characteristics, even that of low-pass filters, resemble the nature of ultrasonic short pulse wave, surprisingly. This encourages the wavelet transmission at ultrasonic transducer.

In case that it is difficult for the 2 channel transducers to cover respective half bands, we can use multi-channel wavelet filters by simply sub-decomposing them repeatedly (then it really becomes filter bank). As sub-decomposition proceeds, each frequency coverage band will become narrower. In practice, the near-zero frequency components (DC values) are hard to transmit or to receive through the transducer. They are usually dismissed because they just contribute to the heat loss. The sub-band filters are also

useful to build a band-limited reconstruction system by excluding the near-DC sub-bands.

Moreover, at collected, those wavelet filters with sub-band spectrums like in Fig. 6 can recover the original frequency characteristics without any distortion while each of them still maintains a short-bursting wave characteristic. It is because the wavelet is short wave basis from by birth, and therefore it will be a natural partner with the ultrasonic pulse echo technique utilizing short pulse interrogation.

In addition to its reconstruction ability, the use of wavelet basis is would provide a new result-presenting frame, for example, for pulse echo image and helps novel post processing techniques to be developed beyond the current imaging paradigm.

Furthermore, when considering the propagation in biologic tissues, if any characteristics of wavelet filters are found to be improper either to their propagation or to the biologic tissue, we can still try to find another filter set to meet the conditions.

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