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Performance Evaluation of Cascaded Integrator-Comb (CIC) Filter

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ABSTRACT

Multirate filters find application in communication, speech processing, image compression, antenna systems, analog voice privacy systems and in the digital audio industry. The cascaded integrator-comb filter is a digital filter which employed multiplier-less realization. This type of filter has extensive applications in low-cost implementation of interpolators and decimators. The basic principles of the CIC decimation filter are presented in this paper. It combines the cascaded integrator-comb (CIC) multirate filter structure with compensation techniques to improve the filter's passband response. This allows the first-stage CIC decimation filter to be followed by the FIR decimation filter. Simulation results show the gain responses of the CIC filters.

Keywords **– Cascaded Integrator-Comb (CIC) filter, sampling rate conversion, decimation, FIR decimation.**

1. INTRODUCTION TO MULTIRATE FILTER

Multirate systems [1] are extensively used in all areas of digital signal processing (DSP). Their function is to alter the rate of the discrete-time signals, by adding or deleting a portion of the signal samples. They are essential in various signal processing techniques such as signal analysis, denoising, compression etc. During the last decade, Multirate filters have increasingly found applications in new and emerging areas of signal processing such as digital communications. The cascaded integrator-comb (CIC) [2] filter is a digital filter which is employed for multiplier-less realization of filters. This type of filter has extensive applications in low-cost implementation of interpolators and decimators. However, there are some drawbacks of CIC-filters like pass-band droop in this filter, but they can be eliminated using compensation techniques.

2. CASCADED INTEGRATOR-COMB (CIC) FILTERS

The cascaded integrator-comb (CIC) filter is a class of linear phase finite impulse response (FIR) digital filters. CIC-filters achieve sampling rate decrease (decimation) and sampling rate increase (interpolation) without using multipliers. A CIC-filter consists of an equal number of stages of ideal integrator and comb filters. Its frequency response may be tuned by selecting the appropriate number of cascaded integrator and comb filter pairs. The highly symmetric structure of a CIC-filter allows efficient implementation. The disadvantage of a CIC -filter is that its pass-band is not flat, which is undesirable in many applications. This problem can be alleviated by a compensation filter.
The transfer function of the CIC-filter in z-domain is given in equation (1) [3].

$$H(Z) = \left(\frac{1-z^{-K}}{1-z^{-1}}\right)^{L} \quad (1)$$

In Equation (1), K is the oversampling ratio and L is the order of the filter. The filter H(Z) can be implemented by cascading the comb section $(1-z^{-K})$ and the integrator section $1/(1-z^{-1})$. Fig.1. shows the Comb Filter gain response.

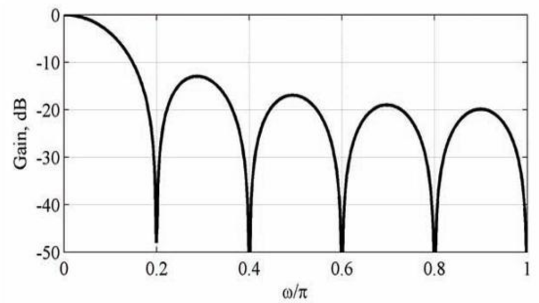


Fig.1. Gain response of the single comb filter for K = 10 and L=1

A very poor magnitude characteristic of the comb filter is improved by cascading several identical comb filters. The transfer function H(z) of the multistage comb filter composed of K identical single-stage comb filters is given by

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

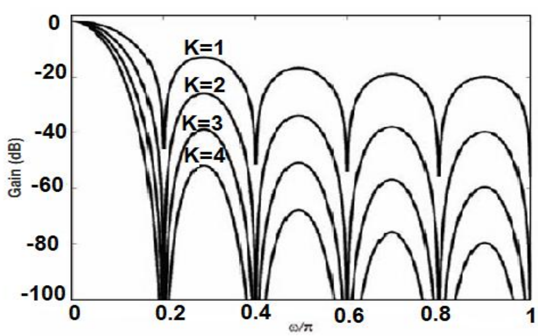


Fig.2. CIC-Filter Gain Responses: single-stage K = 1, two-stage K = 2, three-stage K = 3 and four-stage

K = 4

Fig.2. shows how the multistage realization improves the selectivity and the stop-band attenuation of the overall filter: the selectivity and the stop-band attenuation are augmented with the increase of the number of comb filter sections. The filter has multiple nulls with multiplicity equal to the number of the comb sections (K). Consequently, the stop-band attenuation in the null intervals is very high. Fig.3. shows a monotonic decrease of the magnitude response in the pass-band, called the pass-band droop.

