Design of Modified Three Stage Sharpened CIC Filter for Decimation

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ABSTRACT: This paper presents the design of Sharpened three stage CIC filter for decimation. The proposed decimation filter has Cascaded-Integrator Comb filter as first stage, Sharpened Cascaded-Integrator Comb filter as second and third stage. The CIC filter at first stage operates at input sampling rate, sharpened second stage operates at lower rate as compared to first stage and sharpened third stage operates at lower rate as compared to first as well as second stage. The sharpened second and third stage leads to improvement in pass-band droop and better stop-band alias rejection. Further the reduction of sampling rate at each stage provides many additional benefits like better power efficiency, reduced hardware requirements, reduced cost and better speed. The proposed filter is designed and simulated in MATLAB-Simulink environment. The simulation results and their comparison shows that the proposed decimation filter has improved pass-band droop and better stop-band alias rejection than the existing structures.

KEYWORDS: Digital filters; DDC; digital down converter; CIC; Cascaded-Integrator Comb; SCIC; decimation filter; sharpened decimation filter; decimator; cascaded integrated comb; Filter sharpening; Matlab; Simulink; Xilinx System Generator.

I. INTRODUCTION

In today's world, digital communication is very much popular because of widely used digital representation of signals. In many modern digital systems, signals of different sampling rates have to be processed at the same time and such systems are commonly known as multirate system. In these multirate systems, we continuously need to convert the sampling rate of the given signal into signal with desired sampling rate. For this purpose, decimators and interpolators are used to decrease and increase the sampling rate of the given signal respectively. But the decimation process leads to aliasing and imaging errors [1]. Therefore there is a need of anti-aliasing filter, through which signal must be processed before starting the decimation process [1] and this complete structure is commonly known as decimation filter.

In 1981, Hogenauer [2] introduced the CIC filter structure for economical design of decimation filters. This class of filters require neither multipliers nor storage elements to store filter coefficients and therefore uses less resources as compared to other available filter structures which leads to economical hardware. The basic building blocks of a CIC filter are an integrator and a comb section. Thus CIC filters are best suitable for the applications which aim at low power consumption, low cost and lower hardware complexity, but its pass-band is not flat which is its major disadvantage. The frequency response can be improved by multi-stage implementation approach [1]. Many filter sharpening techniques have been proposed by [3-12] to design CIC decimation filter with improved frequency response. The main motive of this paper is to design a Sharpened decimation filter with all the integrated advantages of existing techniques in order to achieve the better frequency response than the CIC based existing structures.

II. RELATED WORK

Hogenauer [2] introduced the CIC filter structure for economical design of decimation and interpolation filters. This class of filters require neither multipliers nor storage elements and therefore uses fewer resources as compared to other available filter structures. The basic building blocks of a CIC filter are an integrator and a comb section. The comb section consists of simplest low-pass finite-impulse response (FIR) filter which is M point moving-average filter with an impulse response.

$$h(n) = \begin{cases} \frac{1}{M}, & for\ 0 \le n \le M-1 \\ 0, & otherwise \end{cases} \text{eq.(1)}$$

Its transfer function is obtained by taking Z-transform of h(n)

$$H(z) = \frac{1}{M} \sum_{n=0}^{M-1} z^{-n} \text{eq. (2)}$$

The eq.(2) can also be represented as

$$H(z) = \frac{1}{M} \left[\frac{1-Z^{-M}}{1-Z^{-1}}\right] \text{eq.(3)}$$

In multistage implementation approach with K number of stages, the above transfer function can be represented as

$$H(z) = \frac{1}{M} \frac{(1-Z^{-M})^K}{(1-Z^{-1})^K} \text{eq.(4)}$$

Here M is the decimation factor. The frequency response of above filter is obtained by taking Fourier transform of eq. (4).

$$H(e^{j\omega}) = \frac{1}{M} \frac{\sin\left(\frac{\omega M}{2}\right)}{\sin\left(\frac{\omega}{2}\right)} * e^{-\frac{j\omega\,(M-1)}{2}} \text{eq.(5)}$$

Here $e^{-\frac{j\omega\,(M-1)}{2}}$ is phase shift parameter and it can be ignored. Therefore the response of CIC filter can be represented as

$$H(e^{j\omega}) = \frac{1}{M} \frac{\sin\left(\frac{\omega M}{2}\right)}{\sin\left(\frac{\omega}{2}\right)} \text{eq.(6)}$$

Theeq.(6) indicates that the frequency response of CIC filter will have linear-phase low-pass characteristics having pass-band droop dependent on the value of M & K and the aliasing occurred due to decimation is rejected by the CIC filter as the frequency response of eq. (6) will have nulls at integer multiples of $(1/M)F_s$.Here,$F_s$isinput sampling frequency rate. But the overall frequency response does not meet the design specification of various multirate systems.

