Efficient Design of Half-Band IIR Filter using Polyphase Structure

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ABSTRACT

In this paper, the half-band IIR filter is designed as a polyphase structure of all-pass sub-filters. The proposed design method provides desirable properties of the half-band IIR filter to achieve the efficient design. The complexity of the designed filter is considered in terms of number of adders. In order to keep the complexity of the design method as low as possible, we are neglecting the less sensitive coefficients of the designed filter such that there is a trade-off between efficiency and complexity. Simulation results reveals that the proposed method provides a half-band filter with less complexity and smaller filter order. The results affirm that with the removal of less sensitive coefficient, the designed half-band filter approaches the ideal half-band filter.

Keywords: *Half-Band Filter, Infinite-Impulse Response (IIR) Filter, Polyphase Structure.*

I. INTRODUCTION

From the past few decades, a number of different digital filter transfer functions and certain special filter structures have been developed for decimation and interpolation, which is used for the poly phase structure design [1] [2]. These designs include both one-stage and multistage finite impulse response (FIR) filters and infinite impulse response (IIR) filters.

Digital filters [3] can be classified into two major classes, finite impulse response (FIR) filters and infinite impulse response (IIR) filters. Both types of filters have their own characteristics. However, FIR filters are often preferred due to their stability, better phase characteristics, and more flexible implementation capabilities. However, these filters requiring a higher order for the same specification compared with its recursive correspondence, the Infinite Impulse Response (IIR) filter. The design methods of digital integrator generally can be classified into two categories.

To reduce the hardware demands in the IIR filter, the state-of-the-art works focus on filter coefficients and their implementation as a sum of integer powers of two. This allows the coefficients to be implemented using the shifters and adders/subtractors, avoiding multipliers. Since shifts can be simply implemented by rewiring the individual bits of a binary word, they do not incur any additional hardware. The adders represent the majority of the hardware that is needed to construct the filter; therefore, reducing the number of adders is a good system-level optimization to achieve both high hardware and power efficiency in the application-specific integrated circuit implementation. Thus, the complexity of the filter in the state-of-the-art works, such as in [4]-[6], is judged by counting the number of adders that is needed to implement the coefficients.

In this paper, the half-band IIR filter is designed as a polyphase structure of all-pass sub-filters. The proposed design method provides desirable properties of the half-band IIR filter to achieve the efficient design. The complexity of the designed filter is considered in terms of number of adders. In order to keep the complexity of the design method as low as possible, we are neglecting the less sensitive coefficients of the designed filter such that there is a trade-off between efficiency and complexity.

The rest of the paper is organized as follows: In section II, explain the polyphase design of the half band infinite impulse response of the system. Two stage polyphase structures is implemented such that the adder required for the implementation of the half band filter is less compares to other approaches. In Section III, explain the filter design example of IIR half band filter. In Section V, experimental results are presented to analysis the performance of the designed half band filter. Finally, a conclusion is made.

II. POLYPHASE STRUCTURE BASED DESIGN

Overall transfer function of Nth-band recursive filter,

$$T(z) = \sum_{i=0}^{N-1} z^{-i} H_i(z^{-N}) \qquad (1)$$

where, $T_i(z^{-N})$ is cascade of elementary all-pass sub-filters $A_k^{(i)}(z^{-N})$ i.e.

$$T_i(z^{-N}) = \prod_{k=1}^{Ki} A_k^{(i)}(z^{-N}) \qquad (2)$$

Where,

$$A_k^{(i)}(z^{-N}) = (c_k^{(i)} + z^{-N})/(1 + c_k^{(i)} z^{-N}) \qquad (3)$$

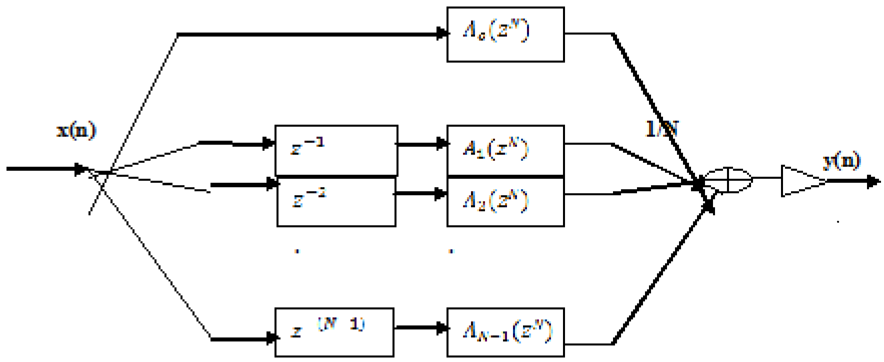

Fig.1. Polyphase Structure

Substituting Eq. (2), (3) into Eq. (1), we get the Overall transfer function of Nth-band recursive filter,

$$T(z) = \sum_{i=0}^{N-1} z^{-i} \prod_{k=1}^{Ki} \frac{c_k^{(i)} + z^{-N}}{1 + c_k^{(i)} z^{-N}} \qquad (4)$$

