Suppression of Doppler Ultrasound Signal Wall Components Based on Local Mean Decomposition Algorithm

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Abstract. The low-velocity blood flow signal close to the blood vessel wall is very important for the early diagnosis of vascular diseases. To obtain more accurate low-velocity blood flow signals from the Doppler ultrasound echo signal, this paper proposes a carotid artery low-velocity blood flow signal extraction method based on local mean decomposition (LMD). First, the LMD decomposes the original signal into a series of product terms. Then, based on the instantaneous frequency and amplitude, the blood flow stratification index is constructed to subdivide the blood flow and blood vessel wall signals in the product component. Finally, the signal is reconstructed, thereby achieving the suppression of the clutter signal of the blood vessel wall. Experimental results show that this method could effectively obtain low-velocity blood flow signals.

1. Introduction

When Doppler ultrasound equipment is used to detect blood flow signals, the ultrasound signals reflected by blood cells will be interfered by the pulsating blood vessel wall and surrounding tissue movement[1]. Moreover, the amplitude of these interference signals is much greater than the amplitude of the signals reflected by blood cells. Therefore, how to effectively eliminate the interference of the blood vessel wall signal on the blood flow signal, while retaining the low-speed blood flow signal near the blood vessel wall, so as to obtain the sensitive parameters for the early diagnosis of the disease is particularly important.
2. Method

2.1. LMD method
Generally, the ultrasonic Doppler of the pulsating blood flow is considered as a non-stationary signal, and the change of the pulsating blood flow velocity will generate the ultrasonic Doppler signal of different frequency components. When the vessel wall beats, it will modulate the amplitude and frequency of these signals. Thus, a complex non-stationary multi-component AM-FM signal will be generated.

The LMD method is an adaptive time-frequency decomposition proposed by Smith in 2005\cite{2}. Compared with Empirical mode decomposition, it can avoid over-envelope and under-envelope, and there is no serious end effect, and the obtained instantaneous frequency will not be negative frequency\cite{3}. The LMD method regards the target signal as a series of components (modes) and a residual signal. The modal function decomposed by the LMD method is a product function (PF), which contains two parts: amplitude envelopes and pure frequency modulation signals. That is to say, the LMD algorithm decomposes the complex signal into a series of single-component AM-FM signals and the superposition of the residual signal. Therefore, this method is very suitable for processing complex AM-FM signals, as well as the analysis of ultrasound Doppler blood flow signals. We can decompose the target signal $x(t)$ into a series of PF components and a residual component $u_m(t)$, which can be expressed as:

$$
x(t) = \sum_{j=1}^{m} PF_j(t) + u_m(t)
$$

(1)

2.2. Suppression method based on phase filtering and LMD
The process of ultrasonic Doppler signal wall clutter suppression based on phase filtering mainly consists of three parts (Fig. 1): the separation of the positive and negative motion directions of the ultrasonic signal, the extraction of blood flow signals, and reconstruction of blood flow signals. The overall realization idea is: First, we used the phase filtering to separate the ultrasonic Doppler signal with clutter interference according to the direction of motion. Then, we implemented the LMD method to decompose the ultrasonic signals into a series of single-component PF functions; and adopted the inverse cosine transform to calculate the instantaneous frequency (IF) of all PFs, and then the vessel wall is distinguished according to the magnitude of the IF. Thus, we filtered the interference of the vessel wall signal from the blood flow signal. Finally, the positive and negative blood flow signals are recombined through the Hilbert transform to obtain orthogonal blood flow signals that suppress the interference of the vessel wall clutter.