Various sharpening techniques have been proposed to improve the frequency response of CIC filter [3-11]. Presti [4] introduced the CIC zero rotation and proposed the Rotated Sinc (RS) filter to increase the attenuations. But to improve the response of stop-band price has to be paid. It introduced the use of two multipliers in CIC structure, but this method did not provided any improvement in pass-band of the filter. Kwentus [5] proposed a new architecture that combines cascaded integrator comb filter structure with filter sharpening techniques to improve the filter's pass-band response. This architecture achieves better resource utilization over existing approaches because in this structure the first stage CIC decimation filter is followed by a fixed-coefficient second-stage filter rather than a programmable-coefficient filter. Further, this structure also improves the overall throughput rate.

Sharpening method by Kaiser and Hamming [12] gives the idea of filter sharpening by multistage use of the same filter. The method is based on idea of amplitude change function (ACF) that is restricted to symmetric FIR filter with constant pass band and stop band. G. J. Dolecek and S. K. Mitra [7-9] [11] proposed several schemes for designing sharpened CIC filter for decimation. The authors proposed the multistage design which consists of cascading of regular comb stages and sharpened comb stages. Instead of sharpening all the comb stages, sharpening technique is applied to the last stage which provided very good results. The main motive of this paper is to design a Sharpened decimation filter based on sharpening technique [12] with all the integrated advantages of existing scheme in order to achieve the better frequency response in pass-band as well as stop-band as compared to existing CIC structures for decimation.

III. SHARPENING TECHNIQUE USED

Kaiser and Hamming[11] proposed a method to sharpen the magnitude response of a digital filter by using multiple realizations of low-order basic filters. This filter sharpening technique is applied to CIC filters to reduce the pass-band droop and to improve stop-band attenuation in CIC filters. A family of sharpening filters Hnm(f) is given by

$$H_{nm}(f) = H^{n+1}(f) \sum_{k=0}^{m} \frac{(n+k)!}{n!k!} [1-H(f)]^k \text{eq. (7)}$$

Here, H(f) is the transfer function of low-order basic filter. By choosing integers n and m, we select order of tangency at frequencies where $H_{11}(f) = 0$ and $H_{11}(f) = 1$. Choosing n=m = 1

$$H_{11}(f) = H^{1+1}(f) \sum_{k=0}^{1} \frac{(1+k)!}{1!k!} [1 - H(f)]^k \text{ eq. (8)}$$

After mathematical simplifications eq. (8) can be rewritten as

$$H_{11}(f) = H^2(f) \{3 - 2 H(f)\} \text{eq.(9)}$$

Assuming the group delay of H(z) to be D samples, where $D = \left(\frac{M-1}{2}\right) * K$

$$H_{11}(z) = H(z)^2 \{3 Z^{-D} - 2 H(z)\} \text{eq.(10)}$$

Here the term Z^{-D} is introduced to make the group delays uniform. The sharpened CIC filter is obtained by replacing the transfer function of basic filter H(z) in eq. (10) with the transfer function of CIC filter given by eq.(4).So, after replacing, the transfer function of sharpened CIC filter is given by eq.(11).

$$H_{SCIC}(z) = \left[\frac{1}{M}\frac{(1-Z^{-M})}{(1-Z^{-1})}\right]^{2K} \left[3 Z^{-D} - 2\left[\frac{1}{M}\frac{(1-Z^{-M})}{(1-Z^{-1})}\right]^{K}\right] \text{eq.(11)}$$

