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COMPARISON OF CLASSICAL CIC AND A NEW CLASS OF STOPBAND-IMPROVED CIC FILTERS FORMED BY CASCADING NON-IDENTICAL COMB SECTIONS

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Abstract. *In this paper we propose a new class of selective CIC filters in recursive and nonrecursive form. The filters use a modification of CIC concept, which is achieved by applying a set of non-identical comb sections in cascade. We illustrate examples of the proposed filter function and calculate integer coefficients of filter impulse response. Detailed comparison between the proposed selective filter class and classical CIC filters is given. The results show that the stopband selectivity can be improved significantly in comparison with classical CIC filters with the same filter complexity.*

Key words: *selective CIC filter, comb filters, FIR filters, recursive form, nonrecursive form, classical CIC filter*

1. INTRODUCTION

Comb-based digital filters have become widely used in multirate systems in the recent years, primarily because of their low complexity and power consumption [1]. Classical comb filter functions with finite impulse response and linear phase characteristics $H_N(z)$ have all their zeroes on a unit circle, and the total number of zeroes is N.

With cascade synthesis of identical comb filter functions, one can generate conventional CIC filter functions whose attenuation characteristics are given by:

$$\alpha_{CIC}(N,\mu,\omega) = \left|\frac{\sin N\omega}{N\sin\omega}\right|^{\mu} \tag{1}$$

CIC filters have a great importance in telecommunication techniques and especially in multirate processing and sigma-delta modulation [2, 3]. They have two very important characteristics:

1. Linear phase response, and
2. Multiplierless operation, since they require only delay, addition and subtraction.

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However, classical CIC filters also have the following important shortcomings:

1. Very high value of filter function normalization constant N^{μ},
2. High ratio of max. and min. values of integer coefficients in impulse response:

$$\begin{aligned} h_{CIC_{\max}}(N,\mu) &= \max_{r}\{h_{CIC}(N,\mu,r)\} \\ h_{CIC_{\min}}(N,\mu) &= \min_{r}\{h_{CIC}(N,\mu,r)\} \end{aligned} \qquad r = 0,1,\ldots(N-1)\mu \tag{2}$$

3. Comparatively low stopband attenuation. For example, by setting N = 9, and using μ = 7 cascades, one can obtain stopband attenuation of: $|H_{CIC}(9, 7, z)|$ = 90.27 dB. Stopband attenuation of classical CIC filters is equal to the depth of the first sidelobe, and therefore can be estimated as:

$$\alpha_{CIC,\,s}(N,\mu) \approx \left[N\sin\left(\frac{3\pi}{2N}\right)\right]^{\mu} \tag{3}$$

Some of the attempts to sharpen the filter response and improve the stopband selectivity are described in literature, for example [4-12]. Table 1 summarizes the values of normalization constants, ratios of maximal and minimal impulse response coefficients, and stopband attenuation for different filter parameters N and μ.

Table 1 Characteristic values of classical CIC filter functions

N	μ	Normalization constant	Max/Min coefficient ratio	Stopband attenuation [dB]
5	5	3125	381	60.21
	8	390625	38165	96.33
	11	48828125	4091495	132.45
6	5	7776	780	62.13
	8	1679616	135954	99.40
	11	362797056	25090131	136.68
7	5	16807	1451	63.26
	8	5764801	398567	101.22
	11	1977326743	117224317	139.17

In this paper, we propose a new class of FIR filter function with all zeroes on the unit circle, that improves on all three issues present in classical CIC filters. Normalization constants are lower, ratios of $h_{CICmax}(N, \mu)$ and $h_{CICmin}(N, \mu)$ are reduced, and stopband attenuation values are improved.

2. THE PROPOSED CLASS OF CIC FIR FILTER FUNCTIONS

Classical CIC filter is described by the normalized transfer function which can be condensed into the recursive form:

$$H_N(z) = \frac{1-z^{-N}}{N(1-z^{-1})}, \tag{4}$$

where N is an integer parameter, and filter order is equal to (N-1). When better stopband suppression is required, it is a common procedure to cascade multiple filter sections until the requirements are met. By cascading μ identical comb/integrator stages, the effective transfer function of the cascaded filter is of the form:

$$H_N(\mu, z) = (H_N(z))^{\mu} . \tag{5}$$

By cascading non-identical sections of classical CIC filters, it is possible to obtain filters with different characteristics. Some particular cases of new filter classes based on this approach have been considered previously in [7, 8]. The choice of filter sections can in general be arbitrary, and not every combination would yield justifiable results. On the other hand, the classification of general cascaded filter type has not been attempted in the literature, and we choose to present our own filter class which showed good results towards better stopband performance. In this paper, we propose a filter with transfer function

$$\tilde{H}_N(L, z) = H_{N-2}(L, z) H_N(L, z) H_{N+2}(L, z) H_{N-1}(z) H_{N+1}(z) , \tag{6}$$

which consists of two CIC filters with transfer functions $H_{N-1}(z)$ and $H_{N+1}(z)$, and an L-fold cascade group of three filters with transfer functions $H_{N-2}(z)$, $H_N(z)$, and $H_{N+2}(z)$.