![Flow chart of orthogonal vessel wall clutter suppression method](image)

Literature\cite{4} proposed a method of automatically distinguishing IMFs after EMD decomposition based on the power ratio of the vessel wall and blood flow signal, to separate the blood flow and vessel wall signals. They assumed that the IMFs decomposed by EMD is composed of three parts as shown in Eq.(2), where the first term is the blood flow signal with higher frequency and lower amplitude, and the
latter two are regarded as vessel wall signals, that is wall signal with low frequency and high amplitude and residual signal, respectively. Then, taking the advantage of the characteristics of a 20dB difference in power between the blood cells and the vessel wall caused by the difference in physical properties, the classification of IMFs can be performed.

\[ x(k) = \sum_{i=1}^{l} c_i(k) + \sum_{i=1}^{M} c_i(k) + r_M(k) \]  

(2)

The specific implementation is as follows: assume that the first few layers are blood flow signals in an incremental manner, and the remaining layers and residual signals are vessel wall signals, and then calculate the vessel wall blood flow power ratio curve WBSR according to Eq. (3).

\[ WBSR = \frac{\sum_{k=1}^{n} \left( \sum_{i=1}^{M} c_i(k) + r_M(k) \right)^2}{\sum_{k=1}^{n} \left( \sum_{i=1}^{l} c_i(k) \right)^2} \]  

(3)

where \( M \) represents the number of IMF layers after EMD decomposition, and \( n \) represents the number of sampling points. The curve has an inflection point, which is the critical point of IMF signal stratification. Based on it, literature[5] proposed an automatic layering method according to IF. This method believes that after the EMD, several intermediate IMFs contain both the blood flow and the vessel wall signals. Therefore, it is necessary to distinguish these layers in more detail to improve the efficiency of clutter suppression. Then a ratio can be obtained by comparing the extreme value of the IMF with the average value of each layer. For several layers of IMFs that are mixed with the vessel wall and the blood flow signal, because the amplitude of the vessel wall signal is much larger than the average amplitude, the ratio is generally larger. Otherwise, the ratio is smaller. Thus, the magnitude of the ratio can be used to determine whether the IMF of this layer is a mixed signal. However, since the IMF signal is also frequency-modulated and amplitude-modulated, just judging from the amplitude of the signal may misjudge some low-frequency vessel wall beat signals with low amplitude as blood flow signals, or misjudge high-frequency blood flow signals with large amplitudes as the signal of the vessel wall. Moreover, while the method of calculating the IF by using the Hilbert transform may obtain a negative frequency, which affects the accuracy of separation of blood flow and the signal of the vessel wall.

The LMD decompose the signal into pure frequency modulation signals and amplitude signals, and the IF can be easily obtained by the inverse cosine. Therefore, through the combination of the IF and the instantaneous amplitude (IA), the vessel wall can be distinguished very accurately. Thus, to make it easier to distinguish, we defined the power-frequency ratio as the separation index function, as shown in Eq.(4):

\[ \text{Index}_{WB}(k) = \frac{AI_i(k)}{\text{Normal}(IF_i(k))} \]  

(4)

where, \( AI_i(k) \) and \( IF_i(k) \) represent the amplitude and IF of the PF component of the \( i \)-th layer respectively, and \( \text{Normal}() \) represents the normalization processing.

3. Results

To evaluate this method, we constructed a function to simulate the vessel wall pulsation signal. The mathematical expression of this function is shown in Eq.(5):

\[ x(t) = 3 \left[ 1 + \sin(6\pi t) \right] + 5 \sin^3(\pi t) + \left[ 1 + \sin(6\pi t) \right] \cos(36\pi t + 5 \sin(20\pi t)) \]  

(5)

This signal includes three parts. The first item is a 3Hz sine signal, which simulates a large wall displacement; the second item is a 0.5Hz trend curve, which simulates the slow movement caused by the test probe or other factors; the third item is an FM-AM signal, which simulates the vessel beating. The amplitude of the signal is modulated by the displacement of the wall. When it is large, the amplitude is
larger, and vice versa. And its frequency is modulated by a sine signal (10 Hz). Then, we added a high-frequency random signal with a frequency of 1KHz to the above signal to simulate the blood flow signal. The power of the added high-frequency blood flow signal is 20dB lower than that of the vessel wall.

The mixed-signal is shown in Fig. 2. The method of waveform mirror continuation is used to eliminate the end effect. After LMD decomposition, 7 PFs are obtained (Fig. 3). The corresponding amplitude, pure FM and IF components are shown in Fig. 4-6, respectively.