Now the frequency response of SCIC filter can be obtained from eq. (11) by using eq.(6)

$$H_{SCIC}(e^{j\omega}) = 3\left[\frac{1}{M}\frac{sin\left(\frac{\omega M}{2}\right)}{sin\left(\frac{\omega}{2}\right)}\right]^{2K} - 2\left[\frac{1}{M}\frac{sin\left(\frac{\omega M}{2}\right)}{sin\left(\frac{\omega}{2}\right)}\right]^{3K} \text{eq.(12)}$$

The block diagram of the 2nd order (k=2) SCIC filter given by eq. (12)is shown in Fig. 1. It can be observed that the implementation of SCIC filter requires three identical CIC filters, two multipliers of values -2 & 3 respectively and an adder.
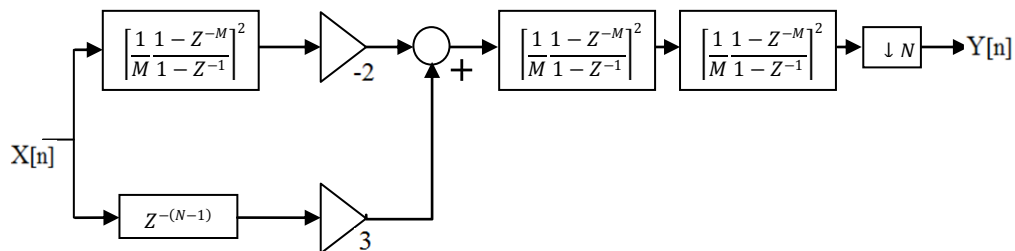

Fig.1.Block diagram of the 2nd order (k=2) SCIC filter

IV. PROPOSED DESIGN OF SHARPENED FILTER

The above discussed sharpening technique is efficiently applied in multistage configuration to improve the response of proposed filter over existing structures. The proposed structure is implemented in three stages as shown in Fig. 2.

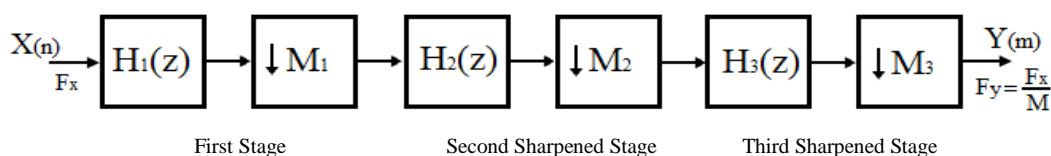First Stage   Second Sharpened Stage   Third Sharpened Stage
Fig. 2 Proposed three stage sharpened decimation filter

As the proposed sharpened filter is implemented in three stages, the total decimation factor M can be represented as $M = M_1 * M_2 * M_3$. Therefore the transfer function of proposed filter can be written as

$$H(z) = H_1(Z)H_2(Z^{M_1})\, H_3(Z^{M_1 M_2}) \quad \text{eq.(13)}$$

Here $H_2(Z)$, $H_2(Z)$ and $H_3(Z)$ are transfer functions of first, second and third stage respectively.

$$H_1(Z) = \frac{1}{M_1}\left[\frac{1-Z^{-M_1}}{1-Z^{-1}}\right] \quad \text{eq.(14)}$$

$$H_2(Z^{M_1}) = \frac{1}{M_2}\left[\frac{1-Z^{-M_1 M_2}}{1-Z^{-M_1}}\right] \quad \text{eq.(15)}$$

$$H_3(Z^{M_1 M_2}) = \frac{1}{M_3}\left[\frac{1-Z^{-M}}{1-Z^{-M_1 M_2}}\right] \quad \text{eq.(16)}$$

The corresponding magnitude responses of three stages are given below

$$H_1(e^{j\omega}) = \frac{1}{M_1}\frac{\sin\left(\frac{\omega M_1}{2}\right)}{\sin\left(\frac{\omega}{2}\right)} \quad \text{eq.(17)}$$

$$H_2(e^{j\omega M_1}) = \frac{1}{M_2}\frac{\sin\left(\frac{\omega M_1 M_2}{2}\right)}{\sin\left(\frac{\omega M_1}{2}\right)} \quad \text{eq.(18)}$$

$$H_3(e^{j\omega M_1 M_2}) = \frac{1}{M_3}\frac{\sin\left(\frac{\omega M}{2}\right)}{\sin\left(\frac{\omega M_1 M_2}{2}\right)} \quad \text{eq.(19)}$$

