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ISA Transactions ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Design of two-channel filter bank using nature inspired optimization based fractional derivative constraints

B. Kuldeep [a], V.K. Singh [a], A. Kumar [a,*], G.K. Singh [b,1]

[a] PDPM-Indian Institute of Information Technology Design and Manufacturing, Jabalpur 482005, India
[b] Indian Institute of Technology Roorkee, Roorkee 247667, India

ARTICLE INFO

Article history:
Received 28 January 2014
Received in revised form
23 May 2014
Accepted 14 June 2014
This paper was recommended for publication by Dr. Y. Chen

Keywords:
QMF bank
Multi-rate filter bank
Cuckoo search
WDO
ABC
PSO
Fractional derivative

ABSTRACT

In this article, a novel approach for 2-channel linear phase quadrature mirror filter (QMF) bank design based on a hybrid of gradient based optimization and optimization of fractional derivative constraints is introduced. For the purpose of this work, recently proposed nature inspired optimization techniques such as cuckoo search (CS), modified cuckoo search (MCS) and wind driven optimization (WDO) are explored for the design of QMF bank. 2-Channel QMF is also designed with particle swarm optimization (PSO) and artificial bee colony (ABC) nature inspired optimization techniques. The design problem is formulated in frequency domain as sum of L_2 norm of error in passband, stopband and transition band at quadrature frequency. The contribution of this work is the novel hybrid combination of gradient based optimization (Lagrange multiplier method) and nature inspired optimization (CS, MCS, WDO, PSO and ABC) and its usage for optimizing the design problem. Performance of the proposed method is evaluated by passband error (ϕ_p), stopband error (ϕ_s), transition band error (ϕ_t), peak reconstruction error (PRE), stopband attenuation (A_s) and computational time. The design examples illustrate the ingenuity of the proposed method. Results are also compared with the other existing algorithms, and it was found that the proposed method gives best result in terms of peak reconstruction error and transition band error while it is comparable in terms of passband and stopband error. Results show that the proposed method is successful for both lower and higher order 2-channel QMF bank design. A comparative study of various nature inspired optimization techniques is also presented, and the study singles out CS as a best QMF optimization technique.

1. Introduction

Fractional derivative is a branch of fractional calculus. The fundamental definition of fractional derivative is very much similar to conventional definition of derivative. The only basic difference is that the integer order of derivative is replaced by the fractional order that means, in fractional derivative case, order becomes more generalized. The idea of fractional derivative is very old from mathematical point of view; but in terms of application, it is very new and novel concept. Recently, fractional derivative has been exploited in various field of signal processing such as image sharpening [1], estimation of noise and de-nosing [2], estimation of blur in moving image [3], image contrast enhancement [4], design of flexible RL and RC circuits [5], design of differentiator and fixed fractional delay FIR filter design [6]. Recently, fractional derivative has been exploited in the field of linear phase FIR filter design which is a basic building block of multi-rate filter banks [7].

Multi-rate filter bank plays a pivotal role in signal processing applications such as image processing [25], data compression [11], communication systems, security systems [26], design of wavelet bases [27] etc. The wide area of applications inspires signal processing researchers to enhance the performance of multi-rate filter bank. The basic operation of multi-rate filter bank is sub-banding. The multi-rate filter banks divide the signal into different frequency sub-bands then particular operations are performed on each sub-band and then all these sub-bands are combined to get the original signal. 2-Channel QMF bank is the smallest unit of any multi-rate filter bank. Firstly, 2-channel QMF bank was implemented on speech to eliminate the aliasing distortion during sub-band coding. The working of 2-channel QMF bank is divided into two parts: first, analysis of signal; and second, synthesis of signal. Analysis of signal is performed in analysis section of 2-channel QMF bank, in which input signal $x(n)$ is splitted into two overlapping sub-bands using low-pass and high-pass analysis filters $H_0(z)$ and $H_1(z)$.After performing the desired operation, synthesis

* Corresponding author.
E-mail addresses: kuldeep_gec2000@yahoo.co.in (B. Kuldeep), viiitdmj@gmail.com (V.K. Singh), anilkdee@gmail.com (A. Kumar), gksngfee@iitr.ernet.in (G.K. Singh).
[1] Present address: Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.

http://dx.doi.org/10.1016/j.isatra.2014.06.005
0019-0578/

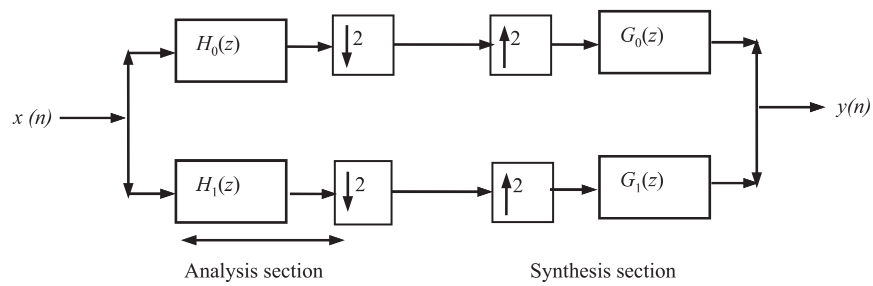

Fig. 1. Quadrature mirror filter bank.

section synthesizes the original signal using synthesis filters $G_0(z)$ and $G_1(z)$.The fundamental block diagram of 2-channel QMF bank is shown in Fig. 1.

