Improved Maximally Flat Wideband CIC Compensation Filter using Sharpening Technique

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ABSTRACT
This paper presents the design and implementation of sharpening of maximally flat cascaded integrator comb compensation filters. The modified sharpened cascaded integrator comb compensation filter is used to improve magnitude response and gain. For wide-band compensation fourth-order linear phase filters is considered. The decimation factor of CIC filter is D and number of adders are depends upon decimation factor D. The compensation filter is a multiplier less design which works at low rate. The comparison within some methods reported in the literature is provided.

Keywords
Cascaded Integrator Comb Filters, Compensation, Decimation, Finite Impulse Response filter, Sharpening

1. INTRODUCTION
The simplest multiplierless decimation filter is cascaded-integrator comb filter proposed in [1] used in communication systems first. But the magnitude response of this filter has high passband droops, which is not desired in many applications. A CIC structure consists of a cascade of N integrators running at a high sample rate and N comb filters, which run at the down sample rate. No multipliers are needed and the storage requirement is minimal which can be viewed in [1]. The transfer function of CIC filter is given by:

$$H_{CIC}(z) = \left(\frac{1}{D}\frac{1-Z^{-D}}{1-Z^{-1}}\right)^N = \left[\frac{1}{D}\sum_{i=0}^{N-1} Z^{-i}\right]^N \quad (1)$$

Where, D= Decimation factor

N= Number of stages

However there is droop in pass band gain which depends upon decimation ratio, but can be compensated using FIR filter at second stage in the decimation process. The sharpening filter proposed in [2] can be used to overcome the disadvantages of CIC filter in [1]. The transfer function for sharpened CIC filter is given as [3]:

$$\mathbf{H_{SCIC}(z) = 3H^2_{CIC}(z) - 2H^3_{CIC}(z)} \quad (2)$$

The CIC filter also has the disadvantages that the frequency response of comb filter does not satisfy the design and also required more power. To solve these problems various methods were developed, but if one method is suitable to solve one problem then another problem cannot be solved by that method. The recursive and non-recursive structures can also be used. The non-recursive method results in increase in speed and lower power consumption. The polyphase decomposition also used to reduce the sampling rate of sharpening filter [3]. The sharpening methods of Kaiser and Hamming does not always work so if sharpening a filter twice can overcome the problems with the sharpening method proposed in [4].

Another design of decimation filter called GCFs are suitable for $\sum\Delta$ modulator in terms of better selectivity and quantization noise rejection as compared to conventional comb decimation filter [5]. The decimation filter without multipliers is based on IFIR filter and rounding and sharpening techniques is proposed in [6]. Various investigators also proposes the simple second-order compensation filters for both narrow and wide band compensation with low computational complexity [7] – [9]. The sharpening technique proposed in [10, 11] reduces the pass band droop as well as increase the attenuation in folding band.

Moreover, compensators based on closed form equations are suitable for application in narrow-band software radio receivers. Interpolator has designed by using direct form polyphase serial and Parallel structures and DALUT algorithm based decimator are used to enhance speed and to reduce area proposed in [12]. In [13] authors proposed a high speed CIC decimator SDR and GSM which increases the speed and also saves the resources. A high speed interpolator using embedded LUT structure for software defined radios is proposed in paper [14]. The proposed design increases the speed and also save the resources. In paper [15] compensator based on maximally flat criterion is suitable for narrow-band as well as wide band applications is proposed. The non-recursive methods proposed in [16, 17] is used to improve the alias rejection in first folding band.

In paper [18] author proposed an optimized half band polyphase decomposition technique used for decimator in multi-rate applications. Paper [19] proposed a hybrid approach for GSM digital down converter. This proposed technique reduces the cost, filter order and hardware complexity. A multirate structure of decimation is proposed in paper [20] is used in many applications.

Optimized hardware co-simulation approach is proposed in [21] for GSM based digital down convertor, which reduces resource requirement. Polyphase decomposition structure is used to improve the hardware complexity and system performance in terms of speed and area is enhanced using embedded multipliers, LUTs and BRAMs.

The main goal of this study is to extend the results given in [15] for wideband CIC compensation filter. Multiplierless design is proposed and closed form equations are used to compute filter coefficients. The forthcoming section represents wideband CIC compensation filters with multiplierless design along with results and discussion followed by conclusion.

2. WIDEBAND CIC COMPENSATOR
Even increasing the number of stages wide and flat pass band frequency response of CIC filters cannot be obtained. So to overcome the resulting response, an FIR filter is used, which has a magnitude response that is the inverse of the CIC filter.

Such filters are called "compensation filters." The compensation filter follows the CIC filter for down sampling and for up sampling the compensation FIR filter is placed before a CIC filter.