2.1 Recursive form of the proposed filter class

Following from (4), the proposed filter function has a recursive form:

$$\tilde{H}_N(L, z) = \frac{1 - z^{-N+1}}{(N-1)(1 - z^{-1})} \frac{1 - z^{-N-1}}{(N+1)(1 - z^{-1})} \left(\frac{1 - z^{-N+2}}{(N-2)(1 - z^{-1})} \frac{1 - z^{-N}}{N(1 - z^{-1})} \frac{1 - z^{-N-2}}{(N+2)(1 - z^{-1})} \right)^L \tag{7}$$

Frequency response characteristic is:

$$\tilde{H}_N(L, e^{j\omega}) = \frac{e^{j(N-1)K\omega/2}}{\sin^K(\omega/2)} \frac{1}{(N^2-1)} \sin\left(\frac{(N-1) \quad \omega}{2} \right) \sin\left(\frac{(N+1) \quad \omega}{2} \right) \left(\frac{1}{N(N^2-4)} \sin\left(\frac{(N-2) \quad \omega}{2} \right) \sin\left(\frac{N\omega}{2} \right) \sin\left(\frac{(N+2) \quad \omega}{2} \right) \right)^L , \tag{8}$$

where we denote the total number of CIC cascades as $K = 3L + 2$. Normalized amplitude response is:

$$\tilde{A}_N(L, \omega) = \frac{\sin((N-1)\omega/2) \sin((N+1)\omega/2)}{(N-1)(N+1) \sin^2 \omega/2} \left(\frac{\sin((N-2)\omega/2) \sin(N\omega/2) \sin((N+2)\omega/2)}{N(N-2)(N+2) \sin^3 \omega/2} \right)^L , \tag{9}$$

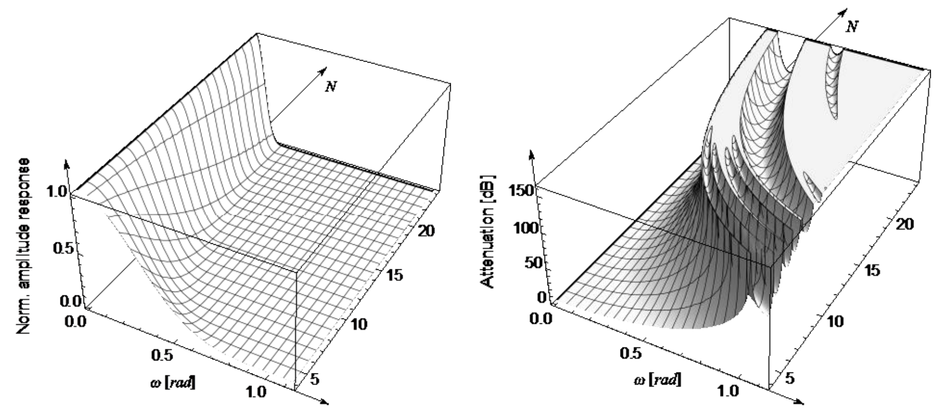
and the magnitude response is obtained when we take absolute value of the amplitude response. As it is obvious from (8), the phase response characteristic is linear and expressed as

$\tilde{\varphi}_N(L,\omega) = (N-1)K\omega/2 + 2k\pi$, where $k \in \{0, \pm 1, \pm 2, \ldots\}$, while the group delay of the proposed filter class is:

$$\tilde{\tau}_N(L,\omega) = (N-1)(3L/2+1) \tag{10}$$

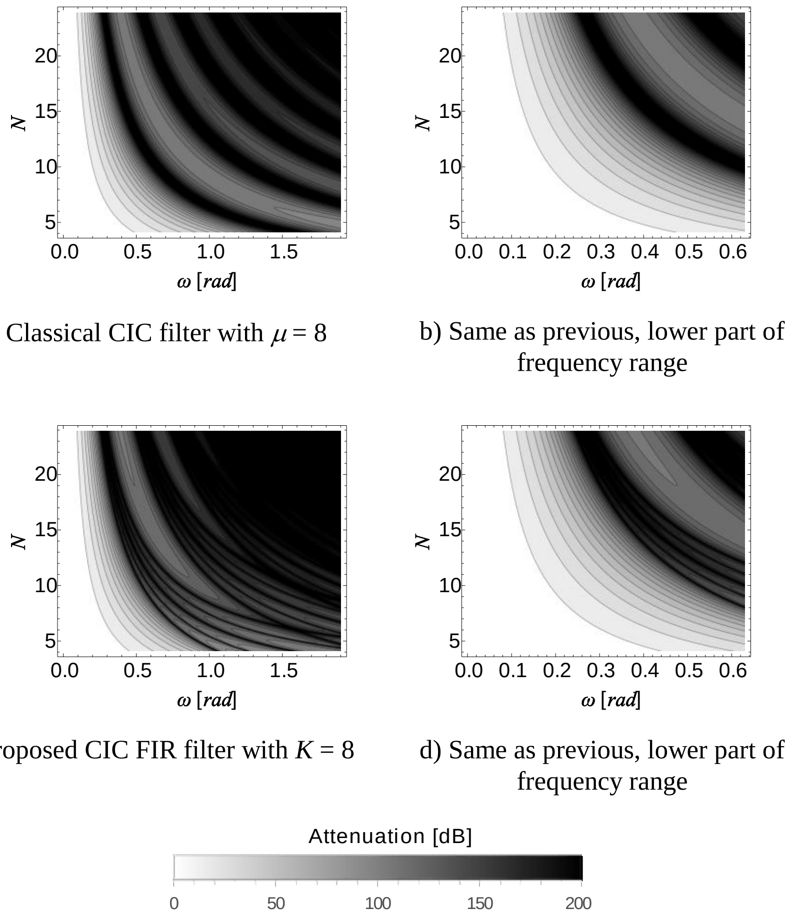
Normalized response characteristics are shown in Fig. 1, for L = 2, and $3 < N < 25$. Amplitude response shows that there are no visible variations in the passband. There is also the smooth transition towards the stopband, which is consistent with general behavior of the classical CIC filters. As the filter order increases, the passband decreases as expected.

Magnitude response shows strong attenuation in the stopband, and this is clearly the consequence of filter zeroes. However, attenuation drops to much lower values between the zeroes, effectively defining the stopband attenuation limit. Lines that define the locations of filter zeroes are clearly visible for lower filter orders and the overall effect of cascading non-identical filter sections is in fact in dispersion of the zeroes. This is also obvious in the Fig. 2 where we show contour plots of the attenuation for different filter orders versus angular frequency. Fig. 2 also compares the magnitude response of the classical CIC filters and the proposed filter class, so that the differences can be highlighted. While the classical CIC filters have strong attenuation bands, and comparatively low attenuation between them, we see that the proposed filter functions have dispersed high attenuation bands, and significantly better attenuation between those bands. As the filter order increases, after certain point the characteristics begin to look similar, so we expect significant results in stopband attenuation improvement at lower filter orders. Figs. 2b and 2d compare the magnitude response spanning lower frequencies close to passband. We can also see that the passband responses of the classical CIC and the proposed filters are very similar, and therefore we can assume that the compensation techniques used for classical CIC filters [14-16] can also be used here successfully.



a) Amplitude response b) Magnitude response

Fig. 1 Normalized response characteristics of the proposed CIC FIR filter class for $N \in \{4\text{-}24\}$, and $L = 2$.



a) Classical CIC filter with $\mu = 8$

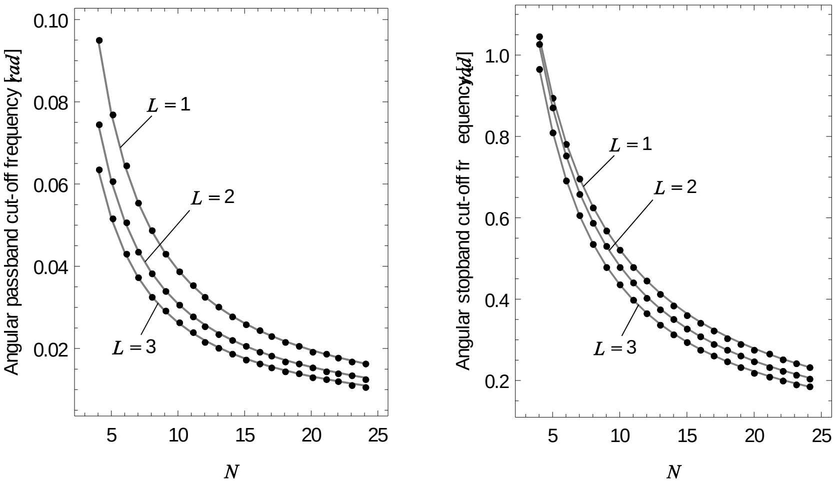
b) Same as previous, lower part of frequency range

