Cascading Sharpened CIC and Polyphase FIR Filter for Decimation Filter

V. Jayaprakasan and M. Madheswaran

Abstract—This paper is concerned with design of cascading CIC filter and FIR filter to improve the passband droop and stopband attenuation for decimation filter. Decimation filter has wide application in both analog and digital systems for data rate conversion as well as filtering. We have three classes of filters FIR, IIR and CIC filters. IIR filters are simpler in structure, but not satisfy linear phase filter requirements, which are required for time sensitive features like video and speech. CIC filter don’t have this drawback, they are coefficient less, hardware requirement is much reduced, but as they don’t have well defined frequency response. So another structure is proposed which takes advantage of good features of both CIC and FIR filter structures. Hence in this paper concerned about cascading sharpened CIC filter and polyphase structure of FIR for efficient compensation in decimation is designed, which has better passband and stopband performance.

Keywords— Multirate filtering, CIC, Compensation Technique, Polyphase structure, FIR

I. INTRODUCTION

The decimator is one of the basic building blocks of a sampling rate conversion system. The decimation filter performs two operations. Low pass filtering and down sampling. The filter converts low resolution high bit rate data to high resolution low frequency data. It has been widely used in audio, speech processing, radar systems, and communication systems. Considerable attention has been focused in the last few years on the design of high efficiency decimation filters.

Eugene Hogenauer [1] in 1981 designed a new class of economical digital filters for decimation and interpolation called a cascaded integrator comb (CIC) filter. This filter has two sections namely integrator and comb section, as well as it’s a multiplier less structure. The implementation of CIC filters in hardware also efficient due to its symmetric structure. This CIC filter has two sections, namely integrator and comb sections, which perform the operation of digital low pass filtering, decimation simultaneously.

The essential function of decimation is to decrease the sampling rate and to keep the passband aliasing within prescribed bounds. In this paper CIC [1] filter introduced that requires no multipliers and use limited storage hereby leading to more economical hardware implementations. They are designated cascaded integrator-comb (CIC) filters because their structure consists of an integrator section operating at the high sampling rate and a comb section operating at the low sampling rate. Using CIC filters, the amount of passband aliasing or imaging error can be brought within prescribed bounds. Several schemes have been proposed to design comb filters with improved magnitude response [2] - [4]. The methods outlined in [5] and [6] use the filter sharpening technique which was originally introduced to improve both the passband and stopband of a symmetric FIR filter by using multiple copies of the same filter. The main drawback of the structure in [5], which uses sharpened comb filter with a building block consisting of a K-stage comb filter, is that the integrator section works at the high input rate resulting in higher power consumption.

In 1973, McClellan, J. H & Parks [7] developed a computer program to design a optimum FIR linear phase digital filters. The program has options for designing standard filters as low-pass, high-pass, band-pass, band-stop filters. The program is also used to design filters which arbitrary frequency specifications which are provided by users. This program is written in FORTRAN. Bellanger, M.G., Bonnerot, G. [8] designed a polyphase network structure and analyzed. It permits the use of recursive devices for efficient sample-rate alteration. The comparison with conventional filters shows that, with the same active memory, a reduction of computation rate approaching a factor of 2 can be achieved when the alteration factor increases.

A.G. Dempster [9] examined the use of efficient shift and adds multiplier structures and multiplier blocks to reduce computational complexity in filter banks. He also examined the farrow structure used in interpolator. Gustafsson, O. Johansson, K [10] implemented a polyphase decomposed FIR filters using MCM techniques i.e. realizing a number of constant multiplications using minimum number of adders and subtracters. For interpolations, direct form subfilters lead to fewer registers as the shared among the subfilters but using transposed direct form subfilters, the registers cannot be shared. For decimation filters the opposite holds for direct form and transposed direct form subfilters. Finally implementation results for area, speed, and power for different realizations are compared. Eghbali, A [11] this paper presents the multiplierless FIR filter structures realization. They derived the total number of adders required for the transposed
direct form, polyphase and reduced complexity polyphase FIR filter structures and compared.

The main idea of this paper is to integrate the advantages of the structures presented in [4-6], [10] and [13] in order to obtain the structure that can provide the best passband droop and stop attenuation is designed and analyzed using MATLAB. The paper is organized as follows. In Section 2, we first describe the main characteristics of cascaded-comb filter (CIC). Section 3, describes the FIR filters structures and polyphase implementation. Section 4, we outline the new efficient proposed structure. Finally in Section 5, shows results obtained by the proposed design.