The generalized transfer function of proposed three stage decimation filter is given below

$$H_{PS}(Z) = [H_1(Z)]^L\{3[H_2(Z^{M_1})\,]^{2K} - 2[H_2(Z^{M_1})\,]^{3K}\}\{3[H_3(Z^{M_1 M_2})\,]^{2K} - 2[H_3(Z^{M_1 M_2})\,]^{3K}\} \quad \text{eq.(20)}$$

Here, L represents the number of sub-stages in first stage and K represents the number of sub-stages in sharpened second & third stage respectively. $H_1(Z)$, $H_2(Z^{M_1})$ and $H_3(Z^{M_1 M_2})$ are given by eq. (14), eq. (15) and eq. (16) respectively. The complete structure can be implemented from eq. (20). The implementation of second and third sharpened stage is shown in Fig. 1. In proposed sharpened structure, the first stage is with decimation factor M_1 can be realized in conventional recursive or non-recursive scheme. Thus the second sharpened stage operates at lower sampling rate which is M_1 times lower than the input sampling rate. Further the third stage operates at M_2 times the lower sampling rate than the second stage and the frequency response of second stage is further sharpened by third stage.

V. SIMULATION RESULTS

The Proposed sharpeneddecimation filter is realized and simulated in MATLAB-Simulink environment. The three stage implementation of proposed sharpened decimation filter in Matlab-Simulink is shown in Fig.3.
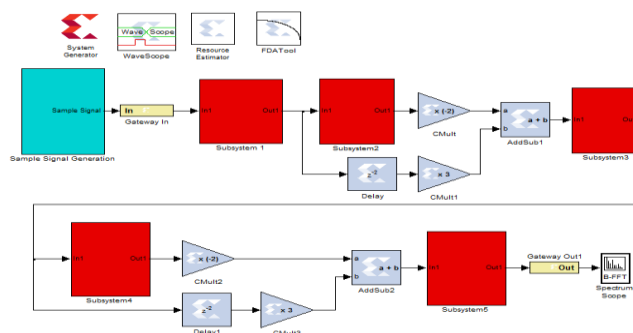

Fig. 3 Matlab-Simulink implementation of proposed sharpened sharpened filter

The proposed sharpened decimation filter is designed to decimate the input sampling rate by 16 (M=16). For comparison with existing results, the value of K =2 and L=4 is chosen. The decimation factor M=16 can be realized with different possible combinations of $M_1 M_2 M_3$. The proposed filter is simulated for three different combinations of $M_1 M_2 M_3$. Simulation results for $M_1 = 4\ M_2 = 2\ M_3 = 2$, $M_1 = 2\ M_2 = 4\ M_3 = 2$ and $M_1 = 2\ M_2 = 2\ M_3 = 4$ are shown respectively.
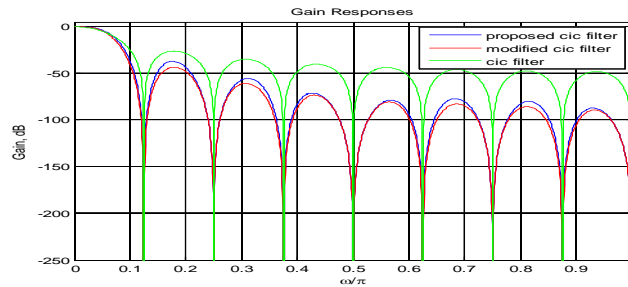

Fig. 4 Magnitude response for M=16, $M_1 = 4$, $M_2 = 2$, $M_3 = 2$, K = 2 and L= 4 (Case I)