c) Proposed CIC FIR filter with $K = 8$

d) Same as previous, lower part of frequency range

Fig. 2 Contour plots of magnitude response characteristics of classical CIC and the proposed CIC FIR filters for $N \in \{4\text{-}24\}$, and total number of cascaded sections $\mu = K = 8$.

We further investigate the passband and stopband cut-off values of the proposed filter class, and the obtained results are shown in Fig. 3. The results are suitable for determining filter parameters N and L when the required values of passband and stopband cut-offs are given. We observe that filter order strongly influences the values of pass- and stopband cut-offs, while the number of cascades does less so. As a consequence, in many cases requirements can be met using more than a single combination of parameters, which gives a certain degree of freedom in choosing the efficient filter function.



a) Passband cut-off values for 0.28 dB response variation

b) Stopband cut-off values for 100 dB attenuation

Fig. 3 Passband and stopband cut-off values of the proposed filter class, for $N\in\{4\text{-}24\}$, and $L\in\{1,2,3\}$.

2.2 Nonrecursive form of the proposed filter class

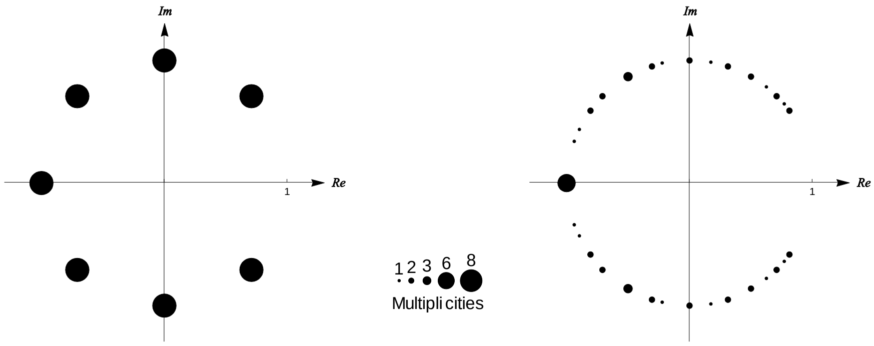
Using the non-recursive form [17, 18] of the normalized classical CIC filter impulse response:

$$H_N(z) = \frac{1}{N}\sum_{i=0}^{N-1} z^{-i} , \tag{11}$$

as a building block, we can write directly the non-recursive form of the proposed filter class impulse response:

$$\tilde{H}_N(L,z) = (N-1)^{-2} N^L (N-2)^{2L} \sum_{i=0}^{N-2} z^{-i} \sum_{j=0}^{N} z^{-j} \left(\sum_{k=0}^{N-3} z^{-k} \sum_{l=0}^{N-1} z^{-l} \sum_{m=0}^{N+1} z^{-m} \right)^L , \tag{12}$$

Classical CIC filters have all zeroes (the number of zeroes is equal to filter order, N-1) on the unit circle in the z-plane, and their multiplicity increases linearly with increasing number of cascades. Therefore, increased multiplicity of the zeroes is a side-effect of cascading filter element in order to improve the stopband attenuation. In the proposed filter class, there are also multiple filter section, but in contrast with classical CIC, the sections are not of the same order. This diversity allows wide spread of zeroes, which are also distributed on the unit circle. By distributing zeroes more evenly for the proposed filter class, we hope to get significantly better stopband characteristics while retaining the other desirable characteristics of the CIC filters. An illustrative example is given in Fig 4, where locations and multiplicities of zeroes are compared for the two types of filters with the same total number of cascades and the same group delay.



a) Classical CIC filter b) Proposed filter

Fig. 4 Locations and multiplicities of filter function zeros in *z*-plane for $N = 8$, and $\mu = K = 8$ cascades.