Here design of linear phase FIR compensation filter, with maximally flat magnitude response is described. The proposed compensation CIC filter is expressed as:

$$G(z) = H(z)P(z)^D \quad (3)$$

Where, H (z) is CIC filter defined in (1) and P(z) is a Type I linear phase FIR filter. CIC decimator is usually followed by second decimator stage. The second stage having decimator factor v and passband edge frequency w_p. The worst case droops occur at $w_p = \pi/_{Dv}$. If $v \geq 4$ filter is narrow band, otherwise it is considered wide-band. From (1), the frequency response of the CIC filter is given by:

$$H(e^{jw}) = e^{-j(D-1)N_w/2} H_R(w) \quad (4)$$

Where, $H_R(w)$ is a real valued function. The Type I linear phase FIR compensation filter P(z) is given as:

$$P(z) = \sum_{n=0}^{L} a_n z^{-n} \quad (5)$$

Where, L is an even integer and is the order of P (z) and n= 0,1………,K. To design a compensation filter P (z), the error function is defined as:

$$E(w) = P_R(w)H_R(w) - 1 \quad (6)$$

Where,

$$P_R(w) = a_{K/2} + 2\sum_{n=0}^{K/2-1} a_n \cos\left(w\left(K/2 - 1\right)\right)$$
(7)

For maximally flat condition E (0) = 0 and $P_R(0) = 1$

For the design of wide-band compensator L=4 so the transfer function P (z) is:

$$P(z) = a + bz^{-1} + a_1 z^{-2} + bz^{-3} + az^{-4} \quad (8)$$

By using maximally flat conditions, we get:

$$a = 2^{-8}N.B(2^{-3}N.B + 1 - 2^{-2}C) \quad (9)$$

$$b = -2^{-6}N.B(2^{-3}N.B + 3 - 2^{-2}C) \quad (10)$$

$$a_1 = 1 - 2a - 2b \quad (11)$$

Where, B and C are given as:

$$B = \frac{1-D^{-2}}{1-2^{-2}}, \quad C = \frac{1-(2D)^{-2}}{1-2^{-4}} \quad (12)$$

For multiplierless design the decimation factor is the power of two in such as $D = 2^{2M-1}$, where M is positive integer. For the design parameters D= 32, N= 5 and v= 2, the resulting passband edge frequency w_p= 0.0156 π rad. WB CIC and WB compensated CIC filters at edge frequency having gains -5.54 and -0.58 dB as shown on Fig. 1 and Fig. 2. Blue solid lines represent the wideband compensated CIC and red dotted line represents basic CIC filter magnitude responses. the fig.2 shows the resultant flat pass band of WB CIC compensator, which is obtained by multiplying basic CIC and compensator filter.

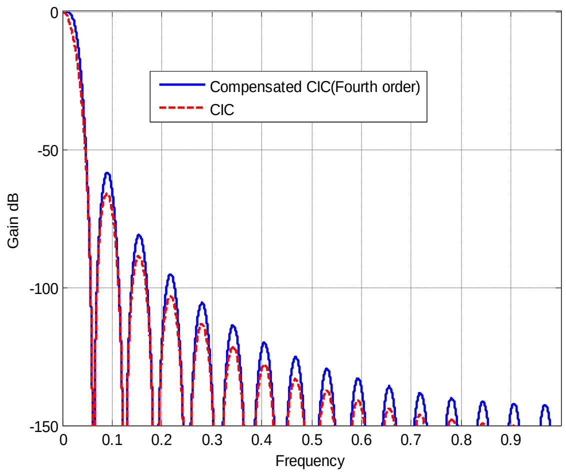

Fig 1: Magnitude Response of the Wideband CIC

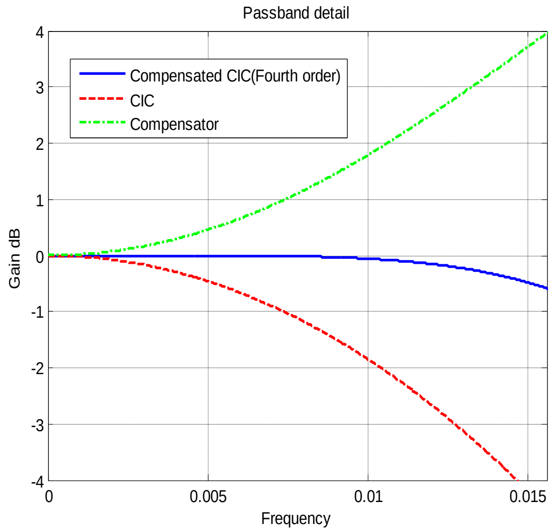

Fig 2: Passband Details of Wideband CIC

3. PROPOSED SHARPENED CIC COMPENSATORS

By using equations (13), (14),(15) for the sharpening of filter coefficients before compensation without changing them, a wideband CIC compensators results in the improved gain , sideband attenuation and also reduces the passband droops. The improved magnitude response is shown in figure 3.

$$H_2(z) = 2H_{CIC}(z) - H_{CIC}^2(z) \quad (13)$$

$$H_3(z) = H_{CIC}^2(z) - 2H_{CIC}^3(z) \quad (14)$$

$$H_4(z) = H_{CIC}^3(z) - 3H_{CIC}^2(z) + 3H_{CIC}(z) \quad (15)$$

Figure 3 represents the different magnitude responses of basic CIC, WB compensated CIC, WB 2nd order sharpened compensated CIC, WB 3rd order sharpened compensated CIC and WB 4th ordered sharpened compensated CIC filters.