II. CASCADED INTEGRATOR COMB [CIC] FILTER

Cascaded integrator comb [1] or Hogenauer filter, are multirate filters used for realizing large sample rate changes in digital systems. CIC filters are multiplierless structures, consisting of only adders and delay elements which is a great advantage when aiming at low power consumption. So the CIC filters are frequently used in digital down converter and digital up converters. The CIC filter is a class of hardware efficient linear phase FIR digital filter consists of an equal number of stages of ideal integrator and comb filter pairs. The highly symmetric structure of this filter allows efficient implementation in hardware. However the disadvantage of a CIC filter is that is passband is not flat, which is undesirable in many applications. This problem can be overcome through the use of compensation filter. CIC filter achieve sampling rate decrease (decimation) without using multiplication. The CIC filter first performs the averaging operation then follows it with the decimation.

The transfer function of the CIC filter in z-domain is given as [1].

$$H(z) = \frac{1}{N} \left[ \frac{1 - z^{-N}}{1 - z^{-1}} \right] \quad (1)$$

Where, $N$ is the decimation factor

In equation (1) the numerator $\left( 1 - z^{-N} \right)$ represents the transfer function of comb and the denominator $1/(1 - z^{-1})$ indicates the transfer function of integrator.

By operating at differentiator at the lower sampling rate the power consumption is achieved.

A poor magnitude characteristic of the comb filter is improved by cascading [3] several identical comb filters. The transfer function of multistage comb filter composed of identical single stage comb filter is given by,

$$H(z) = \frac{1}{N} \left[ \frac{1 - z^{-N}}{1 - z^{-1}} \right]^K \quad (2)$$

Fig. 2 Structure of CIC filter with K stages

The magnitude response of this filter is given by

$$|H(e^{j\omega})| = \left[ \frac{1}{N} \frac{\sin(\omega N/2)}{\sin(\omega/2)} \right]^K \quad (3)$$

Fig. 3 Magnitude response of multistage realization structure of CIC filter with different K values

Fig. 3 shows the multistage realization, which improves the selectivity and the stopband attenuation of the overall filter. Fig. 4 indicates the main performance of the comb based decimation filter, here only the magnitude response is considered, since the phase is linear.
The signal band at the decimator input occupies the frequencies \([0, F_m]\). For the input signal sampling frequency \(F_x\) and the decimation factor \(N\), the aliasing bands of the bandwidths \(2F_m\) are located around the natural null frequencies \(F_x/N, 2F_x/N, 3F_x/N \ldots J F_x/N\); \(J = N/2\) for even and \(J = (N-1)/2\) for odd. The main parameters that characterize the comb filter performance are the passband droop and the selectivity factor.

The passband droop denoted by \(d_c^K\) in fig. 4 indicates the maximum attenuation at the edge of the useful signal bandwidth compared to the ideal LPF. The selectivity factor \(\Phi_c^K\) in figure 4 is defined as the ratio between the exact values of the filter magnitude response achieved at the passband edge frequency \((F_m)\) and at the lower edge frequency of the first aliasing band \((F_x/N - F_m)\).

Expression for passband droop \(d_c^K\) for \(K\) stage comb filter is given by,

\[
d_c^K = \left| \frac{G_c^K (F_m)}{G_c^K (0)} \right| \left| \frac{\sin(\pi N F_m / F_x)}{N \sin(\pi N F_m / F_x)} \right|^K
\]

(4)

Normalization to the half of the sample frequency \(f = F/(F_x/2)\), then

\[
d_c^K = \left| \frac{\sin(\pi N f_m / 2)}{N \sin(\pi f_m / 2)} \right|^K
\]

(5)

The selectivity factor for the \(K\) stage comb filter is given by,

\[
\Phi_c^K = \left| \frac{G_c^K (F_m)}{G_c^K (F_x / N - F_m)} \right|^K \left| \frac{\sin(\pi (1 / N - F_m / F_x))}{\sin(\pi F_m / F_x)} \right|^K
\]

(6)

The magnitude response of \(K\) stage comb filter is given in fig. 5.

\[
\text{Magnitude response}\]

\[
\text{Normalized frequency}
\]

Fig. 5 Gain response of CIC filter: Passband droop

A. CIC filter for sample rate conversion

The CIC filters are utilized in multirate systems for constructing digital up converter and down converter. The ability of comb filter to perform filtering without multiplication is very attractive to be applied to high rate signals; moreover CIC filters are convenient for large conversion factor, since the low pass bandwidth is very small. In multistage decimators with large conversion factor, the comb filter is the best solution for first decimation stage, whereas in interpolation, the comb filter is convenient for the last stage.