When all products in (12) are taken into account, the impulse response is written simply as:

$$\tilde{H}_N(L,z) = C_{N,L} \sum_{k=0}^{(3L+2)(N-1)} a_k z^{-k} , \tag{13}$$

where $C_{N,L} = (N-1)^{-2} N^L (N-2)^{2L}$ is the normalization constant. We can observe that the result can be interpreted as a scalar product of the two vectors:

$$\tilde{H}_N(L,z) = C_{N,L} \ \ \mathbf{A}_{N,L} \cdot \mathbf{Z}_{N,L}^T , \tag{14}$$

where $\mathbf{A}_{N,L} = [a_0, a_1, \cdots, a_{(3L+2)(N-1)}]$, $\mathbf{Z}_{N,L} = [1, z^{-1}, z^{-2} \cdots, z^{-(3L+2)(N-1)}]$, and symbol T denotes the vector transpose. Coefficients a_k are computed easily for the given filter parameters N and L, and although general symbolic formula for the a_k may exist, we have not pursued its derivation. Instead, we give the coefficients vectors values for filters with $N \in \{7, 8\}$, and $L \in \{1,2\}$:

For sixth order filter ($N = 7$), with $L = 1$, we have the following 31 coefficients:

$\mathbf{A}_{7,1}$ = [1, 5, 15, 35, 70, 125, 204, 309, 439, 589, 750, 910, 1055, 1171, 1246, 1272, 1246, 1171, 1055, 910, 750, 589, 439, 309, 204, 125, 70, 35, 15, 5, 1],

and with $L = 2$, we have the following 49 coefficients:

$\mathbf{A}_{7,2}$ = [1, 8, 36, 120, 330, 790, 1699, 3350, 6142, 10578, 17243, 26758, 39710, 56562, 77553, 102602, 131233, 162538, 195191, 227520, 257635, 283600, 303628, 316274, 320598, 316274, 303628, 283600, 257635, 227520, 195191, 162538, 131233, 102602, 77553, 56562, 39710, 26758, 17243, 10578, 6142, 3350, 1699, 790, 330, 120, 36, 8, 1]

Coefficients of seventh order filter with $L = 1$, are:

$\mathbf{A}_{8,1}$ = [1, 5, 15, 35, 70, 126, 209, 324, 474, 659, 875, 1114, 1364, 1610, 1835, 2022, 2156, 2226, 2226, 2156, 2022, 1835, 1610, 1364, 1114, 875, 659, 474, 324, 209, 126, 70, 35, 15, 5, 1], while the same order filter with L = 2 has the following 57 coefficients:

$\mathbf{A}_{8,2}$ = [1, 8, 36, 120, 330, 792, 1714, 3415, 6353, 11147, 18586, 29618, 45313, 66796, 95150, 131293, 175839, 228957, 290246, 358645, 432396, 509073, 585684, 658844, 725007, 780736, 822984, 849356, 858322, 849356, 822984, 780736, 725007, 658844, 585684, 509073, 432396, 358645, 290246, 228957, 175839, 131293, 95150, 66796, 45313, 29618, 18586, 11147, 6353, 3415, 1714, 792, 330, 120, 36, 8, 1]

In order to compare the filter responses, we observe the classical CIC filter with same order and group delay has the following impulse response

$$H_N(\mu, z)\ \Big|_{\mu=3L+2} = \frac{1}{N^{3L+2}}\left(\sum_{k=0}^{N-1} z^{-k}\right)^{3L+2} \tag{15}$$

Using the multinomial theorem, previous equation can be written in its expanded form:

$$H_N(\mu, z)\ \Big|_{\mu=3L+2} = \frac{1}{N^{3L+2}} \sum_{k_0+k_1+\cdots+k_{N-1}=L} \frac{L!}{k_0!k_1!\cdots k_{N-1}!} z^{-\sum_{t=0}^{N-1} t\, k_t}\ , \tag{16}$$

and finally in the form analogue to (13):

$$H_N(\mu, z) = \frac{1}{N^{3L+2}} \sum_{k=0}^{(3L+2)(N-1)} b_k z^{-k} \tag{17}$$

In order to further compare the coefficients of classical CIC and proposed filters, we have computed the coefficient vectors for both filters, using the same filter order and group delay. Relative difference of the coefficients is shown in Fig. 5, with classical CIC filter taken as reference, i.e. we define relative difference as $(a_k - b_k)/b_k$. Since the relative difference is always negative, corresponding coefficients of the proposed filter class are always less or equal to those of the classical CIC filters, and this is especially true for the largest coefficients.

