International Journal of Automation and Computing
14(5), October 2017, 589-602
DOI: 10.1007/s11633-017-1091-x

High Order Stable Infinite Impulse Response Filter Design Using Cuckoo Search Algorithm

N. Agrawal[1] A. Kumar[1,2] V. Bajaj[1] G. K. Singh[3]

[1]Department of Electronics and Communication Engineering, the Pandit Dwarka Prasad Mishra, Indian Institute of Information Technology, Design and Manufacturing, Dumna 482005, India

[2]School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology, Korea

[3]Department of Electrical Engineering, Indian Institute of Technology, Roorkee 247667, India

Abstract: In this paper, an efficient technique for optimal design of digital infinite impulse response (IIR) filter with minimum passband error (e_p), minimum stopband error (e_s), high stopband attenuation (A_s), and also free from limit cycle effect is proposed using cuckoo search (CS) algorithm. In the proposed method, error function, which is multi-model and non-differentiable in the heuristic surface, is constructed as the mean squared difference between the designed and desired response in frequency domain, and is optimized using CS algorithm. Computational efficiency of the proposed technique for exploration in search space is examined, and during exploration, stability of filter is maintained by considering lattice representation of the denominator polynomials, which requires less computational complexity as well as it improves the exploration ability in search space for designing higher filter taps. A comparative study of the proposed method with other algorithms is made, and the obtained results show that 90% reduction in errors is achieved using the proposed method. However, computational complexity in term of CPU time is increased as compared to other existing algorithms.

Keywords: Cuckoo search algorithm, infinite impulse response (IIR), means square error (MSE), evolutionary algorithm, stability.

1 Introduction

In modern engineering, digital infinite impulse response (IIR) filters are extensively used in numerous signal processing applications such as biomedical signal filtering[1, 2], adaptive filtering[3], linear filtering, and system identification[4] due to their simplified design and low memory requirement. Therefore, several algorithms have been devised and exploited in various applications[5−7]. However, they were not efficient as the design problem formulated through these algorithms was multi-model and non-differentiable. In addition, the filter designed using conventional methods suffers from inefficiency, quantization error, ignorance of phase response, and has no control on transition width[8, 9].

During the last decade, a marked progress for the development of evolutionary algorithms such as genetic algorithm (GA), ant colony optimization (ACO), particles swarm optimization (PSO), and artificial bee colony (ABC) algorithm has been made for various engineering and science applications due to their better exploration capability to determine the solution of nonlinear multi-model, and non-differentiable problems[10, 11]. Therefore, researchers have used swarm based techniques for adaptive filtering[12, 13], satellite image processing[14, 15], multi-rate signal processing[16−18], fault diagnosis of nonlinear system[19], whereas authors in [20−27] have employed these algorithms for designing digital filters. The researchers in [8, 9, 24, 28, 29] have used the GA for designing IIR filters. However, GA suffers from problem of getting trapped in local minima during exploration, and the solution is also highly dependent on the initial guess. Therefore, PSO and different variants have been proposed and used for designing IIR filters due to their improved computation time and better capability of exploration[27, 30, 31]. A hybrid method based on PSO and ABC algorithms was proposed and exploited for designing multirate filter bank in [32], and has been further extended for the design of IIR filters[33].

Recently, several new techniques have been proposed and exploited to improve the design accuracy of IIR filters using evolutionary techniques[34−37]. In all such methods, a mathematical function was constructed that was either minimized or maximized depending on the problem formulation of digital filters using different design objectives such as minimization of mean squared error (MSE) or minimization of passband ripple (δ_p) and stopband ripple (δ_s). In digital IIR filter design, stability is a major requirement, which is assured by decomposing the transfer function into first and second order transfer function. Then, the values of coefficients of these low order transfer functions are kept in a prescribed range[8, 9]. This approach is extensively preferred, but it requires complex design structure, and hence not suitable for higher order filter design. A new meta-heuristic technique, known as cuckoo search (CS) al-

Research Article
Manuscript received May 25, 2016; accepted April 19, 2017; published online June 29, 2017
Recommended by Associate Editor Victor Becerra

gorithm has been proposed with immense exploitation abilities than previously developed techniques[38, 39]. Therefore, CS algorithm has been extensively applied in various signals processing optimization problems[13−15, 18]. Kumar and Rawat[40] have proposed a new scheme for designing fractional delay all pass filter using CS algorithm. In this method, phase error has been optimized. While in [41], authors have designed adaptive IIR filter using system identification based on CS algorithm. This algorithm yields good performance for smaller filter taps. CS algorithm is highly dependent on tuning parameters, whose effect has not been considered for IIR filter design.