B. CIC filter for decimation

The basic concept of CIC filter is given in fig. 6, which consists of factor of \(N\) down sampler and \(K\)-stage CIC filter.

\[
x[n] \rightarrow \left[ 1 - \frac{1}{N} z^{-1} \right]^{K} \rightarrow N \rightarrow \left[ 1 - z^{-1} \right]^{K} \rightarrow y[m]
\]

Fig. 6 Cascade of CIC filter and down sampler

Applying third identity, the factor of \(N\) down sampler is moved and placed behind the integrator section and before the comb section as shown in fig. 7. Finally the CIC decimator is implemented as a cascade of \(K\) integrator, factor of \(N\) down sampler and the cascade of \(K\) differentiator sections. The integrator portion operates at the input data rate, whereas the comb portion operates at \(N\) time’s lower sampling rate which is shown in fig. 2.

\[
x[n] \rightarrow \left[ 1 - \frac{1}{N} z^{-1} \right]^{K} \rightarrow N \rightarrow \left[ 1 - z^{-1} \right]^{K} \rightarrow y[m]
\]

Fig. 7 Cascade of integrator section, down-sampler and comb section

C. Two stage sharpened comb filter

The structure consisting of a cascade \([4]\) of a comb filter based decimator and sharpened comb decimator \([5, 6]\). In this realization allows the sharpened comb section to operate at a lower rate that depends on the decimation factor of the first section. Using the polyphase decomposition \([3]\) the subfilters of the first section can also be operates at this lower sampling rate.

The magnitude response of two stage sharpened comb filter

\[
H_sh(e^{j\omega}) = \left\{ \begin{array}{ll}
\frac{1}{N_1} \sin(\omega N_1 / 2) & 2^{3K} \left[ \frac{1}{N_2} \sin(\omega N_2 / 2) \right]^{3K} \\
\frac{1}{N_1} \sin(\omega N_1 / 2) \end{array} \right.
\]

(7)

where \(N\) is decimation factor and \(N = N_1 * N_2\)

\(K\) is number of stages
III. FIR Filter Structure

The non-recursive nature of FIR filter [7] offers the opportunity to create implementation schemes that significantly improve the overall efficiency of the decimator. Let us consider the factor M-decimator of which uses a FIR antialiasing filter with the impulse response $h[n]$. The time domain relation for the filter are expressed by the convolution sum,

$$ v[n] = \sum_{k=0}^{N-1} h[k] x[n-k] \quad (8) $$

Where $N$ is the order of the filter.

The decimated signal $y[m]$ is obtained after applying down sampling is given by,

$$ y[m] = \sum_{k=0}^{N-1} h[k] x[nM-k] \quad (9) $$

\[ \text{Fig. 9 Factor of M-decimator with FIR filter} \]

A. Efficient implementation of M-factor decimator

In conventional FIR filter implementation of figure (9), the number of multiplications per input sample in the decimator is equal to FIR filter length $N$. The efficient implementation structure of fig. 10 reduces the number of multiplications per input sample to $N/M$. This property significantly improves the efficiency of multirate FIR filter.

\[ \text{Fig.10 Efficient implementation of M-factor decimator} \]

B. Polyphase structure for FIR decimator

A higher order FIR filter can be realized in parallel structure based on the polyphase [8] decomposition of the transfer function. The FIR transfer function is decomposed into $M$-lower order transfer function called polyphase components, which are added together to compose the original transfer function.

$$ H(z) = \sum_{k=0}^{N-1} h[k] z^{-k} \quad (10) $$

In expanded form,

$$ H(z) = h[0] + h[1] z^{-1} + h[2] z^{-2} + \cdots + h[N-1] z^{-(N-1)} \quad (11) $$

Here we consider $N$ is odd number and the equation (10) can be expressed as a sum of two terms.