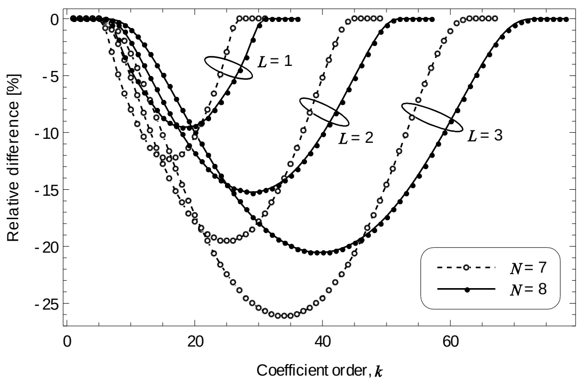


Fig. 5 Relative difference of the impulse response coefficients of the proposed filter class compared to corresponding coefficients of the classical CIC filters.

Normalization constants and max/min coefficient ratios of the proposed filter class are compared to appropriate values of classical CIC filters, and the results are listed in Table 2. Relevant values are about 10% to 45% lower, relative to classical CIC.

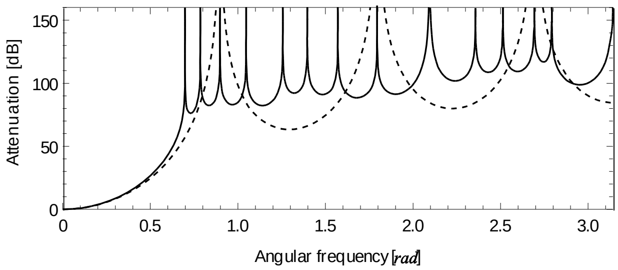
Table 2 Characteristic values of the proposed filters impulse responses, and comparison to corresponding values for classical CIC filters

N	L	μ	Normalization constant	Relative to classical CIC [%]	Max/Min coefficient ratio	Relative to classical CIC [%]
5	1	5	2520	-19.35	292	-23.36
	2	8	264600	-32.26	24544	-35.69
	3	11	27783000	-43.10	2209862	-45.99
6	1	5	6720	-13.58	651	-16.54
	2	8	1290240	-23.18	100716	-25.92
	3	11	247726080	-31.72	16524804	-34.14
7	1	5	15120	-10.04	1272	-12.34
	2	8	4762800	-17.38	320598	-19.56
	3	11	1500282000	-24.13	86589572	-26.13

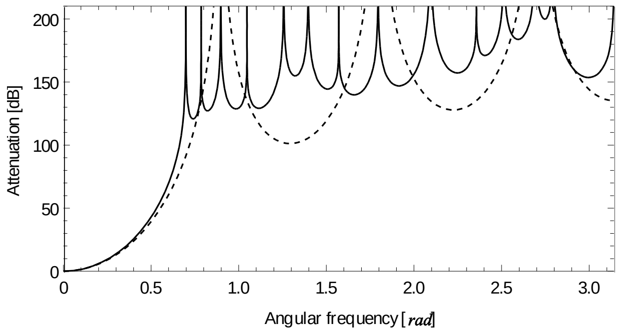
3. Comparison of Stopband Characteristics

As mentioned previously, the most significant effect of zeroes dispersion in the proposed filter class is expected to be the stopband attenuation improvement. To study and illustrate the effect, we show detailed analysis of numerical results obtained for even and odd filter orders $N \in \{7, 8\}$, and different number of cascaded sections, corresponding to $L \in \{1, 2, 3\}$.

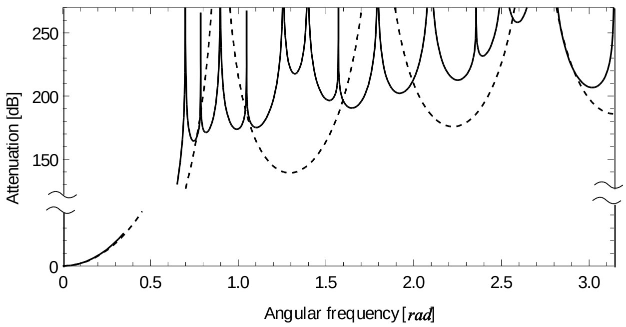
In Fig. 6 we show filter attenuation in dBs, for the angular frequency span of $0 \leq \omega \leq \pi$. It is immediately obvious that the proposed filter outperforms classical CIC filters in the stopband. At the same time, passband characteristics are closely matched, potentially allowing the use of compensators designed for classical CIC filters. As the number of cascades increases, so does the benefit of attenuation improvement. This is in agreement with our initial assumption that the zeroes multiplicity of classical CIC filters can be traded for stopband performance. Numerical values of stopband attenuation, as well as stopband cut-off values are shown in the Fig. 7, which shows zoomed areas of interest from the Fig. 6. It is evident that the stopband improvement can be significant, ranging from about 19 dB for L = 1, 26 dB for L = 2, up to 32 dB for L = 3.