Fig. 4 shows the response of proposed sharpened filter for $M_1 = 4\ M_2 = 2\ M_3 = 2$ (Case-I) and its comparison with existing conventional CIC filter [2] and modified sharpened CIC filter [11]. In this case, the proposed sharpened decimation filter has shown a little improvement in pass-band droop and stop-band alias rejection as compared to existing conventional CIC filter [2] and modified sharpened CIC filter [11]. For more rigorous analysis of the results, the pass-band as well as stop-band of Fig. 4 are zoomed and shown in Fig. 5 & Fig. 6 respectively.
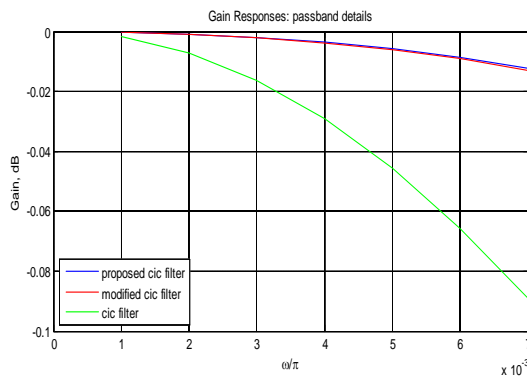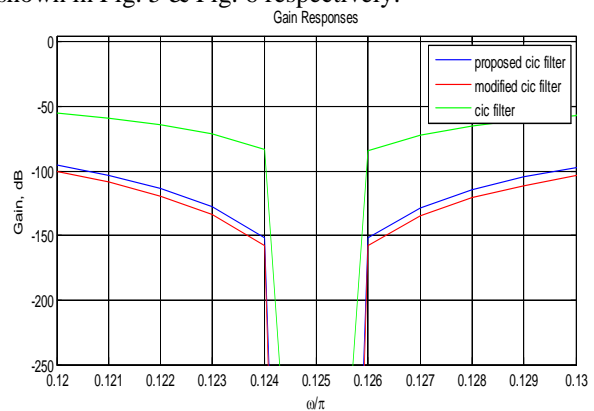

Fig. 5 Pass-band zoom of Case-I

Fig. 6 Stop-band zoom of Case-I

Fig. 7 shows the response of proposed sharpened filter for $M_1 = 2\ M_2 = 4\ M_3 = 2$ (Case-II) and its comparison with existing conventional CIC filter [2] and modified sharpened CIC filter [11].
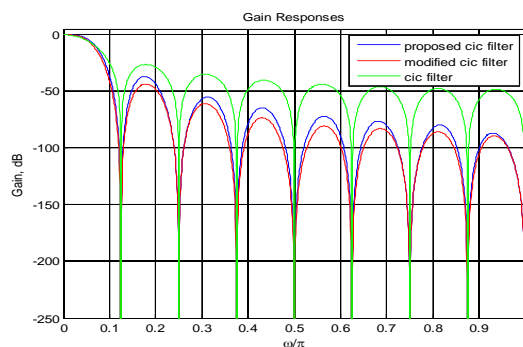

Fig. 7 Magnitude response for M=16 , $M_1 = 2$, $M_2 = 4$, $M_3 = 2$, K = 2 and L= 4 (Case II)

In this case, the proposed sharpened decimation filter has shown much improvement in pass-band droop and a little improvement in stop-band alias rejection as compared to existing conventional CIC filter [2] and modified sharpened CIC filter [11]. For more rigorous analysis of the results, the pass-band as well as stop-band of Fig. 7 are zoomed and shown in Fig. 8 & Fig. 9 respectively.
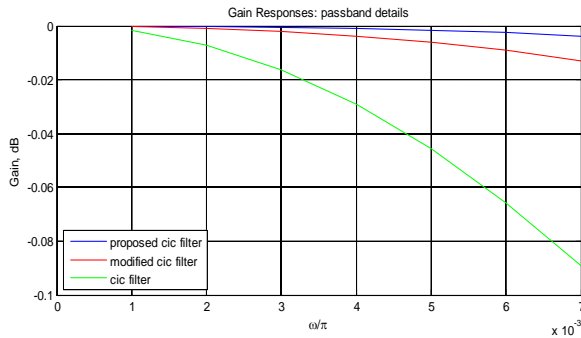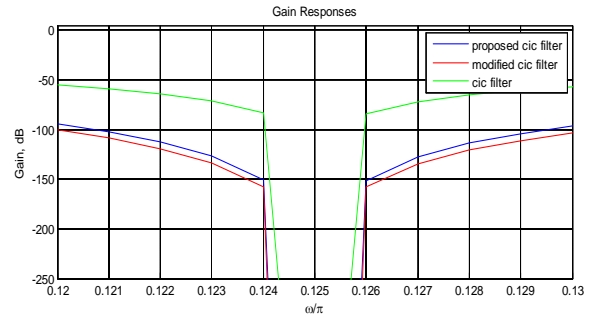

