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의료용 초음파 영상시스템을 위한 Wavelet 과 Subband Filter Bank 에 기반한 새로운 탐침 파형의 설계: A Simulation Study

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A New Design of the Interrogating Waves for Medical Ultrasonic Imaging Based on Wavelets and Subband Filter Banks: A Simulation Study

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요 약 : 의료용 초음파 영상 장비는 안전하면서도 사용이 편리할 뿐 아니라, 인체 내부의 구조적 영상을 포함하여 혈류나 내부 장기의 움직임에 이르기까지 진단을 위한 다양한 정보를 제공한다. 뿐만 아니라 조직 특성화 영상에서는 반사된 초음파 신호로부터 생체 조직의 물리적인 특성을 파악하여 진단에 활용하기도 한다. 하지만 영상의 획득을 위해 사용하는 탐침용 초음파 펄스 신호는 인체내부를 거쳐 그 흔적이 반사신호에 남게 되고, 이는 영상의 화질 저하로 이어져 미세한 조직이나 인접한 부분의 세밀한 관찰이 어려운 단점이 있다. 이를 해결하기 위한 다양한 연구가 시도 되었으나, 한정된 반사 신호로부터 탐침 펄스의 영향을 제거하고 매질의 특성을 복원하는 데에는 어려움이 있었다. 본 연구에서는 wavelet 과 subband filter bank 에 기반한 새로운 탐침용 초음파 펄스 및 그에 따른 영상획득 방법을 제안하였다. Perfect reconstruction (PR) 조건을 만족하는 일련의 wavelet filter 세트를 초음파 펄스로 구현하여 탐침에 사용하고, 반사되어온 신호를 적절히 재조합 하면 탐침 펄스의 영향이 배제되어, 매질의 세밀한 특성을 복원한 영상을 얻게 된다. 이는 조직 특성화 영상등을 위해 중요한 정보가 된다. 검증을 위해 2 종류 (A-mode 와 B-mode) 의 초음파 영상 시뮬레이션에서, 제안된 방법으로 영상을 획득하였다. 그 결과, 탐침 대상의 주파수 특성을 복원할 수 있었으며, 기존의 방법에 비해 향상된 화질의 초음파 영상을 얻을 수 있었다.

Abstract : Medical ultrasonic imaging is a useful imaging facility known to be most safe and easy. It enables physicians to observe the inside structures of the bodies, blood flow, and motions of internal organs. Some physical properties of biologic tissues can also be estimated from backscattered sounds. However, the ultrasonic pulses interrogating the living organisms leave their footprints in the returning signals during imaging. Some significant details are buried in the footprints and their overlaps from adjacent particles. These distortions also decrease the quality of the images. Many research efforts have been made to enhance the image quality and to recover the acoustic information in various ways. In this study, a new interrogation method based on the wavelet and subband filter bank is proposed. It adopts the subband wavelet filters satisfying the perfect-reconstruction (PR) conditions as the interrogating pulses to restore the details useful in tissue characterization and to enhance the image quality. The proposed method was applied to two types of simulations of ultrasonic imaging. The results showed its ability to restore the detailsin the simulated interrogation of biologic tissues, and verified the improved image quality in the simulated imaging of general ultrasonic phantom compared with the conventional method.

Key words : Medical ultrasonic imaging, Wavelets, Subband filter bank, Perfect reconstruction (PR).

INTRODUCTION

Medical ultrasonic imagingtechnique is still attractive as one of the useful diagnostic tools. It is less harmful and easy to use in detecting any structural and functional abnormality in the living organisms. It enables us to view the inside of the living organisms, to investigate some physical properties of biologic tissues [1], and to observe the flow dynamics in blood vessels. Some rhythmic internal motions such as heartbeats and carotid pulses can be traced. Therefore, it is truly multimodal compared to other imaging modalities like magnetic resonance imaging (MRI),computer tomography (CT) and positron emission tomography (PET). The transceivers and signal processing mechanisms for the ultrasonic imaging are cheaply achievable than the other

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radio active or nuclear imaging facilities considering the type of interrogating source, its energy level, and the frequencies of the signals involved. It can show a comprehensive picture of the internal structures of the subjects, visualizes the properties of the tissues, or trace the rhythmic motions by interpreting the backscattered ultrasonic waves in various ways. The full usage of diagnostic ultrasounds makes it still attractive.

However, the ultrasonic pulses interrogating the living organisms leave their footprints in the returning signals during imaging. They are sinusoidal with frequencies up to several MHz known to be almost harmless to the biologic tissues. The wavelengths take at least some millimetres when propagating in biologic medium. The size of the footprints and their blurring effects become not ignorable in the medical use considering the scales of the scattering particles in biologic medium. Thus, some details of the acoustic traces and the diffusive scattering components are buried in the footprints and their overlaps between adjacent particles. Unfortunately, there is significant information in small diffusive scattering components in biologic tissues [1]. The distortions by the footprints also make it difficult to discern the close acoustic boundaries. Consequently, the quality of the images are decreased.