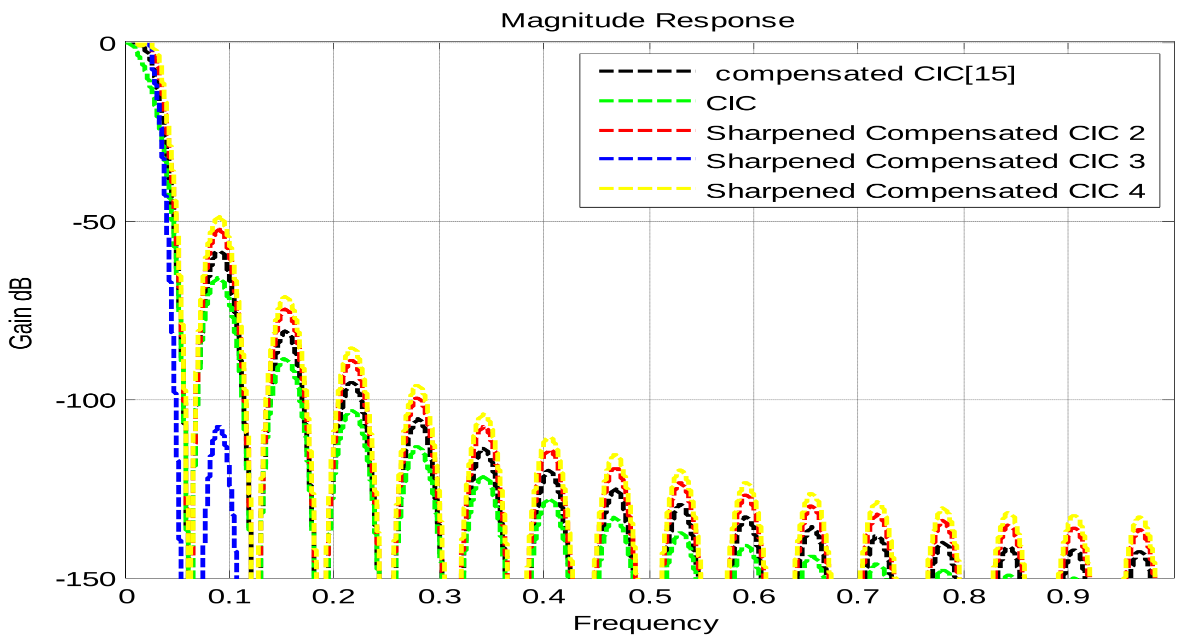

Fig 3: Magnitude Responses Comparison for Wideband CIC Compensators

4. RESULTS AND DISCUSSION

The proposed sharpening technique is applied for maximally flat wideband CIC compensation method. The resulted magnitude 3, and also, Table 1 shows the gain and stop band attenuation of basic CIC [1], maximally flat CIC compensator and proposed 2^{nd}, 3^{rd} and 4^{th} ordered wideband sharpened CIC compensation filter. It is observed that proposed 4^{th} ordered CIC structure after sharpening gives gain 0.034 dB with -49.15 dB stop band attenuation. It is observed that the proposed 2^{nd} , 3^{rd} and 4^{th} ordered sharpening of filter coefficients before compensation provide better attenuation as well as gain than the basic CIC and existing methods of [15]. Proposed 3^{rd} ordered sharpening of CIC compensator gives better side band attenuation among all the techniques. The proposed sharpening of coefficients also improves the passband droops. Proposed 2^{nd}, 3^{rd} and 4^{th} ordered sharpened wideband CIC has -2.91 dB, -4.17 dB and – 3.04 dB, while basic wideband CIC has -3.00 dB passband droop.

Table 1: Wideband sharpened CIC compensator details

Filter Type	Gain(dB)	Stopband Attenuation (dB)
CIC [1]	-3.903	-66.17
Reference [15]	-0.4019	-58.53
Proposed 2^{nd} order sharpening	0.161	-52.53
Proposed 3^{rd} order sharpening	0.423	-107.5
Proposed 4^{th} order sharpening	0.034	-49.15

5. CONCLUSION

This paper discusses the design and implementation scheme of sharpening of maximally flat compensated CIC decimation filter employing a fourth order compensator used for wide-band applications. Random search algorithm is employed in order to find power-of-2 coefficients for the sharpening polynomial. It is concluded that the proposed 2^{nd}, 3^{rd} and 4^{th} ordered sharpening before compensation provide better attenuation and gain. All the results are carried out using MATLAB simulation. However, as future implementation 2^{nd} ordered sharpened CIC compensator in cascaded combination form can be used to give optimized multiplierless design along with improved magnitude characteristics.

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