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Artificial bee colony algorithm to design two-channel quadrature mirror filter banks

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ABSTRACT

Artificial bee colony (ABC) algorithm has been introduced recently for solving optimization problems. The ABC algorithm is based on intelligent foraging behavior of honeybee swarms and has many advantages over earlier swarm intelligence algorithms. In this work, a new method based on ABC algorithm for designing two-channel quadrature mirror filter (QMF) banks with linear phase is presented. To satisfy the perfect reconstruction condition, low-pass prototype filter coefficients are optimized to minimize an objective function. The objective function is formulated as a weighted sum of four terms, pass-band error, and stop-band residual energy of low-pass analysis filter, square error of the overall transfer function at the quadrature frequency and amplitude distortion of the QMF bank. The design results of the proposed method are compared with earlier reported results of particle swarm optimization (PSO), differential-evolution (DE) and conventional optimization algorithms.

1. Introduction

The design of two-channel quadrature mirror filter (QMF) banks has been comprehensively studied in recent years [1–8]. Interest in efficient design of QMF banks is due to their significant applications in many engineering fields, such as analog to digital conversion [9], design of wavelet bases [10,11], image processing [12,13], digital trans-multiplexers [14], discrete multi-tone modulation systems [15], 2-D short-time spectral analysis [16], antenna systems [17,18], biomedical signal processing [19], wideband beamforming for sonar [20] and in wireless communication for noise cancellation [21].

Relevant previous state-of-the-art work on the design of linear phase two-channel QMF banks [1–8,22–29] can be classified into a number of different approaches. The least-squares [22–24] and weighted least-squares (WLS) [25–27] design methods had been applied previously. In [23,24], an eigenvector-eigenvalue approach was presented to find the optimum prototype filter tap weights in time domain. Chen and Lee [25] proposed a WLS method for QMF bank in frequency domain. This method uses a linearization technique to reformulate the highly nonlinear design problem into quadratic form and obtain optimized filter coefficients. Lu et al. [27] developed a method based on self convolution technique to reformulate a fourth order objective function as a quadratic function. But due to complex optimization techniques these methods are not suitable for higher order filter banks. Various iterative methods [6–8,28,29] have been applied for the design problem of two-channel QMF bank based on single objective or multi-objective, and constraint or unconstraint nonlinear optimization. Authors in [6] have developed an efficient technique by considering filter responses in transition band as well as in pass-band and stop-band regions. Reference [8] presented a modified field function method for the design of QMF bank by finding the global minimum of the non-convex optimization problem.

The conventional design methods may fail to achieve the optimal design for highly nonlinear and complex objective functions. Gradient based methods [6,26–29] may easily be trapped at local minima on search space and some methods [25,29] requiring intensive matrix inversion calculations therefore, not suitable for designing QMF bank in real-time. Consequently, nowadays researchers have been attempting the design methods for QMF bank based on modern global optimization algorithms. The authors in [30] applied a genetic algorithm for the design of multiplier-less lattice QMF. Neural networks [4], differential-evolution [3,31] and swarm intelligence [1,2] based approaches have been presented for the design of optimum QMF bank.

In recent years, swarm intelligence has become very popular among researchers for solving optimization problems from various engineering fields. The swarm intelligence models the population of interacting agents that are able to self-organize [32]. Typical examples are: an ant colony, an immune system, a flock of birds, fish schooling and bees swarming around their hive. Particle swarm optimization (PSO) algorithm has emerged as a powerful tool for solving non-linear equations in multi-dimensional space and it has been applied successfully for the design of two-channel

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QMF bank [2]. Rafi et al. [1] proposed an improved particle swarm optimization method for designing linear phase QMF banks. Ghosh et al. [3] presented an approach based on adaptive-differential-evolution algorithm for the design of two-channel QMF banks.

ABC algorithm is a newly introduced optimization algorithm for both constrained and unconstrained problems based on intelligent foraging behavior of honeybee swarms and has many advantages over earlier swarm intelligence algorithms [33]. The scout bee phase is a peculiar stage of ABC algorithm in comparison to PSO and DE algorithms that provides diversity in the population. In [34], Karaboga successfully applied ABC algorithm for design of digital IIR filters. The authors in [35] used ABC algorithm to design multiplierless nonuniform filter bank transmultiplexer.

In this paper, a novel method based on ABC algorithm is described for designing two-channel QMF bank. The results of proposed method are also compared with existing algorithms based on PSO, modified PSO and DE. The organization of rest of paper is as follows. Section 2 reviews the design problem of QMF bank based on Marquardt optimization method presented in [6]. Section 3 describes the ABC algorithm and modified ABC algorithm. Section 4 presents ABC algorithm based design of prototype filter for QMF bank. Section 5 discusses the design results of the filter bank and comparison with already existing methods. Finally, conclusions are drawn in Section 6.