Many research efforts have been made to solve above problems. Some contrast-enhancing agents are used to obtain better image quality by increasing the signal-to-noise ratio (SNR) of the sound echoes despite the complicated imaging protocols including injection of the contrast agents. Zheng [2] proposed to restore the original information by applying blind deconvolution. This method showed some good results based on properties of random signals [2]. By the way, from the signal processing point of views, the restoration of the undistorted originals from frequency-dependent scattering by removing the footprints belongs to an inverse problem [1]. Generally speaking, some wide-band signals are more proper for the interrogating pulses because they don't damage anyacoustic information of the scattering medium in frequency domain when backscattering occurs. Fomitchev [3] proposed to use pulse-shaping filter modifying the pulse as close as possible to the dirac delta function because it is an ideal form of the wideband signal. However, such impulse may cause some overloads to the acoustic transceivers and driving electronics in the imaging system. Frequency-rich waveforms, such as chirping signal and the Golay code, have been considered [4]. The chirping with gradually increasing frequency is a good alternative to the ideal impulse for realizing the wideband signal. The Golay code based on the principles of "pseudochirp" excitation and equalization filtering is more widely used in real implementation. Nevertheless, since the chirpings are composed of finite sinusoids at various frequencies there are still errors when restoring the original frequency components. The digital codes taking the form of square wave also cause some errors and overloads to the transceivers and driving electronics.

In this study, a new interrogation method based on wavelet and subband filter bank was proposed [5-7]. It is promoted by the perfect-reconstruction (PR) property of the wavelets and filter banks, which has been normally used in digital signal processing [5-7]. It adopts subband wavelet filters as the interrogating pulses and restores the acoustic traces by collecting the reflected echoes through subband filter banks. The PR condition is key feature to restore the original acoustic characteristics of the biologic scattering mediums from the echo signals [5-7]. The proposed method is applied to the two types of ultrasonic simulations [1] to verify the restoration of the detail information useful in tissue characterization and improved image quality. The results are compared with the conventional envelope imaging

BACKGROUND THEORY

A. Wavelet transform and subband filter banks

A wavelet is a decaying oscillatory signal like in Fig. 1. It provides set of wavelet bases simply by modifying its scale and position in time domain as in Eq. (1). They are commonly used in time-frequency analysis of signals [7]. When we decompose signals up to some finite levels, the set of wavelet bases normally represent the fast oscillating components of the signals. The residual components are handled by adopting the proper complementary bases. Generally, the complementary bases are also categorized as wavelets because they also have the short decaying properties just as wavelets. Equation (2) shows a decomposition of a signal in finite-levels using wavelets. Every signal can be represented by the weighted sum of wavelets. The inner products multiplying the individual wavelets are the wavelet transforms defined by Eq. (3).

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

$\Psi_{u,s}(t)$: wavelet function translated by
μ: and scaled by s
s: scale (frequency) parameter.

$$\begin{aligned} f(t) &= \sum_{u,s} < f, \psi_{u,s} > \psi_{u,s}(t) \\ &= \sum_{u,s1\le s2} < f, \psi_{u,s1} > \psi_{u,s1}(t) + \sum_{u,s2} < f, \varphi_{u,s2} > \varphi_{u,s2}(t) \end{aligned} \tag{2}$$

$f(t)$: function to be decomposed by wavelets.
$s1$, $s2$: decomposition level.
$\Psi_{u,s}(t)$: scale function.

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

$\psi^{*}u,s(t)$: complex conjugate of $\psi u,s(t)$

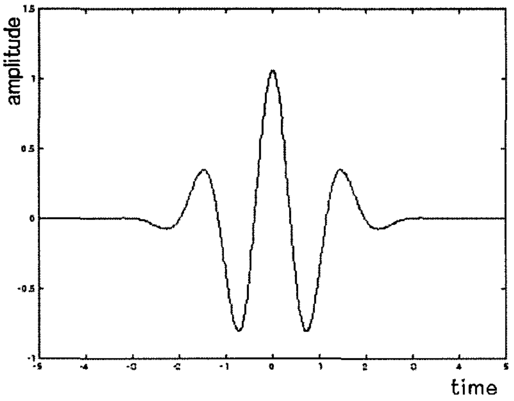


Fig. 1. A typical example the Gaussian wavelet.

For discrete-time signal, the wavelet transform in Eq. (3) is usually simplified by using dyadic multi-resolution analysis with subband filters shown in Fig. 2-(a). The filters usually consist of low-pass filter h0[n] and high-pass filters g0[n] containing the properties of their corresponding wavelets, respectively. In fact, they are based on the two-scaledifference equations providing some useful properties of wavelets and their relationships during down sampling [6]. This multi-resolution analysis substitutes the wavelet transform with the successive filtering and down sampling of the signals with subband filters. This is called discrete wavelet transform (DWT) [6]. Every filtered and down-sampled result at each step implies a series of the wavelet transform of the signal x[n] at that down-sampled scales. The set of filters involved in the decomposition compose the subband filter banks. Every repetitivefiltering-and-down-sampling along each branch is substituted with equivalent operations by using noble identities [6].