From Fig. 3, it can be obviously observed that the PF1 and PF2 should be high-frequency blood flow signals; and the PF3 and PF4 should contain the information of vessel wall pulsation. Moreover, from the IFs of these two components in Fig. 6, we observed that they contain relatively high-frequency components. And we also observed that the IF amplitudes of these two components at about 0.1 second, 0.4 second, and 0.75 second are relatively low. Thus we inferred that these two PFs contain both high-frequency blood flow components and low-frequency vessel wall pulsation components. By observing the IF in Fig. 6, the PF5-PF7 correspond to the beating signal of the vessel wall.
The IF obtained by the LMD method shown in Fig. 6 clearly shows the change of the IF of the corresponding component with time, and can more accurately reflect the frequency characteristics of the vessel wall and blood flow. For example, IF3 in Fig. 6 has a high IF at most times and should correspond to the blood flow signal; while its IF is low around the time of 0.1 second and should correspond to the vessel wall signal. Therefore, the IFs of the LMD method have a better physical meaning, and can provide a better basis for the separation of blood flow and vessel wall signals.

Figure 5 Pure FM of the PF

Figure 6 The IF of the PF

Figure 7 Blood flow vessel wall signal separation index
Then, we calculated the separation index of each layer according to Eq.(4), and drew it as shown in Fig. 7. We observed that during vessel wall pulsation (for example, around the time of 0.1 second, 0.4 second, 0.7 second, etc.), the index values of layer 3-5 are large, while the index values are small at other times. By setting a reasonable threshold, we completed the separation of the vessel wall and the blood flow signal in the mixed PF components.

So far, we used an artificial method to determine which layers of the PF component contain both the vessel wall signal and the blood flow signal. It can be seen from Fig. 7 that the IF of the component signals of the last several layers is very small, resulting in a large power-to-frequency ratio, so the aforementioned separation index cannot be used directly as the basis for layering. However, by observing Fig. 4, we found that the amplitude changes of the last layers are very small. Therefore, referring to the method in[^5], we modify the Eq. (4) to construct the layering index function as shown in the following equation:

\[
\text{Index}_{L_i} = \frac{\text{Normal}(\text{AIM}_i - \text{Aver}_i)^2}{\text{Normal}(\text{IF}_i(M))}
\]

where \( \text{AIM}_i \) and \( \text{Aver}_i \) represent the maximum value and average value of the amplitude of the \( i \)-th layer PF component respectively, and \( \text{IF}_i(M) \) represents the IF at the moment when the amplitude is the maximum, and \( \text{Normal}() \) represents the normalization process. Fig. 8 shows the layered index function graph calculated according to Eq. (5), and the x-axis is the number of layers. It can be seen that the third layer has the largest index value, and the value of the fourth and fifth levels are about 4-5. The values of the other layers are all small, below 1. Therefore, we can set a threshold, select the PF component with a larger index value from it, and then use the aforementioned subdivision method to process these layers to separate the blood flow and the vessel wall components.

According to the above method, the mixed signals PF3-PF5 decomposed by the simulation signal are subdivided. And the high-frequency blood flow signals are extracted, as shown in Fig. 9. The upper sub-picture is the original blood flow signal, and the lower sub-picture is the blood flow signal extracted after processing by the above-mentioned subdivision method. It can be seen that the blood flow signal extracted by the above method has good consistency with the original signal.
4. Conclusion
The LMD method obtains the IF and IA, which can well reflect the local characteristics of the signal, and is very suitable for the analysis and extraction of non-stationary ultrasound Doppler blood flow signals. This method can improve the detection accuracy of the slow blood flow signal near the inner wall of the lumen.

In this paper, a moving average method is used to obtain the envelope of the extreme value, which requires a lot of calculation time. To improve the calculation efficiency, in future research, we will explore other methods to obtain the extremum envelope, and solve the modal aliasing problem by determining the decomposition scale and other methods.

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