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A novel quadrature clutter rejection approach based on the multivariate empirical mode decomposition for bidirectional Doppler ultrasound signals

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ABSTRACT

A novel quadrature clutter rejection approach based on multivariate empirical mode decomposition (MEMD), which is an extension of empirical mode decomposition (EMD) to multivariate for processing multichannel signals, is proposed in this paper to suppress the quadrature clutter signals induced by the vascular wall and the surrounding stationary or slowly moving tissues in composite Doppler ultrasound signals, and extract more blood flow components with low velocities. In this approach, the MEMD algorithms, which include the bivariate empirical mode decomposition with a nonuniform sampling scheme for adaptive selection of projection directions (NS_BEMD) and the trivariate empirical mode decomposition with noise assistance (NA_TEMD), are directly employed to adaptively decompose the complex-valued quadrature composite signals echoed from both bidirectional blood flow and moving wall into a small number of zero-mean rotation components, which are defined as complex intrinsic mode functions (CIMFs). Then the relevant CIMFs contributed to blood flow components are automatically distinguished in terms of the break of the CIMFs' power, and then directly added up to give the quadrature blood flow signal. Specific simulation and human subject experiments are taken up to demonstrate the advantages and limitations of this novel method for quadrature clutter rejection in bidirectional Doppler ultrasound signals. Due to eliminating the extra errors induced by the Hilbert transform or complex FIR filter algorithms used in the traditional clutter rejection approaches based on the directional separation process, the proposed method provides improved accuracy for clutter rejection, and preserve more slow blood blow components, which could be helpful to early diagnose arterial diseases.

1. Introduction

Doppler ultrasound is a noninvasive methodology broadly applied in medicine for the diagnosis and assessment of cardiovascular diseases by dynamically detecting and quantifying the disturbed blood flow velocities [1,2]. However, the clutter components scattered from the vessel walls and the surrounding stationary or slow-moving tissues typically have intensive amplitude and lower frequency shift, and can cause corruption in Doppler blood flow signals, especially those echoed from blood near the edge of vessel wall, which could embody the information of the diseases' existence for improving the diagnosis efficiency at an early stage [3,4].

In order to effectively suppress the strong clutter components, clutter rejection approaches [5,6] were investigated on account of a strategy in frequency domain to determine the wall components by marked distinction between the blood and wall amplitudes in the spectrum, and then remove them from the compound signal in time domain. However, these approaches are usually based on a kind of spectrogram analysis algorithm, which may introduce errors in spectral estimation. Moreover, determination of blood flow signals in frequency domain is also difficult as flow signals with low velocities and the clutter components occupy the same frequency distribution. The other clutter filters [7–10] were investigated for improving the accuracy of clutter component removal in time domain based on the amplitudes of decomposed components obtained by signal analysis methods, such as principal components analysis [7], eigen decomposition [8], blind source separation [9]

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and matching pursuit method [10]. Although the accurate performance of the clutter rejection is improved to a certain extent by using these time domain methods, a lack of objective criteria to distinguish the components echoed from blood flows and vessel walls may bring unstable accuracy to blood velocity estimation and clutter suppression. In 1998, Huang proposed a data driven analysis algorithm, empirical mode decomposition (EMD) [11], which is proven to be feasible for analysis of nonlinear and nonstationary signals with components overlapping in time-frequency frame, such as seismic signals and medical clinical signals. As an application [12], the EMD was explored to reject clutter components from composite Doppler signals by using an objective criterion based on the break point of the clutter to blood (C/B) ratio for automatically identifying and removing the relevant intrinsic mode functions (IMFs) of the clutter components. The results revealed that this EMD based clutter filter with the C/B discrimination strategy could remove the clutter components efficiently, and reserved more blood signal with low velocities. Recent years, with several improved EMD [13,14] based clutter suppression methods were proposed and investigated, the accuracy and stability of the separation between the blood and vessel wall signals within a large range of velocities were significantly enhanced. However, these original and improved EMD based suppression methods are inapplicable to quadrature signals, whose phase relationship conveys the information of flow and clutter moving directions. When inphase and quadrature signals are decomposed by using the EMD algorithm, respectively, nonlinear sifting process in the EMD may contort the phase relationship, and cause the insuccess of bidirectional blood flow signal detection.

For the sake of avoiding aliasing artifacts in the quadrature clutter rejection by the nonlinear signal processing algorithms, a specific design for filtering process is required [15–18]. In these specific filters, the original demodulated quadrature signals were firstly separated into two unidirectional real Doppler signals scattered from forward and backward movements, respectively. After that, each directional signal was disintegrated into a series of elements, such as wavelet coefficients [15–17] and IMFs [18], and then certainly elements were selected and accumulated to produce the needed components by a strategy according to the specific goal in time or frequency domain. In the end, the quadrature blood signals incorporating bidirectional moving information were rebuilt by an arithmetic operation from the selected unidirectional-components. It has been proved that these approaches are practical for quadrature clutter rejection. However, Hilbert transform (HT) used in the directional separation [18] or quadrature reconstruction [15–18] to produce a 90° phase shift in its output signal, requires that the signal being analyzed is band-limited symmetric. Due to the complicated blood flow distribution, especially for the turbulence occurring in flow of stenotic vessels, the Doppler signals usually cannot meet this requirement. Furthermore, extra errors may also be induced due to the complex FIR filter with a pass band used for directional separation [15–17], whose arbitrarily determined orders and cutoff frequencies may not in accord with the requirements for actual Doppler blood flow signal processing.

