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Application of Empirical Mode Decomposition to Remove the Wall Components in Doppler Ultrasound Signals: A Simulation Study

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Abstract—**Doppler ultrasound blood flow analysis systems normally use a hiss-pass filter to remove the large, low frequency components from the vessel wall from the blood flow signal. Unfortunately, the filter also removes the low frequency Doppler signals arising from slow moving blood. In this paper, we propose to use a novel technique, called the empirical mode decomposition (EMD), to remove the wall components from the mixed signals. The EMD is used to decompose a Doppler signal into finite individual components. Then the wall components are automatically identified and removed by using a strategy. This method is applied to process the simulated Doppler signals. Compared with the results based on the tradition high-pass filter, the new approach obtains improved performance for wall removal from the mixed Doppler signals, and provide us with more accurate low blood flow.**

I. INTRODUCTION

IN Doppler ultrasound systems, the signal scattered from blood is corrupted by echoes from stationary or slowly moving muscular tissue, such as vessel walls and the surrounding tissue. This clutter components introduced by the moving wall and tissue usually have stronger amplitude and lower frequency shift than the signal from blood as they are scattered from slow-moving vascular walls that are much stronger ultrasound reflectors than the blood [1]. Adequate suppression of vessel wall and stationary signals is necessary for precise measurement of blood velocity. Usually, a high pass filter can be used to separate the signals from blood and tissue [2]. Unfortunately, this filter also removes the low frequency Doppler signals arising from slow moving blood, including that close to the vessel wall. However, it has long been recognized that flow conditions close to the vessel wall have an influence on cardiovascular disease initiation and growth and researchers in this area have an interest in the measurement of the low blood velocity in this region [3].

In order to detect the blood velocity accurately, it is necessary to separate wall components from the blood flow signal. Several clutter or wall filters were proposed to meet this requirement according to the distinctive difference of the amplitude of the blood and wall components in the spectrogram [4-6]. In these methods, spectrograms of the Doppler blood flow signals were computed. Then a strategy was established in the frequency domain to determine the spectral components regarded as the contribution of the wall echo signal, and put to zero or remove from the time domain signal. Although the accuracy of the blood flow component extracted from the mixed signal has been improved by using these methods, the signal process was still based on the time-frequency analysis, which introduced an inaccuracy for the extraction of blood flow signals when they share the same frequency with wall components. Alternative techniques, which separated the wall components from the blood flow signal in time domain, have been proven to improve the accuracy of wall removal [7-9]. For these methods, the mixed Doppler signals were decomposed in time domain, then blood and wall signals were separated according to the decomposed components amplitude. However, these wall removal processing in time domain mentioned above rarely consider the characteristics of wall components, which usually have both stronger amplitude and stationary lower frequency shift.

In this paper, we propose to use a novel technique, called the empirical mode decomposition (EMD), first introduced by N. E. Huang et al. in 1998 [l0], to remove the wall components from the mixed Doppler blood flow signals. The EMD is firstly to decompose a signal into a finite and usually small number of individual components named intrinsic mode functions (IMFs), which contain from the finest scale or the shortest period component to the residue trend or the longest period component of the signal. Then a strategy has been developed to automatically identify and remove the relevant IMFs that contribute to the wall components. This method is applied to process the simulated signals. Compared with the results based on the tradition high-pass filter, the new approach obtains improved performance for wall removal from the mixed signals.

II. METHODS

A. *Empirical Mode Decomposition*

The EMD algorithm extracts the oscillatory mode that exhibits the highest local frequency from the data, leaving the remainder as a "residual". Successive applications of the algorithm on the sequence of residuals produce a complete decomposition of the data. The final residual is a constant, a monotone trend or a curve with a single extremum. Then, we get what is referred to as an intrinsic mode function. Intrinsic

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mode functions are obtained using the algorithm called *sifting*. Details of this algorithm can be found in the work by N. E. Huang et al. [10].