a) Number of cascades is $\mu = 5$ (corresponding to $L = 1$ for the proposed filter)

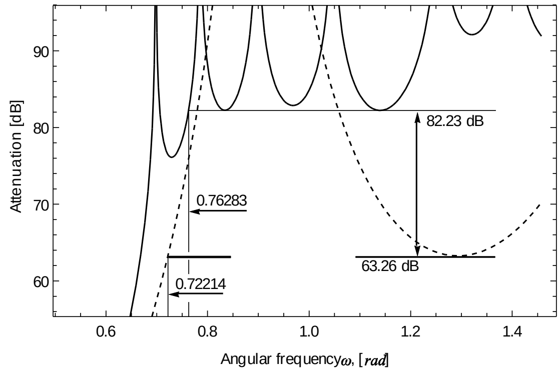


b) Number of cascades is $\mu = 8$ (corresponding to $L = 2$ for the proposed filter)

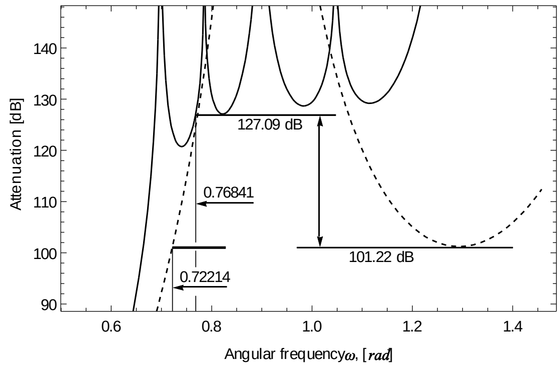


c) Number of cascades is $\mu = 11$ (corresponding to $L = 3$ for the proposed filter)

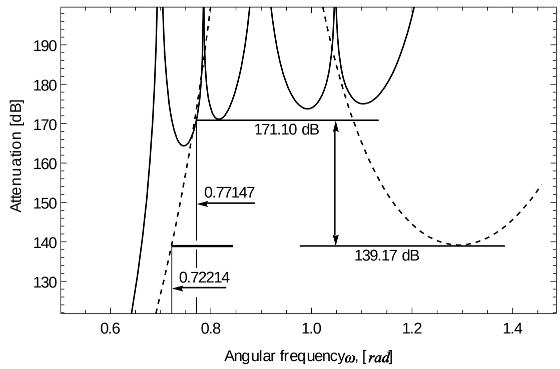
Fig. 6 Comparison of normalized magnitude response characteristics in dB for classical CIC filter with $N = 7$ (dashed lines), and the proposed CIC FIR filter functions with $N = 7$ (solid lines).



a) Number of cascades is $\mu = 5$ (corresponding to $L = 1$ for the proposed filter)



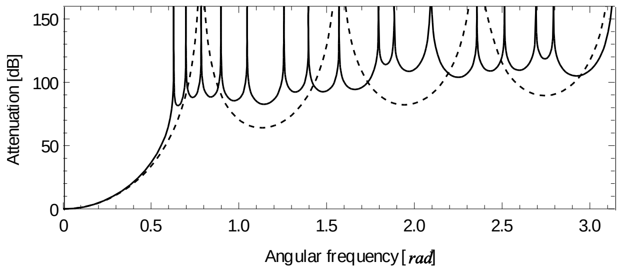
b) Number of cascades is $\mu = 8$ (corresponding to $L = 2$ for the proposed filter)



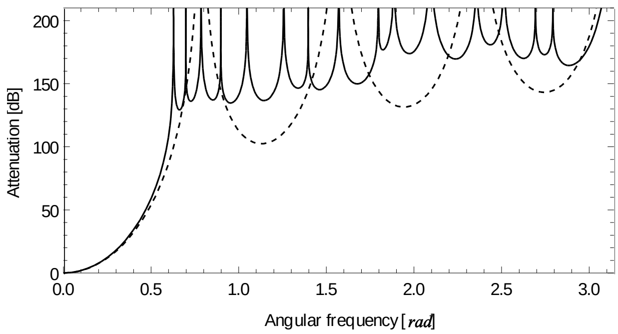
c) Number of cascades is $\mu = 11$ (corresponding to $L = 3$ for the proposed filter)

Fig. 7 Details of comparison shown in Fig.6, with enlarged sections of interest and specific values shown. Characteristics of the classical CIC filters are shown using dashed lines, and those of the proposed filter are in solid lines.