B. Perfect reconstruction (PR) of signal

As shown in Eq. (2), the signal x[n] can be recomposed from the DWT results when we know the filters used in the decomposition. Considering that the DWT results are also discrete time series, it is convenient to implement the recomposing process with another filter bank structures shown in Fig. 2-(b). When the filters h1[n], g1[n], h0[n], and g0[n] satisfy the requirements, called perfect reconstruction (PR) conditions [5-7], the finally composed results xr[n] in Fig. 2-(b) equals to the original x[n] except some time delays. This process is discreteinverse wavelet transform and the wavelets equivalent to the subband filters are called orthogonal or biorthogonal wavelets [6]. From information point of view, the two incoming channels in Fig. 2-(b) are complementary to each other. The depth of the subband trees can be expanded symmetrically in both filter bank structures. Then the number of subband filters will be increased in both filter banks and the individual bandwidth will be decreased.

C. Application of the PR subband filters to ultrasonic interrogating pulses

Biologic tissues contain large reflectors and many diffusive scattering structures in it. It is well known that when an ultrasonic wave propagates in such scattering medium, the backscattered echo can be estimated by convolving the ultrasonic wave and spatial autocorrelation of the random diffusive medium [1]. This promotes the application of the subband filters to the source of ultrasonic interrogation. If the x[n] in Fig. 2-(a) represents a biologic tissues in the form of the autocorrelation and h0[n] indicates an ultrasonic .interrogation pulse, then their filtered result means a backscattered signal. Likewise, if g0[n] indicates another ultrasonic pulse, the filtered result corresponds to another backscattered signal. The subband pulses and separate echoes are an acoustic version of the wavelet transform.

If the receiving system adoptthe latter filter bank structure in Fig. 2-(b) as its processing units and two echoes are filtered and combined through the h1[n] and g1[n], respectively, then the recombination of the echoes is a realization of the DIWT. It is clear that the final xr[n] restores the original x[n] owing to the PR properties of the filter banks. Fig 3 shows the significant analogy between the ultrasonicimaging system and the wavelet transform implemented by using the subband filters. The down samplings are omitted for convenience. The 1st and 2nd pulses are digital sequences realizing the h0[n] and g0[n] stored in digital signal processor (DSP) when implemented. Their echoes are filtered by the h1[n] and g1[n] in the DSP system.

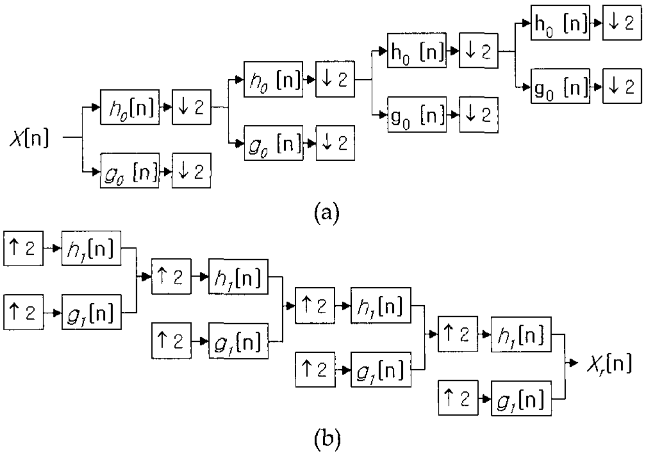


Fig. 2. Filter banks implementation of discrete wavelet transform and inverse wavelet transform. a) analysis bank, b) synthesis bank

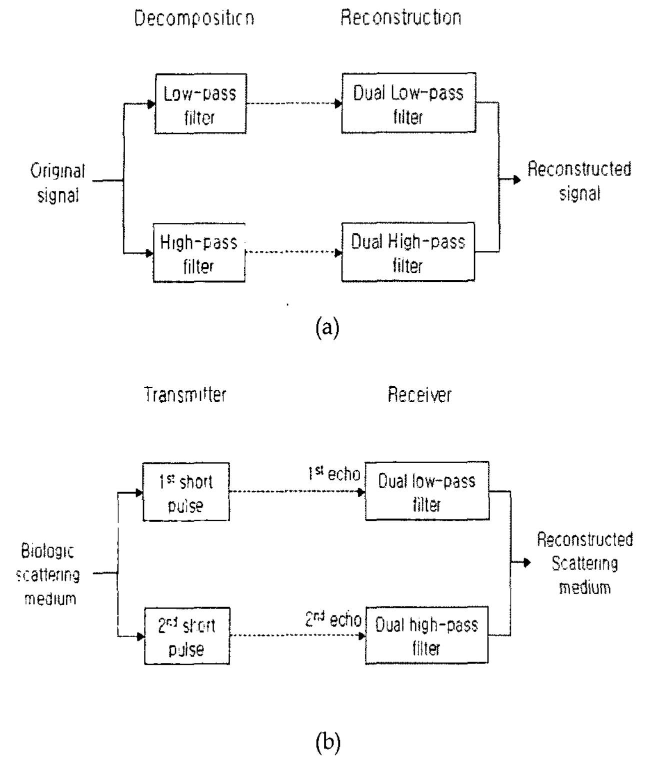


Fig. 3. The analogy between the filter bank and ultrasonic imaging system. a) PR two subbands filter bank in which the down sampling stages are omitted, b) ultrasonic pulse echo imaging adopting the subband filters as its interrogating pulses.