Only few references are available for digital filters design, especially for finite impulse response (FIR) filter. Therefore, there is a strong need to develop an efficient technique for designing IIR filter based on CS algorithm with more design accuracy.

In above context, this paper presents an improved technique for designing digital IIR filters, which are free from limit cycle effect, and efficient in terms of improved response in passband and stopband region. The rest of the paper is organized as follows. Section 1 contains a brief introduction of IIR filters designing and its challenges. Section 2 contains an overview of CS algorithm. In Section 3, detail of digital IIR filter designing is given, whereas problem formulation along with stability constraints is described in Section 4. Section 5 contains the results and comparison of proposed technique with PSO and its variant. Finally, concluding remarks are included in Section 6.

2 Overview of CS algorithm

The evolutionary techniques are the modern population (search space) based randomly guided multi-dimensional search methods. GA, PSO, ABC algorithm, and such other methods belong to this class of evolutionary computation. In literature, complete mathematical description along with their application has been reported and may be formulated according to the requirement[42−45].

Cuckoo search algorithm was motivated from the behavior of offspring parasitism of some cuckoo species, and was improved by introducing Lévy flights algorithm in nest exploration instead of simple walk[46].

Lévy flights. In nature, animals move for the search of food in a random or quasi-random style. Lévy is a name of French mathematician who developed a mathematical representation of random walk, according to which the step-length or step size follows a probability distribution that is heavy-tailed. This concept of Lévy flights is utilized for searching a nest to lay an egg in CS algorithm[39, 46].

Cuckoo search implementation. In CS algorithm, each egg in a nest symbolizes a possible result, and a cuckoo egg symbolizes a newly generated result. The task is to pay more weightage to newly generated and possibly better solution (Cuckoos) to substitute poor solution in the nests[39, 46]. CS algorithm is based on three venerated rules:

1) Each cuckoo produces one egg at a time, and dumps it in a randomly chosen nest.

2) The best nests with high quality of eggs (solutions) will carry over to the next generations.

3) The number of available host nests is fixed, and a host can discover an alien egg with probability $P_\alpha \in |0, 1|$.

2.1 CS algorithm formulation

CS algorithm formulation consists of four stages as discussed below[39, 46]:

Stage 1. (Solution initialization)

$$n_i = ul_i + rand_i[0\ 1] \times (ul_i - ll_i) \tag{1}$$

where $i = 1, 2, 3, \cdots, size$, ul_i and ll_i, are the upper and lower limits for the "n" (search space matrix). Each solution (n) is assigned with uniformly distributed and randomly generated value in "D" space vector, "i" is the index, corresponding to the vector in search space and used for the computation of objective/cost function.

Stage 2. (Modification of search space)

$$nn_i = n_i + \alpha \oplus L\acute{e}vy(\lambda). \tag{2}$$

In (2), nn_i represents the new solution formulated as the dropping of an egg by the cuckoo bird in a random fashion. Lévy flight is used to represent travelling pattern of the bird, because of its dynamic step length. In walk, the random step length is drawn from Lévy distribution evaluated as[39, 46]

$$L\acute{e}vy \backsim u = t^{-\lambda}(1 < \lambda < 3). \tag{3}$$

This phenomenon is analogous to the cuckoo bird, which tries to drop their new eggs in different nests. The detailed study is presented in [39, 46].

Stage 3. (Sorting of best solution)

Evaluation of the fitness function (evaluation of error in case of minimization) is performed from the modified search space, and the new solutions (nn_i) which possess improved fitness are accepted over the previous solutions (n_i) as shown below[46]:

$$n_i = \begin{cases} nn_i, & fitness(nn_i) > fitness(n_i) \\ n_i, & fitness(nn_i) \le fitness(n_i). \end{cases} \tag{4}$$

After this, the solution from the updated search space which has highest fitness is sorted as the best solution, and entitled as "*Bestnest*"

$$Best\,value = \max[fitness(n_i)] \tag{5}$$

$$Best\,sol = n_k, \quad k \in (1\,\text{size}) \tag{6}$$

where n_k is that solution for which maximum fitness is measured amongst the other solution of search space.

Stage 4. (Exploration of poor solution (nest) using random walk)

If an egg is discovered in the nest by the host bird, then it is considered as a worst solution and assumed to be discarded. The mechanism of identification of an egg by host