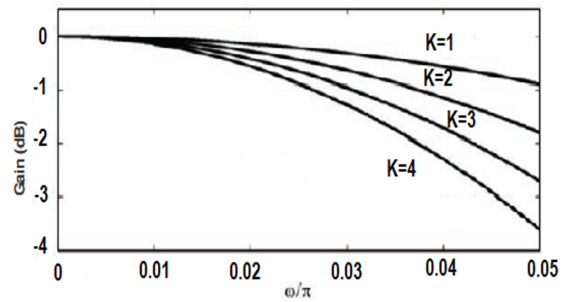


Fig.3. CIC-Filter Gain Response: Pass-band droop

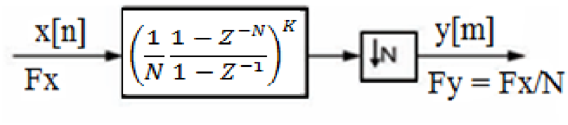
2.1 CIC-FILTER FOR SAMPLE RATE CONVERSION

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 multiplications is very attractive to be applied to high rate signals. Moreover, CIC -filters are convenient for large conversion factors since the low-pass bandwidth is very small. In multistage decimators with a large conversion factor, the comb filter is the best solution for the first decimation stage, whereas in interpolators, the comb filter is convenient for the last interpolation stage.

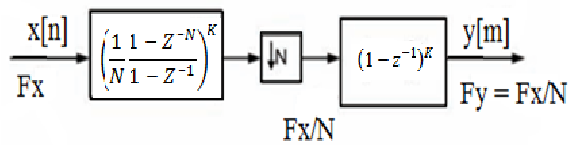
2.2 CIC-FILTERS IN DECIMATION

The CIC-filters are utilized in multirate systems for constructing efficient decimators and interpolators. The comb filter ability to perform filtering without multiplications is very attractive to be applied to high rate signals. Moreover, CIC-filters are convenient for large conversion factors since the low pass bandwidth is very small. The multirate application of comb filters has been proposed first by Hogenauer, and since that time, the so-called Hogenauer filters.

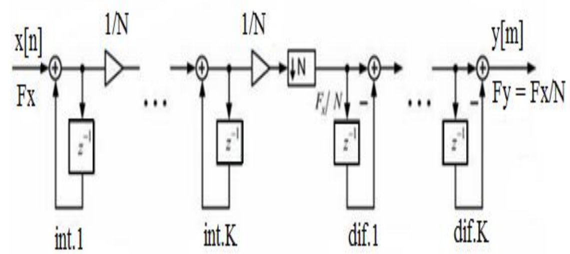
A CIC decimator [4] would have N cascaded integrator stages clocked at f_s, followed by a rate change by a factor R, followed by N cascaded comb stages running at f_s/R.



(a)



(b)



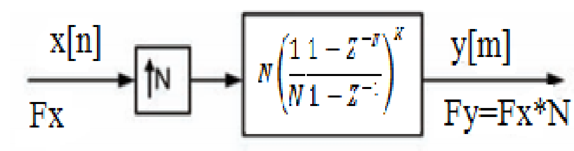
(c)

Fig.4. Block diagram representation of CIC decimator: (a) Cascade of CIC-filter and down-sampler, (b) Cascade of integrator section, down-sampler and comb section, (c) Implementation structure consisting of the cascade of K integrators, down sampler, and the cascade of K differentiators

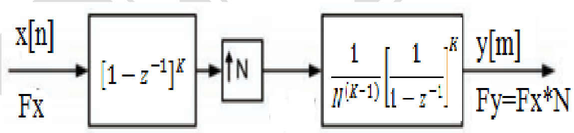
The basic concept of a comb-based decimator is explained in Fig.4. Fig.4.(a) [2] shows the factor-of-N decimator consisting of the K-stage CIC-filter and the factor-of-N down-sampler. Fig.4.(b) shows the factor-of-N down-sampler is moved and placed behind the integrator section and before the comb section and Fig.4.(c) shows the CIC decimator is implemented as a cascade of K integrators, factor-of-N down-sampler, and the cascade of K differentiator (comb) sections. The integrator portion operates at the input data rate, whereas the differentiator (comb) portion operates at the N times lower sampling rate.

2.3 CIC-FILTERS IN INTERPOLATION

The CIC interpolator is implemented as a cascade or K differentiators (comb) sections, factor-of-N down-sampler, and the cascade of K integrators. The basic concept of a comb-based interpolator is explained in Fig.5. Fig.5.(a) [2] shows the factor-of-N interpolator consisting the factor-of-N up-sampler and of the K-stage CIC-filter. Fig.5.(b) shows the factor-of-N up-sampler is moved and placed behind the differentiator section and before the integrator section and Fig.5.(c) shows the CIC decimator is implemented as a cascade of K differentiation, factor-of-N up-sampler, and the cascade of K integrator sections.