Overall transfer function of Half-band recursive filter (i.e. N=2),

$$T(z) = \sum_{i=0}^{1} z^{-i} \prod_{k=1}^{Ki} \frac{c_k^{(i)} + z^{-2}}{1 + c_k^{(i)} z^{-2}} \qquad (5)$$

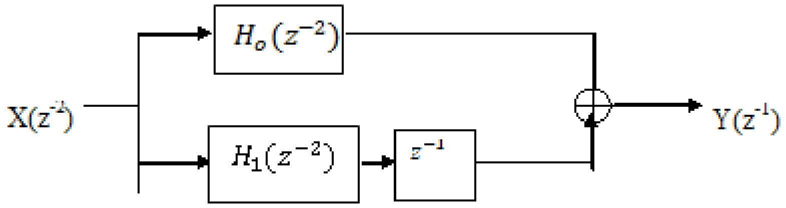

Fig. 2. IIR filter using a Parallel Connection of Two All-Pass Sub-Filters $T_0(z^{-2})$ and $T_1(z^{-2})$.

where, K_i are the number of the all-pass sub-filters that are used in each branch of the filter

$$T(z) = \prod_{k=1}^{K0} \frac{c_k^{(0)} + z^{-2}}{1 + c_k^{(0)} z^{-2}} + z^{-1} \prod_{k=1}^{K1} \frac{c_k^{(1)} + z^{-2}}{1 + c_k^{(1)} z^{-2}} \quad (6)$$

$$T(z) = T_0(z^{-2}) + z^{-1} T_1(z^{-2}) \quad (7)$$

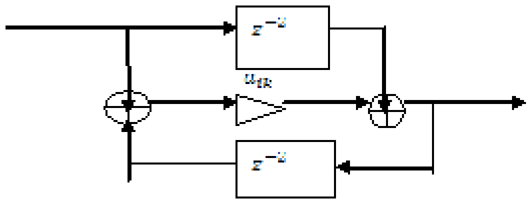

Fig. 3. Second-Order All-Pass Sub-Filter Running at $2f_{s,\,in}$.

Let K_0=3 and K_1=3

$$T(z) = \prod_{k=1}^{3} \frac{c_k^{(0)} + z^{-2}}{1 + c_k^{(0)} z^{-2}} + z^{-1} \prod_{k=1}^{3} \frac{c_k^{(1)} + z^{-2}}{1 + c_k^{(1)} z^{-2}}$$

Each of the branch filters, i.e., $T_0(z^{-2})$ and $T_1(z^{-2})$, in Fig. 2. are constructed using one or more second-order all-pass sub-filters as given in Fig.3., effectively resulting in a half-band IIR filter [3].

III. FILTER DESIGN EXAMPLES

The largest of all the coefficients ($c_3^{(0)}$) in this case) corresponds to the pole that is closest to the unity circle in the z-domain and is most sensitive to quantization [6] and is likely to incur the largest number of adders. In Fig. 4, it can be seen that the IIR filter transfer function shows the most substantial change when coefficient $c_3^{(0)}$is neglected and the smallest change when coefficient$c_1^{(1)}$ is neglected.

A detailed study of coefficient sensitivity and the use of all-pass sub-filters that are more resistant to coefficient quantization can be found in [5]. The transfer function is most sensitive to the change of the coefficient corresponding to the pole that is closest to the unity circle in the z-domain. In Fig. 5, shows the transfer function of the IIR filter for the set of coefficient obtain in step 1, 3 and 4 in [1]. The result indicates the reduction in the complexity of the system parameter with the neglecting the insensitive parameters.

In many hardware or VLSI implementations, it is attractive to carry out the multiplication of a data sample by a filter coefficient value using a sequence of shifts and adds and/or subtracts. For such a purpose, it is desired to express the coefficient values in the form

$$\sum_{r=1}^{R} a^r 2^{-Pr}$$

where each a_r is either 1 or −1 and the P_r's are nonnegative integers in the increasing order. The goal is to find all the coefficient values so that:

1) R (the number of powers-of-two terms) is made as small as possible and
2) P_R (the maximum number of shifts) is made as small as possible.