SIMULATION RESULTS

The proposed method was applied to the typical illustrative simulations of ultrasonic imaging using two types of models of the biological scattering medium. Firstly, the restoration of the detail information about the scattering medium was simulated on a one-dimensional scattering model of the biologic tissues. The overall procedures of the proposed method were shown during obtaining results. Secondly, the method was applied to a two-dimensional simulation of scan-echo imaging of general ultrasonic phantom to verify the improvement in quality of the image. One of a famous wavelet filter set (Daubechies' 10th-order) is selected as the ultrasonic interrogating waves [7]. All of the simulations were implemented by using MATLAB (Mathworks, USA). All of the signals in the simulations assumed the sampling rate of 80 MHz. The scattering model and the test image were scaled in consistent with the wavelengths of the pulses at that sampling rate.The pulses were designed to be centered at five MHz considering the bandwidth of the real transceivers.

A. Restoration of one-dimensional characteristic scattering medium

Figure 4 shows four wavelet subband filters (Daubechies' 10th-order) satisfying the two-channel PR conditions. Their frequency characteristics are also displayed by Fast Fourier Transforms (FFT) plot in Fig. 5. An acoustic scattering model of biologic tissues was generated in Fig. 6 by using random Gaussian distributionssince it has random scattering particles at random positions with random scattering strength. The characteristic scattering medium means that it includes the frequency-dependent attenuation and scattering strength of the ultrasonic waves within the medium [1]. The ultrasonic echo was simulated by letting the wavelet filters travel to and from the scattering model [1]. The mid-band frequencies of the wavelets were five MHz. The wavelengths wereabout 0.3 mm when the sound velocity is about 1540 m/s in the biological tissues. Two backscattered echoes were filtered and recombined by using the two corresponding subband filters, respectively.

Fig. 7 shows two separate echoes backscattered from the simulated biologic tissues. They were recombined through the synthesis filter banks. The original and the recombined results are compared in Fig. 8. It is verified that they are identical except slight time delays by taking the correlation coefficient between them. The details in scattering medium were clearly restored in Fig. 8. The one-dimensional simulation results without complicated mathematical evaluations and proofs verified the feasibility of the proposed method to the more accurate investigation of biologic tissues.

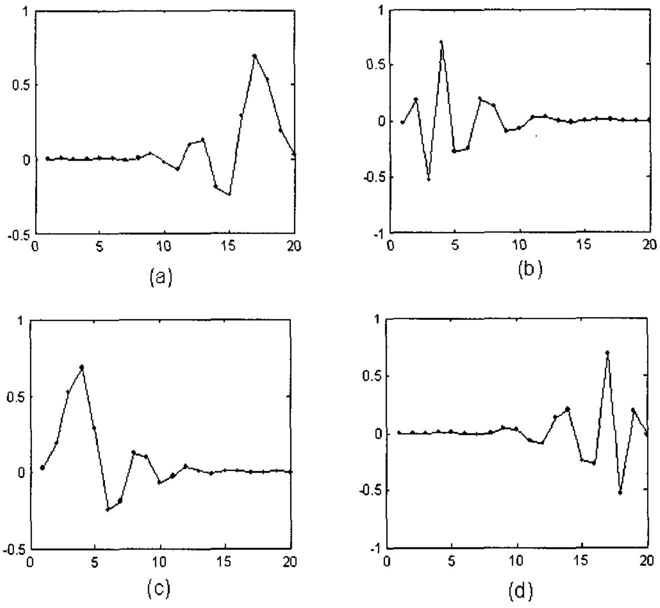


Fig. 4. Time domain appearance of Daubechies' 10th-order wavelet filter set. a) decompositionlow-pass filter, b) decomposition high-pass filter, c) reconstruction low-pass filter, d) reconstruction high-pass filter.