(a)



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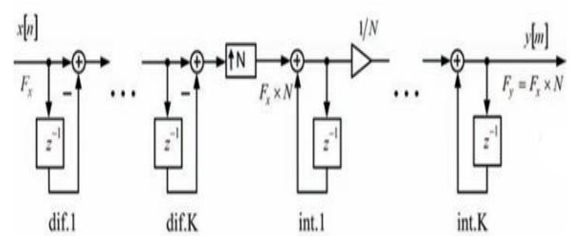


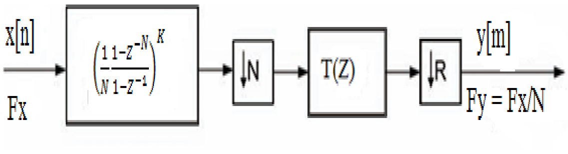
(c)

Fig.5. Block diagram representation of CIC interpolators: (a) Cascade of up-sampler and CIC filter, (b) Cascade of comb section, down-sampler and integrator section, (c) Implementation structure consisting of the cascade of K differentiators, up-sampler, and the cascade of K integrators

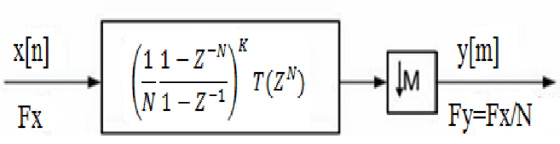
2.4 COMPENSATION OF CIC FILTERS

A CIC-filter can be used as a first stage in decimation when the overall conversion ratio M is factorable as

$$M = N \times R \qquad (3)$$



(a)



(b)

Fig.6. Two-stage decimator composed of a CIC filter and an FIR filter: (a) Cascade implementation, (b) Single-stage equivalent

The overall factor-of-M sampling rate conversion system can be implemented by cascading a factor-of-N CIC decimator [5] and a factor-of-R FIR as shown in Fig.6.(a) The corresponding single-stage equivalent is given in Fig.6.(b).

In the two-stage solutions of Fig.6. the role of CIC decimator is to convert the sampling rate by the large conversion factor N, whereas the FIR filter T(z) provides the desired transition band of the overall decimator and compensates [6] the pass-band characteristic of the CIC filter.

2.5 DESIGN SPECIFICATIONS OF CIC DECIMATOR FILTER AND FIR DECIMATOR FILTER

The overall decimation factor M = 10. The overall decimation filter H(z) is specified by:

• Pass-band edge frequency $\omega_p = 0.05\pi$, and the deviations of the pass-band magnitude response are bounded to $a_p = \pm 0.15$ dB.

• Stop-band edge frequency $\omega_s = \pi/M = 0.1\pi$ with the requested minimal stop-band attenuation $a_s = 50$ dB.

• The phase characteristic is linear.

Fig.7. shows the implementation structure of the factor-of-10 decimator.

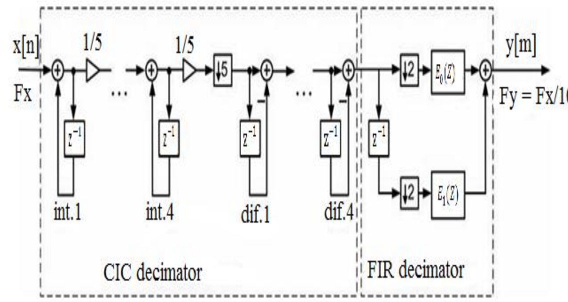


Fig.7. Implementation structure of the two-stage factor-of-10 decimator consisting of the cascade of factor-of-5 CIC decimator and factor-of-2 FIR decimator

2.6 SHARPENED COMB FILTER

Filter sharpening is a technique that improves passband/stopband filter performances in a manner that provides both: smaller passband error and greater stopband attenuation. The implementation of $H_{11}(z)$ requires three copies of $H_p(z)$, an integer multiplier of value 3, a trivial multiplier of value –2, an adder, and a delay line of D samples. The block diagram that implements the sharpened filter $H_{11}(z)$ is shown in Fig.8.[7] and Fig.9.[7] shows the implementation of a sharpened factor-of-N comb decimator for the case K = 2.