B. *The Strategy for separation of blood and wall components*

The EMD algorithm is applied to decompose the mixed Doppler signal $x_d(n)$ into *M*-intrinsic mode functions $c_i(n), (1 \le i \le M, 1 \le n \le N)$, where *M* is the number of the IMFs and *N* is the length of the signal. It has known that the EMD method picks out the highest frequency oscillation that remains in the signal. Thus locally, each IMF contains lower frequency oscillations than the one extracted just before. A change of frequency will appear even more clearly at the level of an IMF [14]. Therefore, the initially extracted IMFs presenting higher frequency oscillation and lower amplitude should correspond to the Doppler blood flow components. The IMFs corresponding to the wall signal are extracted later. Suppose *L* be the number of the IMFs corresponding to the components from the blood flow, the wall-to-blood signal ratio (WBSR) is calculated as follows:

$$WBSR = 10\log_{10} \frac{\sum_{n=1}^{N} \left\{ x_d(n) - \sum_{i=1}^{L} c_i(n) \right\}^2}{\sum_{n=1}^{N} \left\{ \sum_{i=1}^{L} c_i(n) \right\}^2} \qquad (1)$$

In order to separate the signals from the blood and wall automatically and correctly, the WBSR is computed repeatedly by (1) in the number of IMFs' range of 1 to *M* with an increment of 1. In this process, the WBSR is supposed to be gradually converging and approaching to its actual value. When this value reaches stability, the number of the IMFs *L*, which corresponds the component of the signal from the blood flow, can be determined.

III. EXPERIMENTS

A computer simulation's model of the signals from wall and blood proposed by Fish et al. [3] and Wang et al. [12] is used to simulate the mixed Doppler signal. According to this model, the Doppler signals from blood and wall are calculated using the blood flow mean frequency information and the radial vessel wall displacement respectively, and vessel's beam geometry. Then two signals are summed to give the combined Doppler signal. The mean frequency waveform (for simulation of the time-varying blood flow) and the displacement waveform (for simulation of the wall movement) over one cardiac cycle are given in precedence. In present study, they are both acquired from a normal human common carotid, as shown in Fig. 1.

When simulating the blood Doppler signal with a velocity distribution, the artery is divided into a set of hydro-pipes along the radius, and the velocities of scatters in each hydro-pipe are presumed to be equal if the separation along the radius is small enough. Then, the sample volume (SV) is also divided into many sub-volumes along the arterial axis. The Doppler signal from a single sub-volume at a radial and axial position can be calculated using equations derived by Wang [12]. A triangular window is used to simplify the sound beam pattern and the sample gate is rectangular. The Doppler blood flow signal from the complete SV, $x_b(t)$, is simply a summation of the signals from all of its single sub-volumes.

The arterial wall in the sample volume is also divided into a set of small parts along the circle and the vascular axis. Then the wall signal from the whole sample volume, $x_w(t)$, can be simulated by summation of the signals from all of the small parts computed using equations derived by Fish [3].

Finally the combined Doppler signal is then given by:

$$x_d(t) = x_b(t) + x_w(t) \qquad (2)$$

with a wall-to-blood signal ratio of

$$WBSR = 20\log_{10} \frac{|x_w|}{|x_b|} \qquad (3)$$

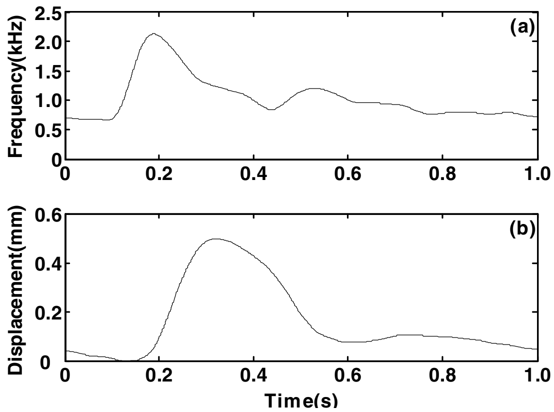

Fig.1. The waveforms of the mean frequency (a) and the wall displacement (b) from a normal common carotid artery.

Parameters in the simulation are chosen to closely resemble those in the realistic Doppler ultrasound measurement system. The fixed parameters are: the sample frequency $f_s = 12.8$ kHz, the transmit frequency $f_0 = 5$ MHz, the ultrasound velocity $c = 1540$ m/s, wall elastic modulus $E = 4 \times 10^5$ Nm^{-2}, artery internal radius $R_i = 0.4$ cm, external radius $R_e = 0.6$ cm and incidence angle $\theta = 60^0$. The SV with the length 6 mm is divided into 200 equal elements along the arterial axis. The blood flow is segmented into 50 hydro-pipes with the decreasing thickness along the radius in order to accommodate the high shear-rate of the blood flow near the arterial wall. The arterial wall is divided into 100 equal segments along the circular circumference. The blood/wall signals from the SV covering the whole vessel. The Doppler signal and the wall signal are generated independently, and then are combined together with a WBSR of 20 dB to generate the 30 realizations of mixed Doppler signal.