There are various optimization methods which have been used for optimizing the design of 2-channel QMF bank. These optimization methods can be divided into gradient based and nature inspired optimization methods. Recently, a number of gradient based methods have been proposed in the field of QMF banks design such as the weighted least square method (WLS) [8], Levenberg–Marquardt algorithm (LM), Quasi-Newton method [9–12] etc. A new WLS technique for designing FIR filter, based on neural network, has been developed by Y.D. Jou, F.K. Chen in [8]. Another approach for design 2-channel QMF bank using Marquardt optimization method is given in [9]. Design methodology was further modified using Quasi-Newton (QN) [10] and Levenberg–Marquardt (LM) method [11]. Recently, authors in [12] have used hybrid form of Levenberg–Marquardt (LM) and Quasi-Newton (QN) optimization methods for effective design of 2-channel QMF bank.

Nature inspired optimization methods have attracted many researchers during the last decade. Nature inspired optimization methods are basically motivated by natural phenomena such as biological process: reproduction, mutation and interaction; social behavior: flock of birds, schooling of fish and intelligence of swarm of bee. Recently, nature inspired optimization methods such as genetic algorithms [13], particle swarm optimization (PSO) and its different variants [14,15], artificial bee colony (ABC) algorithm [15] and adaptive differential evolution (ADE) algorithm [16] have been implemented in the field of QMF bank design. In [13], a signed powers-of-two coefficient perfect reconstruction QMF bank using CORDIC genetic algorithm, which is based on coordinate rotation, is designed. In [14], a QMF bank design by PSO with nonlinear unconstraint optimization is given. QMF design was further improved by modified PSO in [15]. In [15], modification is done by hybridization of PSO with Scout Bee form of the artificial bee colony (ABC) algorithm. In [16], QMF design was further enhanced using the adaptive differential evolution (ADE) algorithm.

It is evident from the above recent literature review that there are numerous optimization methods, which have been exploited in the field of QMF filter design. Recently, Cuckoo Search (CS) [17], its modified version called Modified Cuckoo Search (MCS) [18,19] and wind driven optimization (WDO) [20] are some of the nature inspired optimization techniques that have been proved as a powerful optimization tool for linear and nonlinear function. CS, MCS and WDO have been implemented in various fields of engineering and science [17,19,20] but in the field of QMF bank design, there is no or very less application of CS, MCS and WDO at present. So, it will be interesting to investigate the combined effect of nature inspired optimization (CS, MCS and WDO) and gradient based optimization (Lagrange multiplier method) on 2-channel QMF bank design.

This paper, therefore, presents a hybrid method for QMF bank design optimization. In this work, firstly, design problem formulation is carried out using fractional derivative constraints in which constraints are optimized using the nature inspired optimization method (CS, MCS, WDO, PSO and ABC). In the last, whole problem is optimized using gradient based optimization (Lagrange multiplier method). In the next section, mathematical definition of fractional derivative is presented. In Section 3, a brief review on nature inspired optimization techniques CS, MCS, PSO, ABC and WDO is given. Section 4 covers the overview of two-channel QMF bank. Section 5 explains the design problem formulation and hybrid algorithms for 2-channel QMF design. In Section 6, results obtained by the proposed design method are discussed. Finally, conclusions and future scope are made in Section 7.

2. Fractional derivative

Fractional derivative is a branch of fractional calculus in mathematics. In fractional derivative, order of derivative becomes fractional. There are various definitions of fractional derivatives which have been introduced by mathematicians. The most accepted and popular definitions of fractional derivatives are the Riemann–Liouville, M. Caputo, and Grunwald–Letnikov definition. The definition of fractional derivative given by

Riemann–Liouville is as follows:

$$_aD_x^u f(x) = \frac{1}{\Gamma(k-u)}\left(\frac{d}{dx}\right)^k \int_a^x \frac{f(\tau)d\tau}{(x-\tau)^{u-k+1}} \tag{1}$$

where, $(k-1) \le u < k$, a is the initial limit of integral, u is the real number called fractional derivative constraint co-efficient, and k is an integer.

Caputo redeveloped the definition of Riemann–Liouville fractional derivative so that use of integer order initial conditions is possible for solving the fractional order differential equations. Definition given by M. Caputo is as follows:

$$_aD_x^u f(t) = \frac{1}{\Gamma(u-k)}\int_a^x \frac{f^k(\tau)d\tau}{(x-\tau)^{u-n+1}} \tag{2}$$

Finally, definition given by Grunwald–Letnikov is as follows:

$$D_x^u f(x) = \frac{(d^u f(x))}{(dx^u)} = \lim_{\Delta=0}\sum_{k=0}^{\infty}\frac{(-1)^k C_k^u}{\Delta^u} f(x-k\Delta) \tag{3}$$

where, C_k^u is given by

$$C_k^u = \frac{\Gamma(u+1)}{\Gamma(k+1)\Gamma(u-k+1)} = \begin{cases} 1 & k=0 \\ \frac{u(u-1)(u-2)\ldots(u-k+1)}{1,2,3\ldots k} & k\ge 1 \end{cases} \tag{4}$$

and $\Gamma(\cdot)$ is the gamma function.

In the first two definitions, due to the use of integration, calculation of fractional derivative is more complicated with respect to Grunwald–Letnikov's definition. Summation form of Grunwald–Letnikov fractional derivative reduces the extra calculations and complexity. Because of inherent low complexity as compared to other definitions, in this paper, Grunwald–Letnikov's

Please cite this article as: Kuldeep B, et al. Design of two-channel filter bank using nature inspired optimization based fractional derivative constraints. ISA Transactions (2014), http://dx.doi.org/10.1016/j.isatra.2014.06.005