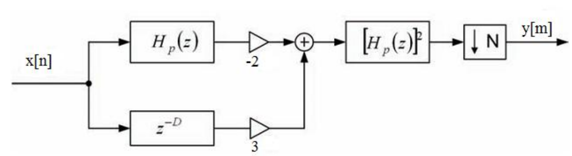


Fig.8. The block diagram of sharpened filter

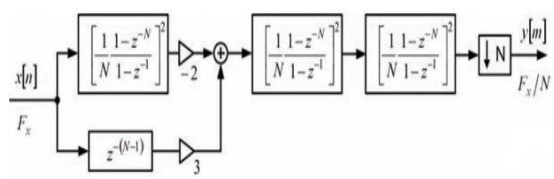


Fig.9. Block diagram of the sharpened comb decimator with comb filters transfer functions, K = 2

3. SIMULATION RESULTS

The role of CIC decimator is to convert the sampling rate by the large conversion factor N, whereas the FIR filter T(z) provides the desired transition band of the overall decimator. Filter $T(Z^N)$ ensures the desired transition band, compensates the pass-band droop of the comb filter of the first stage. The CIC-filter H(Z) has its two nulls just in the undesired pass-bands of the periodic filter $T(Z^N)$ that ensure the requested stop-band attenuation of the target two-stage decimator [7]. Finally, compute the frequency response of the overall two-stage decimation filter and compensates the pass-band characteristic [8] of the CIC-filter.

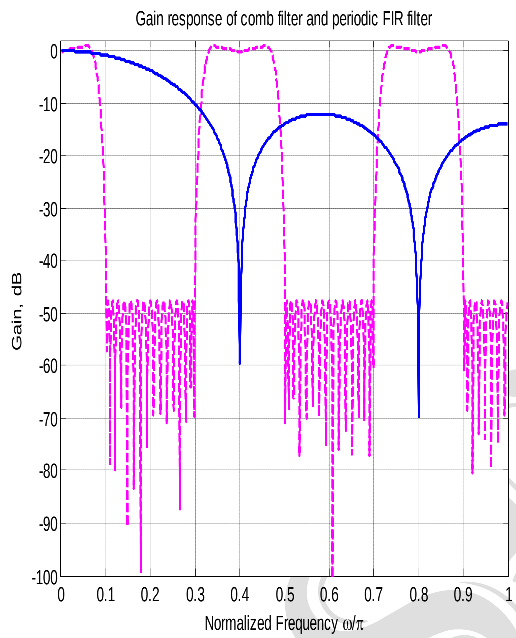


Fig.10. Gain Response of the Comb Filter (blue line) and FIR Filter (dashed line) for K=1

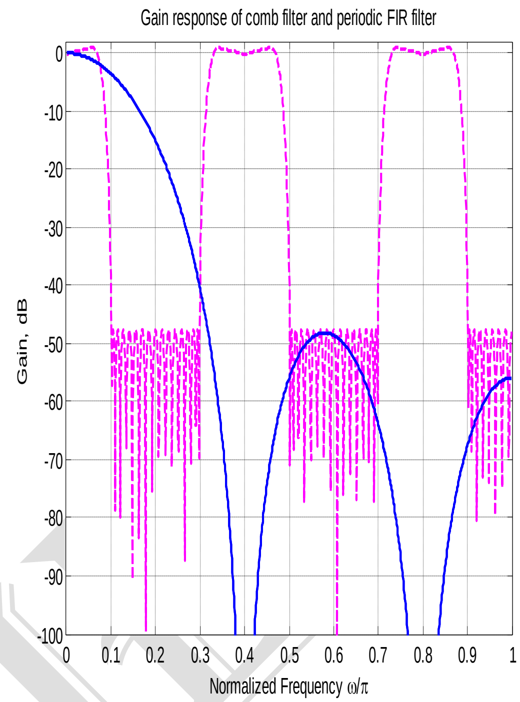


Fig.11. Gain Response of the Comb Filter (blue line) and FIR Filter (dashed line) for K=4

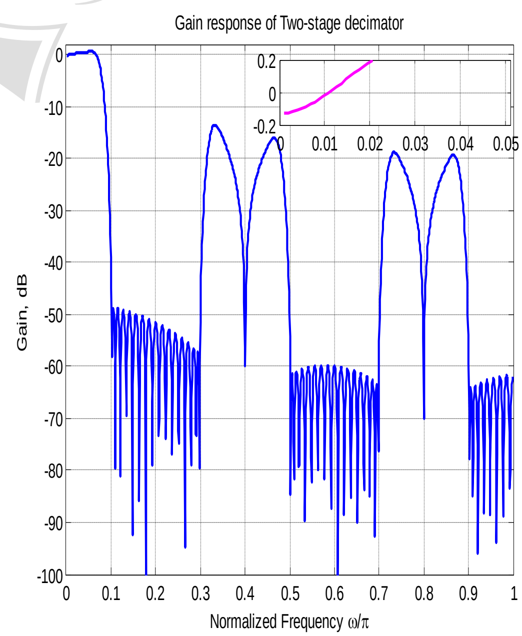


Fig.12. Gain Response of the Two-stage Decimator implemented as a factor-of-5 Comb Decimator and a factor-of-Two FIR Decimator for K=1