2. Design of nearly perfect reconstruction QMF bank

Fig. 1 shows a typical two-channel QMF bank. The reconstructed signal $\hat{x}(n)$ suffers from three types of errors: aliasing distortion (ALD), phase distortion (PHD), and amplitude distortion (AMD). ALD can be canceled totally by selecting the synthesis filters adroitly in terms of the analysis filters and PHD eliminated by using the linear phase finite impulse response (FIR) filters [36,37]. The overall transfer function of such an alias and phase distortion free system turns out to be a function of the filter tap weights of the low-pass analysis filter only and is given by the following equation [6,36]:

$$T_0(z) = \frac{1}{2}\left[H_0^2(z) - H_0^2(-z)\right] \quad (1)$$

where, the synthesis filters are defined in terms of analysis filters to eliminate the ALD as follows:

$$F_0(z) = H_1(-z) \text{ and } F_1(z) = -H_0(-z) \quad (2)$$

Let the prototype low-pass filter $H_0(z)$ has linear phase, then from Eq. (1), the filter bank transfer function $T_0(z)$ also has linear phase and PHD of QMF bank is eliminated. Impulse response $h_0[n]$ of the prototype filter $H_0(z)$ should be symmetric $h_0[n]=h_0[N-1-n]$, $0 \le n \le N-1$, where N is the filter length, to satisfy the linear phase FIR constraint [36]. The discrete-time Fourier transform of $h_0[n]$ is given by the following equation:

$$H_0(e^{j\omega}) = A(\omega)e^{-j\omega(N-1)/2} \quad (3)$$

where

$$A(\omega) = \left[\sum_{n=0}^{(N/2-1)} 2h_0(n)\cos\omega\left(\frac{(N-1)}{2} - n\right)\right]$$

is the zero phase frequency response of $H_0(e^{j\omega})$ and the term $e^{-j\omega(N-1)/2}$ represents the linear phase. Substituting Eq. (3) into Eq. (1) yields the two-channel QMF bank frequency response as follows:

$$T_0\left(e^{j\omega}\right) = \frac{1}{2}(e^{-j\omega(N-1)})[|H_0(e^{j\omega})|^2 - (-1)^{(N-1)}|H_0(e^{j(\omega-\pi)})|^2] \quad (4)$$

As for odd N, $T_0(e^{j\omega})=0$ at $\omega=\pi/2$, resulting in a severe AMD at the quadrature frequency. Filter length N must be chosen to be even. Consequently, from Eq. (4), the condition of exact reconstruction (ER) can be defined as follows:

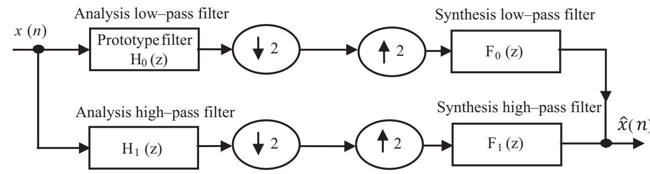

Fig. 1. The 2-channel quadrature mirror filter bank.

$$|T_0(\omega)| = |A(\omega)|^2 + |A(\pi-\omega)|^2 = c, \quad 0 \le \omega \le \pi. \quad (5)$$

The $H_0(z)$ was selected as FIR, then AMD can only be minimized after eliminating ALD and PHD completely, due to mirror image symmetry constraint $H_1(z)=H_0(-z)$ [37].

To minimize the amplitude distortion by optimizing filter tap weights of $H_0(z)$, several objective functions or error criterions have been proposed. Jain-Crochiere [23] had formulated the following objective function:

$$E_{C1} = E_r + \alpha E_{sb} \quad (6)$$

where E_r is the ripple energy and E_{sb} is the stop band residual energy of $H_0(z)$. Sahu et al. [6] proposed an objective function for the design of two-channel QMF bank which was a linear combination of pass band error, stop band residual energy of the low pass prototype filter, and the square error of the QMF bank transfer function at quadrature frequency.

$$E_{C2} = \alpha_1 E_p + \alpha_2 E_s + \beta E_t \quad (7)$$

where E_p and E_s are the measure of pass-band error and stop-band residual energy, respectively, of the prototype filter, and E_t is square error of the filter bank transfer function at $\omega=\pi/2$, α_1, α_2 and β are the real constants. Rafi et al. [1] presented an improved PSO method in frequency domain for the design of QMF bank with following error criterion:

$$E_{C3} = E_t + \alpha E_p + (1-\alpha)E_s \quad (8)$$

where E_p, E_s, and E_t are the errors in pass band, stop band and transition band, respectively, and α is a constant. In [2] Upendar et al. have taken the following error measure to design the two-channel QMF bank:

$$E_{C4} = \alpha_1 E_p + \alpha_2 E_s + \alpha_3 E_t + \alpha_4 mor \quad (9)$$

where α_1, α_2, α_3 and α_4 are the relative weights and E_p, E_s, E_t, and *mor* are the mean square error in pass-band, mean square error in stop band, square error of the filter bank transfer function at $\omega=\pi/2$ and measure of ripple, respectively.

In this paper, to design the low-pass prototype filter $H_0(z)$, a new term E_{MD} (magnitude distortion) is incorporated into the objective function formulated in [6], that improves the overall filter bank response. The modified objective function is expressed as follows:

$$E_{C5} = \alpha_1 E_p + \alpha_2 E_s + \alpha_3 E_t + \alpha_4 . E_{MD} \quad (10)$$

where α_1, α_2, α_3 and α_4 are the relative weights and E_p, E_s, E_t and E_{MD} are defined as follows:

$$E_p = \int_0^{\omega_p} [A(0) - A(\omega)]^2 \frac{d\omega}{\pi} \quad (11)$$

$$E_s = \int_{\omega_s}^{\pi} [A(\omega)]^2 \frac{d\omega}{\pi} \quad (12)$$

$$E_t = \left[A\left(\frac{\pi}{2}\right) - (1/2)^{1/2}A(0)\right]^2 \quad (13)$$