and


By using the notation, equations (11) and (12) can be expressed as,

$$ E_0(z) = h[0] + h[2] z^{-2} + h[4] z^{-4} + \cdots + h[N-1] z^{-(N-1)/2} \quad (14) $$

$$ E_1(z) = h[1] + h[3] z^{-2} + h[5] z^{-4} + \cdots + h[N-2] z^{-(N-3)/2} \quad (15) $$

$$ H(z) = E_0(z^2) + z^{-1} E_1(z^4) \quad (16) $$

In generalized form polyphase transfer function is written as,

$$ H(z) = \sum_{k=0}^{M-1} z^{-k} E_k(z^M) \quad (17) $$

where, $E_k(z) = \sum_{n=0}^{[N/M]} h[Mn+k] z^{-N}, 0 \leq k \leq M-1$ (18)
IV. PROPOSED STRUCTURE

In the proposed structure, sharpened CIC filter is cascaded with polyphase FIR filter to improve the passband droop and stopband attenuation.

The overall conversion ratio is factored as, \( M = N \times R \).

The overall sampling rate conversion systems can be implemented by cascading a factor \( N \) CIC decimator, which is again factored into \( N_1, N_2 \). A factor of ‘\( R \)’ FIR decimator which is shown in fig. (12 -14).
V. RESULTS

Design the two stage decimator and compute the single stage equivalent for the specification.

The decimation factor $M=16$; The overall decimation filter $H(z)$ is specified by, Passband edge $\omega_p = 0.05\pi$, and the decimation of the passband magnitude response are bounded to $a_p = 0.15\text{dB}$. Stopband edge frequency $\omega_s = M/\pi = 0.1$ with the minimal stopband attenuation $a_s = 50\text{dB}$. Consider the phase characteristics is linear.

Solution:
The overall factor 16 decimator is composed cascade of two decimators.

$$M=16; N=8, N_1=4, N_2=2, R=2$$

VI. CONCLUSION

Decimation of a signal at high frequency using FIR filter structure is very complex, since it needs a lot of multiplications and hence the cost is increased. In CIC filter, as the number of stages increases, the stopband attenuation improves but passband droop increases. So this passband droop is compensated with help of some compensation techniques. CIC filter are very economic, computationally efficient and simple to implement in comparison with FIR or IIR for large rate change due to its multiplierless structure. This paper analyzed the performance of CIC decimation filter for efficient compensation by using sharpened CIC filter as a first stage in decimation and FIR filter as second stage as in a cascaded form. This will improve the passband droop of the overall decimation filter. Results show this improvement of passband and stopband attenuation.

REFERENCES


V.Jayaprakasan received his Bachelor’s Degree in Electronics and Communication Engineering from Bharathidasan University, Truchirappalli, India in the year 1999 and Master’s Degree in Communication Systems from Anna University, Chennai, India in the year 2006. He has started his teaching profession in the year 2006 in Ganadipathy Tulsi’s Jain Engineering College, Vellore. Earlier he has 11 years industrial experience in an electronics based industry. At present he is a Professor in Electronics and Communication Department. He has published 1 research papers in International Journal. He is a part time research scalar in Jawaharlal Nehru Technological University Anantapur. His areas of interest are Wireless communication, Networking and Signal Processing. He is a life member of ISTE.

M.Madheswaran received the BE Degree from Madurai Kamaraj University in 1990, ME Degree from Birla Institute of Technology, Mesra, Ranchi, India in 1992, both in Electronics and Communication Engineering. He obtained his PhD degree in Electronics Engineering from the Institute of Technology, Banaras Hindu University, Varanasi, India, in 1999. At present he is a Principal of Muthayammal Engineering College, Rasipuram, India. He has authored over one hundred and twenty five publications in international and national journals and conferences. Currently he is the chairman of IEEE India Electron Devices Society Chapter and Vice Chair of IEEE India Circuits and System Chapter. His areas of interest are theoretical modeling and simulation of high-speed semiconductor devices for integrated optoelectronics application, Bio-optics and Bio-signal Processing and Clinical decision Support Systems development. He was awarded the Young Scientist Fellowship (YSF) by the State Council for Science and Technology, Tamilnadu, in 1994 and Senior Research Fellowship (SRF) by the Council of Scientific and Industrial Research (CSIR), Government of India in 1996. Also he has received YSF from SERC, Department of Science and Technology, Govt. of India. He is named in Marquis Who’s Who in Science and engineering in the year 2006. He is a fellow of IETE and IE (India), life member of ISTE and also a senior member of IEEE. He is also the member of International Association of Computer Science and Information Technology (IACSIT) Singapore.