In order to evaluate the performance of the proposed method, the EMD method and the traditional high-pass filter method, a fifth order Butterworth high-pass filter with a cut-off frequency of 150 Hz are both tested for comparison. The spectrogram of the Doppler signal without wall contaminations is computed by using the short time Fourier transform (STFT). For adequate frequency resolution, a temporal window of 30 ms is adopted with an overlap of 20 ms for STFT. Furthermore, the WBSRs computed from the signals separated by using the EMD and traditional high-pass filter methods are compared with the signal's actual value.

IV. RESULTS AND DISCUSSION

Fig.2 shows a mixed Doppler signal of one cardiac cycle with WBSR=20dB and its spectrogram. It can be found that the contamination from the wall movement is very obvious both from the signal waveform and the spectrogram.

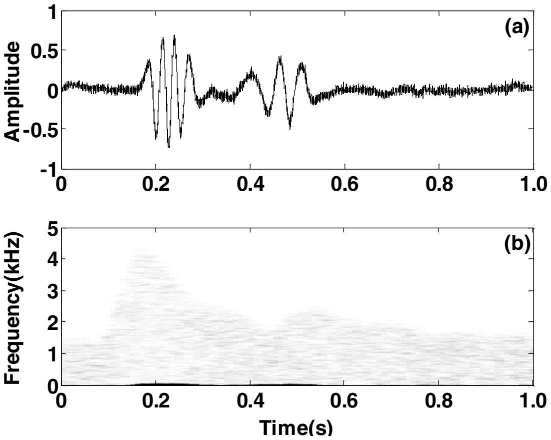

Fig. 2. The simulated mixed Doppler signal of one cardiac cycle with WBSR=20 dB (a) and its spectrogram (b).

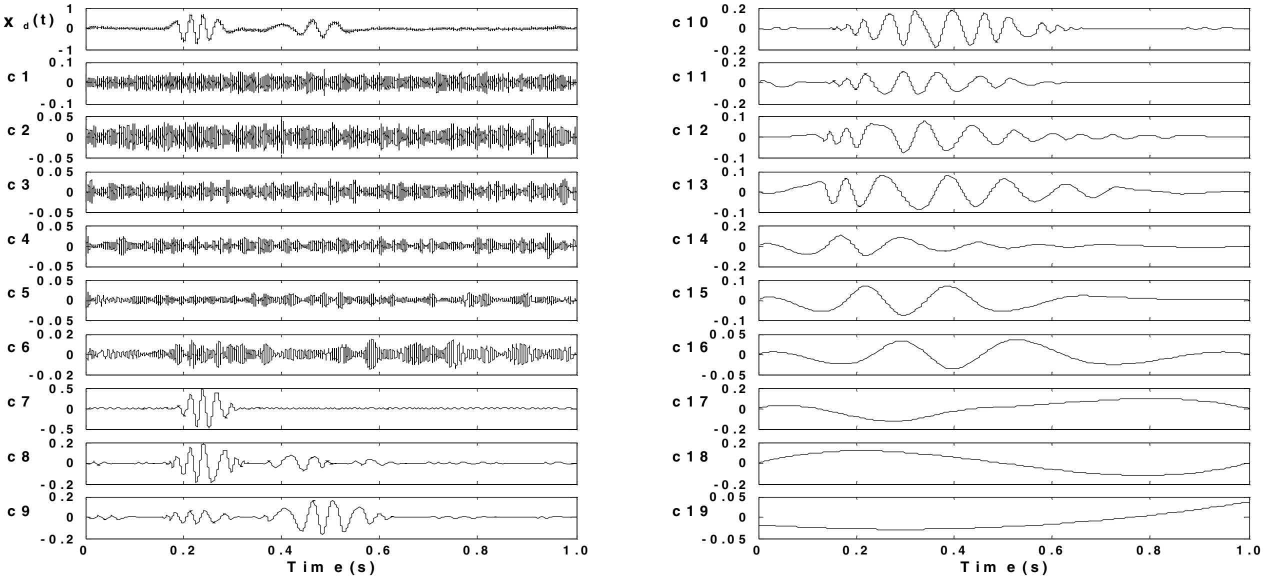

Fig. 3. (top left) Original simulated Doppler signal, all 18 IMFs (c1-c18) and the overall trend (c19)