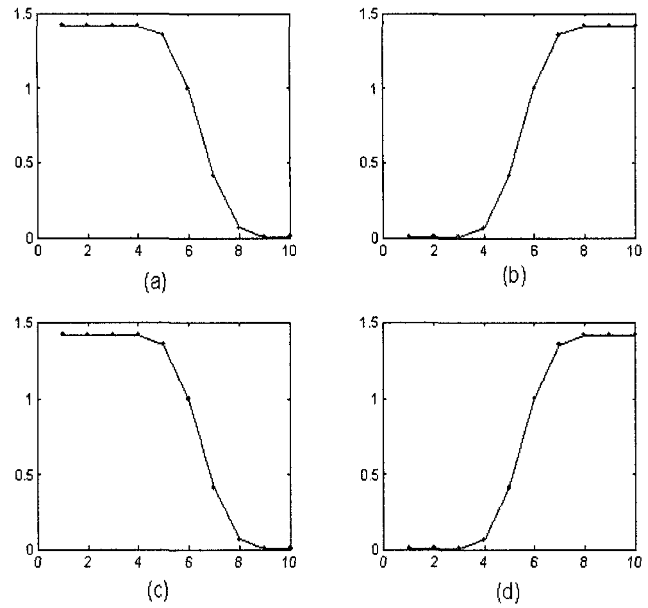


Fig. 5. Frequency domain appearances of the wavelet filters by using Fast Fourier Transform (FFT). a) decomposition low-pass filter, b) decomposition high-pass filter, c) reconstruction low-pass filter, d) reconstruction high-pass filter.

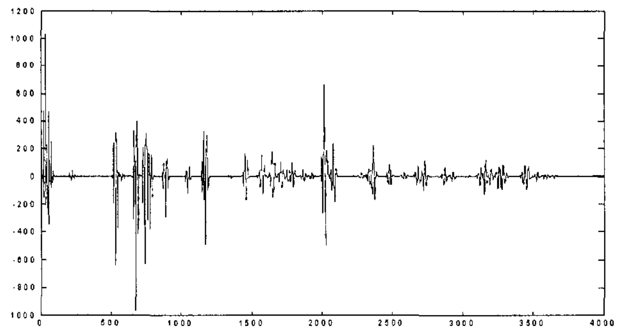
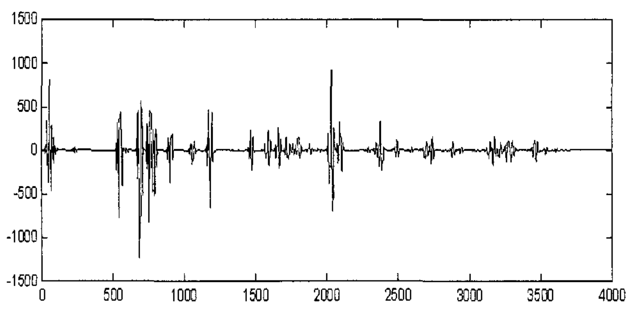
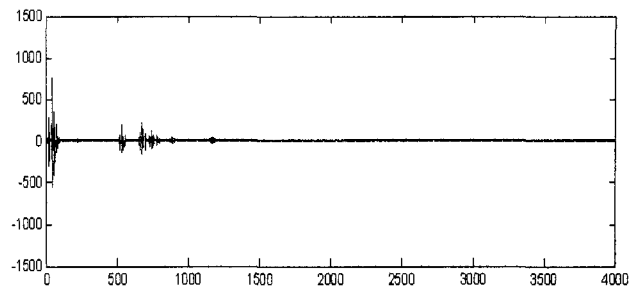


Fig. 6. A simulation model of biologic tissues including random diffusive scatterings and attenuations.



(a)



(b)

Fig. 7. Two separated echoes from the simulation model of the biologic tissues shown in Fig. 6. a) signal returned from the 1st(low-pass) subband pulse, b) signal returned from the 2nd (high-pass) subband pulse.

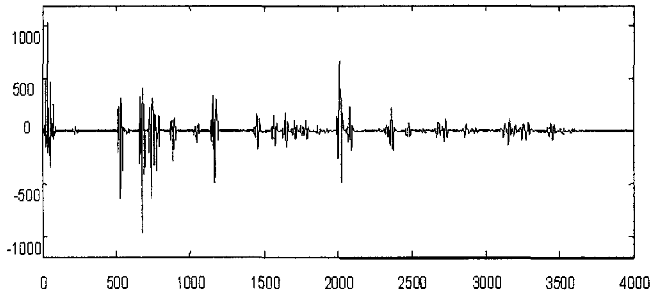


Fig. 8. The reconstructed result of the simulation model of biologic tissues in Fig. 6 by using the synthesis filter bank.