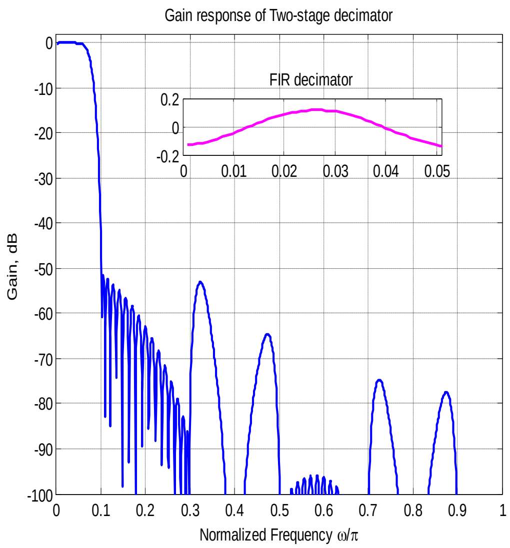


Fig.13. Gain Response of the Two-stage Decimator implemented as a factor-of-5 Comb Decimator and a factor-of-Two FIR Decimator for K=4

Fig.10.. Fig.11., Fig.12. and Fig.13.[9] shows the gain responses of the CIC-filter and that of periodic FIR filter. If the value of K (K is the number of comb filter section) will be increased, so the gain response of the CIC-filter will also be improved and FIR filter gain response does not affected.

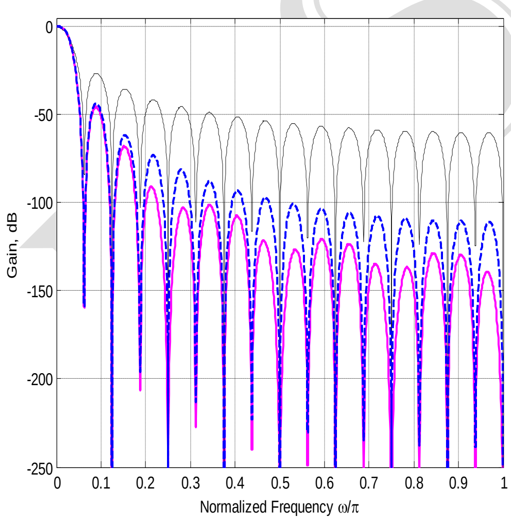


Fig.14. Magnitude responses of the Modified Sharpened Filter (N = 32, N1 = 8, N2 = 4, K = 2, L = 5); Sharpened Filter (N = 32, K = 2); comb filter (N = 32, K= 2)

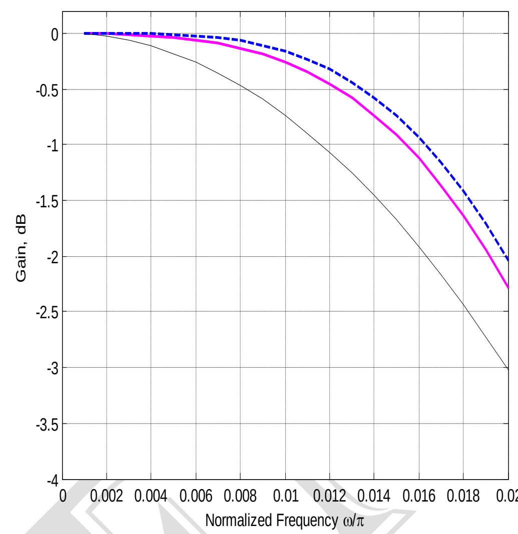


Fig.15. The passband drops

The overall magnitude responses are plotted in Fig.14.[7] and the passband drops are shown in Fig.15.[7]. The effects of sharpening techniques are evident in the augmented stopband attenuation and also in the decrease of the passband droop.

4. CONCLUSION

Performance of CIC (cascaded integrator-comb) decimation filters are studied in this paper. This type of filter has extensive applications in low-cost implementation of interpolators and decimators. With the new structures, the proposed filters can operate at much lower sampling rate. They have advantages in high speed operation and low power consumption. Simulation results show the gain responses of the CIC-filter and filter sharpening technique is used to improve the filter performances in terms of a smaller passband error and greater stopband attenuation.

ACKNOWLEDGEMENTS

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