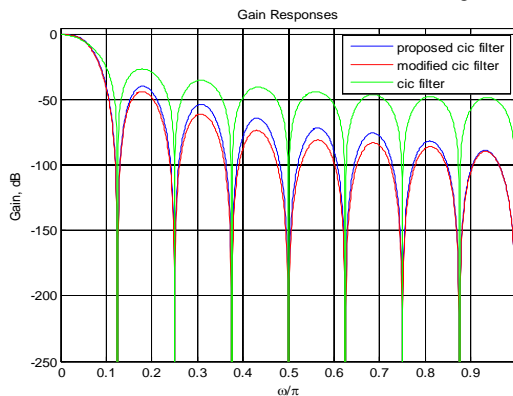Fig. 8 Pass-bandzoom of Case-II

Fig. 9 Stop-band zoom of Case-II

Fig. 10 Magnitude response for M=16,$M_1 = 2$, $M_2 = 2$, $M_3 = 4$, K = 2 and L= 4 (Case III)

Fig. 10 shows the response of proposed sharpened filter for$M_1 = 2$ $M_2 = 2$ $M_3 = 4$ (Case-III) and its comparison with existing conventional CIC filter [2] and modified sharpened CIC filter [11]. In this case, the proposed sharpened decimation filter has shown a much better improvement in pass-band droop and a little improvement in stop-band alias rejection as compared to existing conventional CIC filter [2] and modified sharpened CIC filter [11]. For more rigorous analysis of the results, the pass-band as well as stop-band of Fig. 10 are zoomed and shown in Fig. 11 & Fig. 12 respectively.
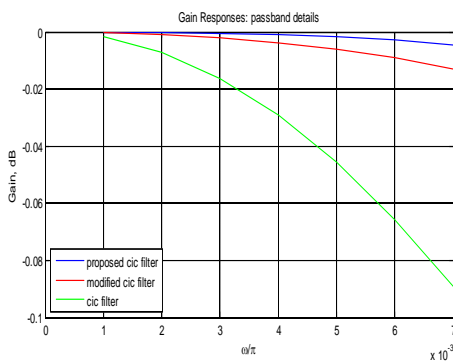

Fig. 11Pass-bandzoom of Case-II
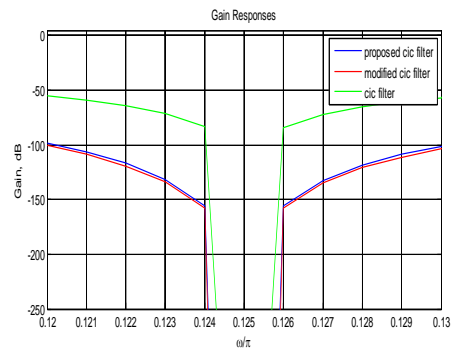

Fig. 12 Stop-band zoom of Case-II

In all the three cases, proposed sharpened decimation filter shown improvement in pass-band droop and stop-band alias rejection as compared to existing conventional CIC filter [2] and modified sharpened CIC filter [11]. But the third case with values $M_1 = 2$ $M_2 = 2$ $M_3 = 4$ produced best results among all proposed cases and existingstructures. Therefore from the above discussed results, it can be concluded that the stage operating at higher sampling rate must have lowest possible decimation ratio to achieve the better frequency response.

VI. CONCLUSION AND FUTURE SCOPE

The proposed sharpened three stage CIC filter is designed and simulated in MATLAB-Simulink environment. The proposed sharpened filter produced much better improvement in pass-band droop and better alias rejection in stop-band than the existing conventional CIC filter [2] and modified sharpened CIC filter [11] for the same decimation factor. The simulation results also verify the design of proposed sharpened decimation filter. Therefore this proposed filter design is best suited for DSP based applications where the best pass-band performance is required. Thus the proposed work can be extended to design decimation filters of any decimation factor and order that can be efficiently applied to many modern multirate applications like digital modems, sampling rate equalization in GSM, 3G, 4G, WiMax and other modern communication systems.

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BIOGRAPHY

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