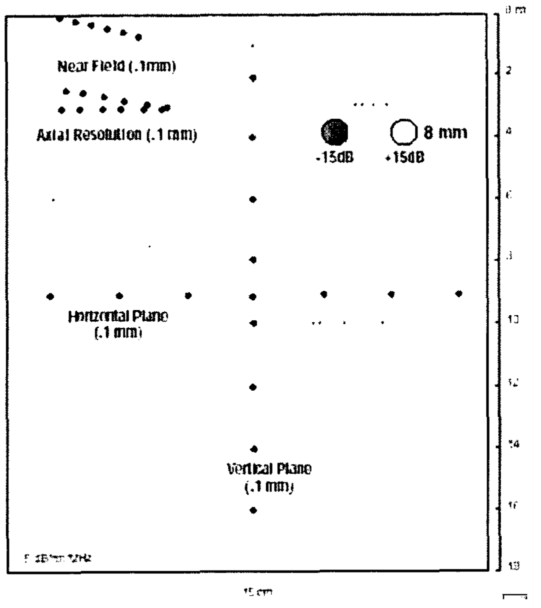
B. Improved image quality on two-dimensional test phantom

The test image for axial resolution was generated by imitating a general-purpose ultrasonic phantom (CIRS, USA) in Fig. 9-(a) complying with the AmericanInstitute of Ultrasound in Medicine (AIUM). The phantom has fibre structures wedged in parallel with gradually decreasing gaps between themselves to investigate the axial resolution of ultrasonic equipments. The test image in Fig. 9-(b) realized the fibre structures on two-dimensional image. The diameter of each fibre is 0.1 millimetre. The image was interrogated by using the proposed wavelet method. The wavelets are identicalto those used in one-dimensional restoration. The pulse-echo was repeated for 270 vertical lines of the image for scan-echo imaging as shown in Fig. 9-(b). The conventional imaging method was applied for the same test image prior to the proposed method, for comparison. The conventional method utilized a sinusoidal pulse (pulse-receiver wave) and extracted the envelope of each scan-echo signal. The characteristics of all the pulses used in the conventional and the proposed method are shown in Fig. 10. For both cases, the frequencies were designed to have realistic values. The mid-band and centre frequencies of them were five MHz. Other frequency dependent attenuation and two-dimensional effects like lateral diffraction were not included in the simulation for simplicity.

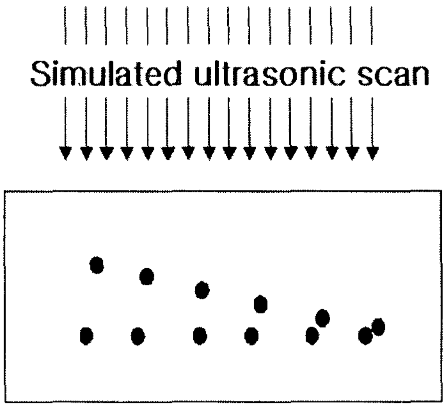
Figure 11 shows a target image for the application of the proposed method and one of its vertical profiles crossing two adjacent fibres. In the general tissue-mimicking phantom, there are many randomly scattering media not shown in Fig. 9-(b). Their effects are included in the more realistic simulation object in Fig. 11-(a). The bright circles imply the fibres for axial resolution test and the small grey dots correspond to the randomly scattering particles in the gel media which fill the inside of the phantom. The two rectangular peaks in Fig. 11-(b) represent the two fibres.

Since the oscillatory components are usually handled by using envelope extraction, the conventional ultrasonic images appear as shown in Fig. 12-(a). Figure 12-(b) shows the vertical profile at the same scanning position. Though the artefacts are partially removed,the blurring overlaps between the close fibres still remain. This causes the degradation in quality of the image.

The results by using the proposed method areshown in Fig. 13. The recombined image and the vertical profile restored the originals more approximately than the conventional envelope imaging. There is no footprint in the recombined profile. The blurring overlaps between the two adjacent fibres are significantly reduced even in the right-most close fibre pair. The image quality was clearly enhanced by the proposed method.

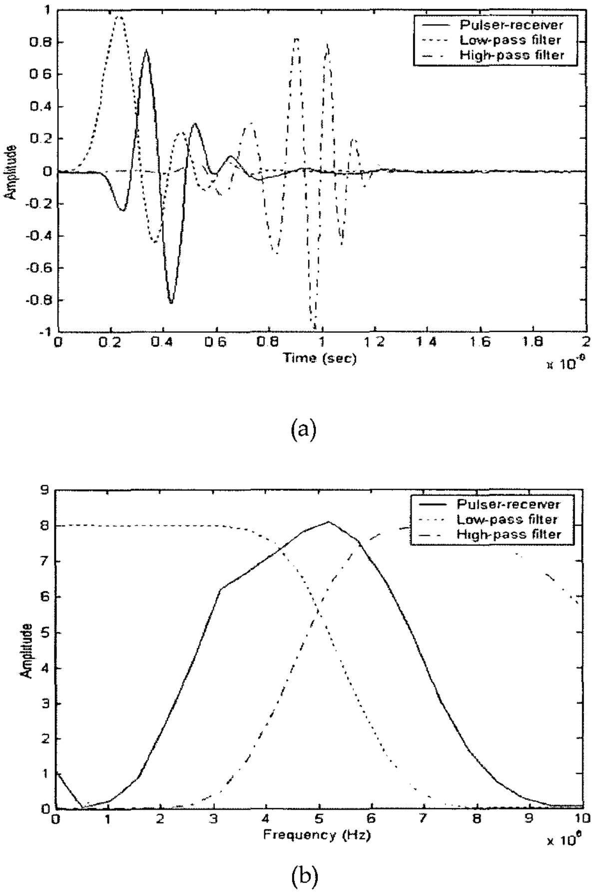


(a)