In this paper, a novel quadrature clutter rejection approach based on multivariate empirical mode decomposition (MEMD) [19], which is an extension of empirical mode decomposition to multivariate for processing multichannel signals, is proposed to suppress the quadrature clutter signals induced by the vascular wall and the surrounding stationary or slowly moving tissues in composite Doppler ultrasound signals, and extract more blood flow components with low velocities. In this approach, the MEMD algorithms, which include the bivariate empirical mode decomposition (BEMD) with a nonuniform sampling scheme for adaptive selection of projection directions (NS_BEMD) [21,22] and the trivariate empirical mode decomposition (TEMD) with noise assistance (NA_TEMD) [19,20], are directly employed to adaptively decompose the complex-valued quadrature composite signals echoed from both bidirectional blood flow and moving wall into a small number of zero-mean rotation components, which are defined as complex intrinsic mode functions (CIMFs). Then the relevant CIMFs contributed to blood flow components are automatically distinguished in terms of the break of the CIMFs' power, and then directly added up to give the quadrature blood flow signal. Specific simulation and human subject experiments are taken up to demonstrate the advantages and limitations of this novel method for quadrature clutter rejection in bidirectional Doppler ultrasound signals.

The layout of present paper is as follows. In Section 2, the main concept of EMD algorithm and further extension for bidirectional clutter rejection combining the phasing filter method (PH_EMD) are briefly reviewed. Then the MEMD algorithm and the proposed methods with NS_BEMD and NA_TEMD algorithms for the quadrature clutter rejection are described in details. A method to generate quadrature composite Doppler ultrasound signals from both bidirectional blood flow and vessel wall in a carotid artery bifurcation for simulation study is also introduced in this section. Section 3 devotes to the experiments for evaluation and comparison in detail, proceeded with results, discussions and conclusions.

2. Methods

2.1. The empirical mode decomposition

As a fully data-driven method, the EMD is originally designed to adaptively disintegrate a real-valued data into a succession of intrinsic mode functions and a residue [11]. Each IMF should be meet two conditions: the numbers of extrema and zero crossings must be equal or differ at most by one; the average of the envelopes established by the local maxima and minima is zero in any point. To draw IMFs from the given real data $x(k)$, a repetition called sifting process is used [11]. After decomposition, the data can be finally expressed as the summation of the M intrinsic mode functions $c_m(k)$ and a residue $r_M(k)$:

$$x(k) = \sum_{m=1}^{M} c_m(k) + r_M(k) \quad (1)$$

2.2. The bidirectional wall rejection by using the PH_EMD

For the purpose of conserving more bidirectional blood flow components with low velocities to possibly provide detail diagnosis information, a specific clutter rejection method combining the phasing shift and the EMD algorithms was proposed [18]. Fig. 1 shows the schematic diagram of the PH_EMD method for extracting the quadrature blood components from a blood and wall composite signal. The method is implemented as follows: divide the directions, extract the blood signals, and rebuild the quadrature blood signals. In the beginning, the forward and reverse directions are divided by three procedures: a 90° phase shift in the inphase composite signal $x_{cI}(k)$ by HT, a delay to make up the time consumed by the HT in the quadrature composite signal $x_{cQ}(k)$ by an all-pass delay filter (DF), and an operation for the unidirectional composite signals by:

$$x_{cf}(k) = x_{mI\_H}(k) + x_{mQ\_D}(k) = A_{bf}\sin\omega_{bf} + A_{wf}\sin\omega_{wf} \quad (2)$$

$$x_{cr}(k) = x_{mI\_H}(k) - x_{mQ\_D}(k) = A_{br}\sin\omega_{br} + A_{wr}\sin\omega_{wr} \quad (3)$$

where $x_{mI\_H}(k) = (1/2)A_{bf}\sin\omega_{bf} + (1/2)A_{br}\sin\omega_{br} + (1/2)A_{wf}\sin\omega_{wf} + (1/2)A_{wr}\sin\omega_{wr}$ and $x_{mQ\_D}(k) = (1/2)A_{bf}\sin\omega_{bf} - (1/2)A_{br}\sin\omega_{br} + (1/2)A_{wf}\sin\omega_{wf} - (1/2)A_{wr}\sin\omega_{wr}$ are the outputs from HT and DF, respectively;