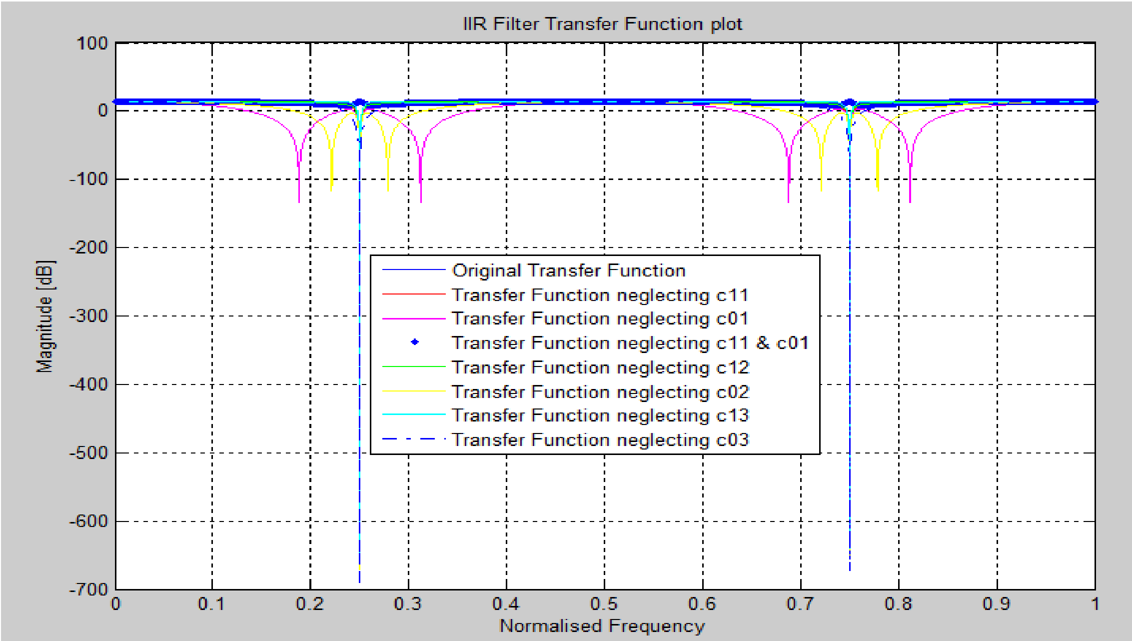

Fig. 4. IIR Filter Transfer Function Sensitivity to Coefficient Changes

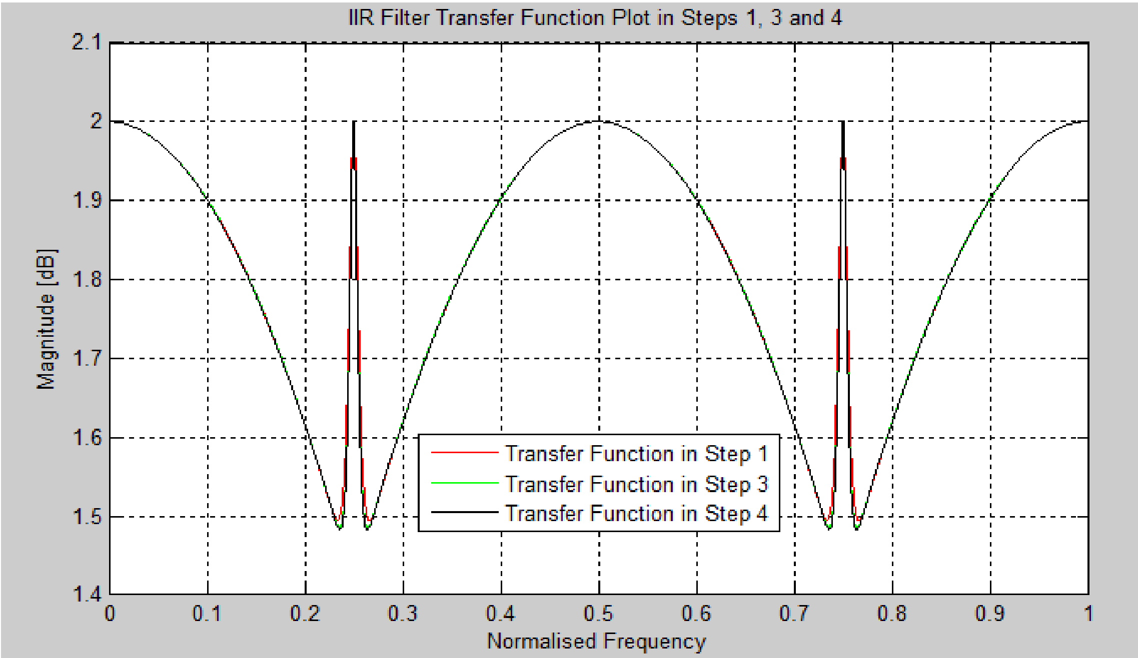

Fig. 5. IIR Filter Transfer Function Plot in Steps 1, 3, and 4.

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IV. CONCLUSION

A simple optimization method is presented for a half-band IIR filter in order to obtain a low hardware complexity of the filter, which is measured in terms of the number of adders. The complexity of the resulting IIR filter is evaluated by counting all the adders in the filter. The proposed method results in hardware complexities on par with the state-of-the-art filter examples that are designed using more computationally intensive methods.

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