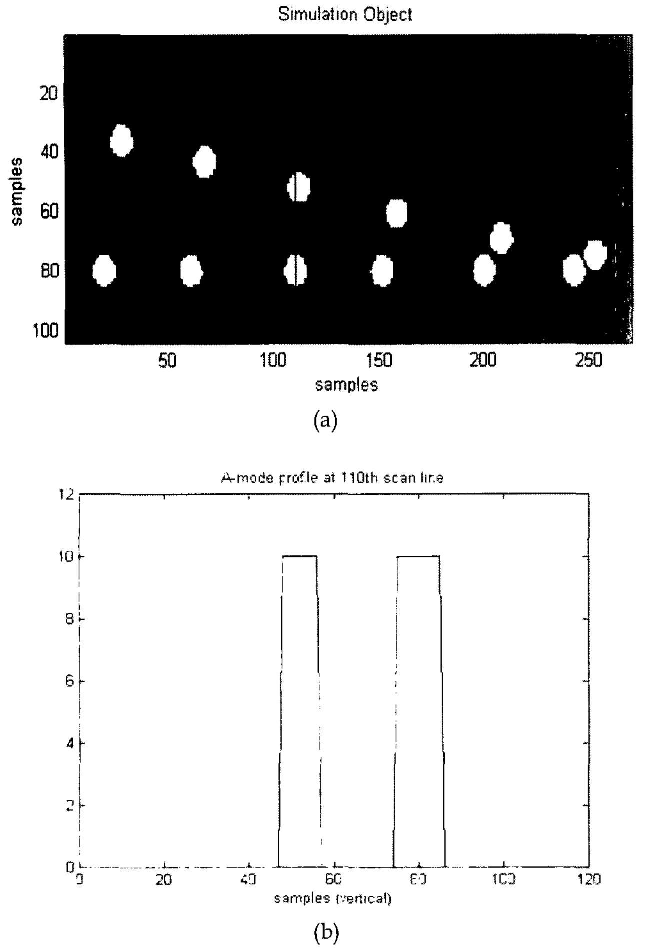
(b)

Fig. 9. Simulated images for image quality test. a) captured image of the general ultrasonic phantom has the predefined region for axial resolution test in the top-left corner, b) the axial resolution testing area was separated for verification of the proposed method.



(b)

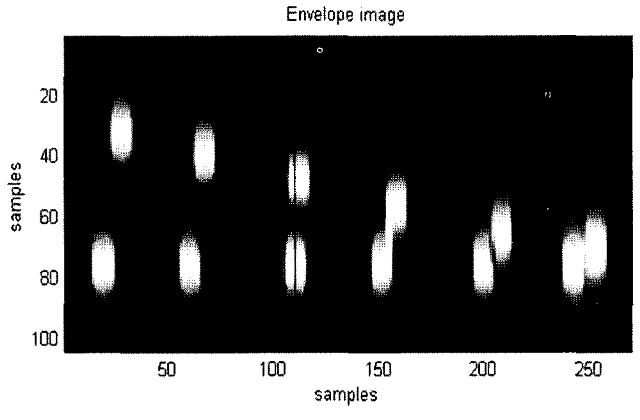
Fig. 10. The comparison between the proposed ultrasonic pulses and the conventional one. The solid lines represent the conventional pulser-receiver wave. The low-pass and high-pass filter indicate the subband filters involved in the DWT. a) their time domain appearances, b) frequency domain appearances.



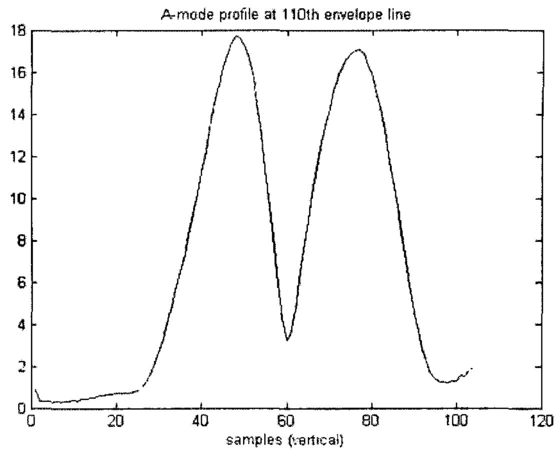
(a)

(b)

Fig. 11. Target image for axial resolution test. a) additional inclusion of random scattering particles with the phantom image shown in Fig. 9-(b), b) one of the vertical profiles is selected for the cross-sectional view.