Fig. 3 shows a simulated Doppler signal along with its 18 resulting IMFs and the overall trend. It can be found that the EMD algorithm decomposes the Doppler signal into IMFs that are selected in a decreasing frequency order. After employing the separation strategy based on the WBSR's convergence described in Section II to the above IFMs for the separation of the signals from the blood and wall, the first six IMFs, c1-c6, have been chosen as the components from the blood flow. The IMFs c1-c6, which include higher frequency and lower amplitude components, may naturally correspond to the signal from the blood flow with high velocities. However, there are some obvious lower frequency components in the c6. This indicates that there are lower frequency and lower amplitude components existing in the signal of the Doppler blood flow. Thus the EMD algorithm could extract the blood flow signal with slower velocity components.

Fig. 4 gives the spectrograms of the separated Doppler blood signals using the EMD and high-pass filter methods. Fig. 4 (a) shows the spectrogram of the summation of c1-c6 IMFs, which selected as the signal from the blood flow by using the EMD algorithm. Compared with the spectrogram shown in Fig.4 (b), which is computed from the blood signal separated by using a fifth order Butterworth high-pass filter with a cut-off frequency of 150 Hz, it is obvious that the EMD method makes a better separation of the blood and wall signals than the high-pass filtering method, especially during diastolic phase when the wall movement is slow. This improvement in time-domain accuracy potentially contributes to the preservation of certain low-frequency blood components that are otherwise removed by high-pass filtering.

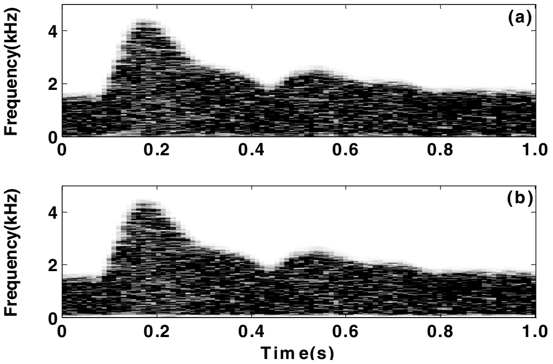

Fig.4. The spectrograms of the Doppler blood signals separated by using (a) the EMD and (b) high-pass filter methods.

In order to quantitatively evaluate the separation performance of the proposed method, the WBSRs computed from the averaged spectrum over 30 realizations of the simulated Doppler signal are compared before and after separation processing. The WBSRs of the original simulated Doppler signal and the Doppler blood signals separated by using the EMD and high pass filter methods in the lower frequency region 0-300 Hz are shown in Fig. 5. Notice that the amplitude of the simulated blood flow signal at zero frequency point is normalized to 0 dB. From this figure, it can be found that the loss of the flow signal processed by using the proposed method is much less than that based on the high-pass filter method. This indicates that the EMD method can produce more accurate estimation of the Doppler blood flow signal because it filters out less components in low-frequency region.

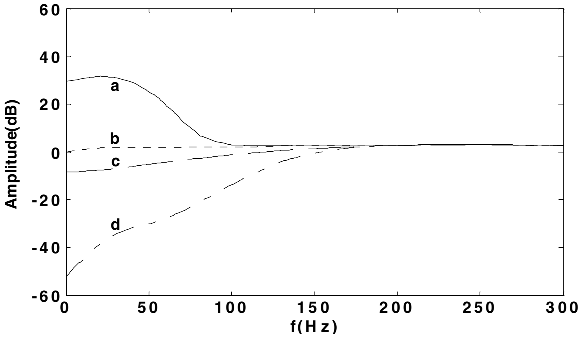

Fig. 5. The WBSRs of (a) the original simulated Doppler signal with WBSR=20 dB, the separated signals using (c) the EMD and (d) high-pass filter methods. The amplitude of the simulated blood flow signal (b) at zero frequency point is normalized to 0 dB.

V. CONCLUSION

A novel method based on the EMD for wall components removal from Doppler ultrasound signal with minimal loss of low blood flow signal is proposed in this study. To validate the novel approach, the Doppler signal from a normal carotid artery is simulated and combined with the wall signal generated from the wall displacement waveform. The comparison experiments are carried out using the conventional high-pass filtering method and the proposed separation method. The results show that the new method obtains improved performance for wall removal from the mixed signals, and provide us with more accurate low blood flow.

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