(a)



(b)

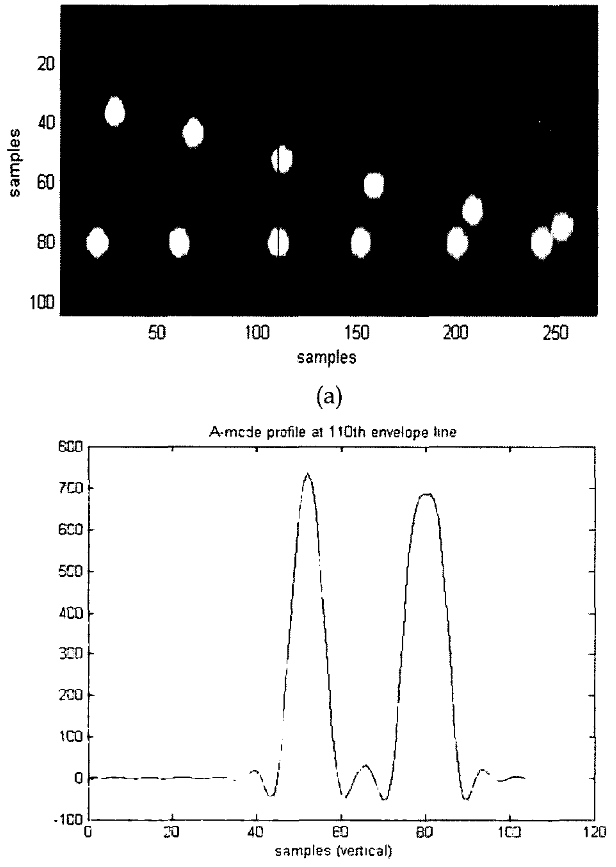
Fig. 12. A conventional scan-echo results after envelope extraction. a) image obtained by extracting the signal envelope from received RF signal, b) the vertical profile selected at the same position. There are blurs near the edges of the fibres.

DISCUSSION AND CONCLUSIONS

The proposed interrogation method using wavelet subband filter banks was proven to restore the original details in the simulated biologic tissues. The restored detail information can be investigated by other signal processing methods for further diagnostic use [1]. The proposed method improved thequality of the image by reducing the distortions and blurring overlaps caused by the interrogating pulses, and hence the enhanced image quality. It was promoted by the wavelet and PR filter banks [5-7] and by the use of the spatial autocorrelation model of the biologic tissues [1]. Though the simulation in this study adopted Daubechies' wavelet filters, any set of wavelet subband filters satisfying the PR conditions can be recruited as the interrogation pulses. The additional requirements of compact (finite) support help the realization of them in the DSP-based system [6]. The proposed wavelet subband filter banks are different from the ordinary subband filter banks in that they have almost finite durations by definition. They are more suitable for the pulse-echo scheme of the ultrasonic imaging than ordinary subband filter banks because of their short durations.

Since the PR filter banks are orthogonal or biorthonal, the separate pulse-echoes can be combined together by transmitting the pulses sim. It is helpful to maintain the frame rate comparable to the conventional single pulse echo imaging though the syste

The small oscillatory degradations of the proposed imaging at the edges of the fibres in Fig. 13-(a) and Fig. 13-(b) are caused by the limited bandwidth of the simulated transceivers. In the simulations, the highest frequency component of the signals is intrinsically limited at 40 MHz, that is, half the assumed sampling frequency. Most of the high frequency components were at the edges of fibres. They were missed during backscattering occurred because the two subband pulses covers the frequency range from 0 to 40 MHz. There would be no such blurred edges if wide band transceivers were utilized. Fortunately, the recent advances in transceiver techniques help us to use wider-band transducers. Moreover, such edge frequency components generally containless information in term of the backscattering coefficient [1].



(a)

(b)

Fig. 13. A scan-echo results by using the proposed method. a) image obtained by applying the proposed interrogation method, b) the vertical profile selected at the same position. There is no footprint of the ultrasonic pulses or overlap near the adjacent fibres.

To accomplish the simulated performances in real system, the bandwidth of the ultrasonic transceiver still should be wide enough to transmit the subband pulses. Otherwise, two different transceivers are needed to transmit and receive the two pulses and echoes, separately. If either of the transceivers has bandwidth insufficient to transceive the corresponding pulse, we can subdivide the filter bank structures in Fig. 2 repeatedly until each bandwidth of the subband filter fits for the corresponding bandwidth of the transceiver. Others proposed to modulate the pulses in the way that the modulated results have high-energy component within the transducer bandwidth so that the pulses can pass the transducer [8].

The feasibility of the proposed method is under experimental validations by using the arbitrary signal generator and ordinary ultrasonic transceivers. The preliminary results confirmed the need for sub-decomposition of the interrogating waves to be launched from several narrow band transceivers.

Finally, it is interesting to note that the short-pulse nature is common to the wavelet transform and the ultrasonic investigating waves. The significant similarity and analogy between them are thought to encourage their partnership in various ultrasonic devices besides the imaging facilities. Furthermore, the applications of the wavelets are expected to expand to the design of hardware beyond the signal processing.

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