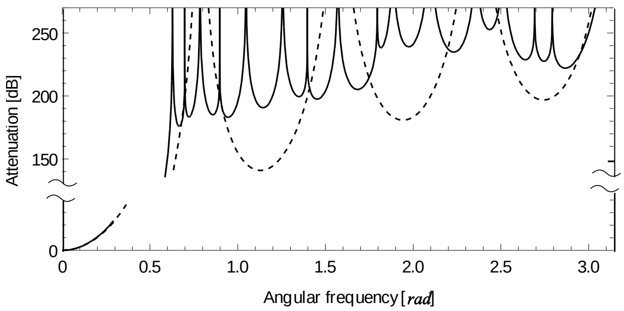
In Fig. 8 we show an example of filter attenuation for odd filter order: $N - 1 = 7$ ($N = 8$). The figure looks very similar to previous example shown in Fig. 6, but there are a few points worth taking notice. Firstly, there are no fundamental differences visible between even and odd filter orders. Secondly, attenuation improvement is not linear, but depends on complex interplay of zeroes locations and multiplicities. Actually, in Fig. 8.a we have a slightly lower improvement than in Fig. 6.a.



a) Number of cascades is $\mu = 5$ (corresponding to $L = 1$ for the proposed filter)

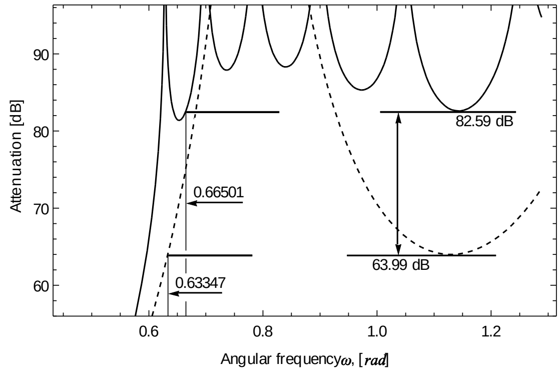


b) Number of cascades is $\mu = 8$ (corresponding to $L = 2$ for the proposed filter)

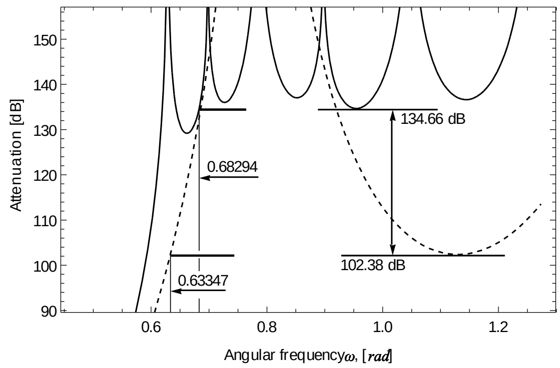


c) Number of cascades is $\mu = 11$ (corresponding to $L = 3$ for the proposed filter)

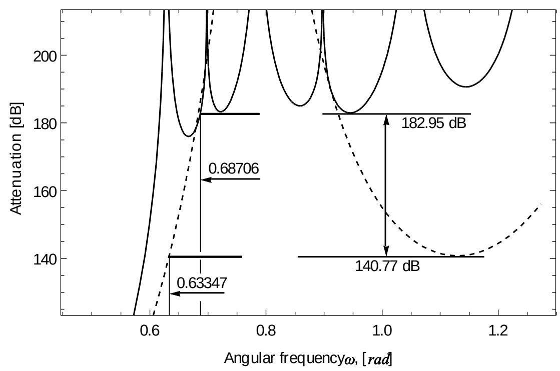
Fig. 8 Comparison of normalized magnitude response characteristics in dB for classical CIC filter with $N = 8$ (dashed lines), and the proposed CIC FIR filter functions with $N = 8$ (solid lines).



a) Number of cascades is $\mu = 5$ (corresponding to $L = 1$ for the proposed filter)



b) Number of cascades is $\mu = 8$ (corresponding to $L = 2$ for the proposed filter)



c) Number of cascades is $\mu = 11$ (corresponding to $L = 3$ for the proposed filter)

Fig. 9 Details of comparison shown in Fig.8, with enlarged sections of interest and specific values shown. Characteristics of the classical CIC filters are shown using dashed lines, and those of the proposed filter are in solid lines.

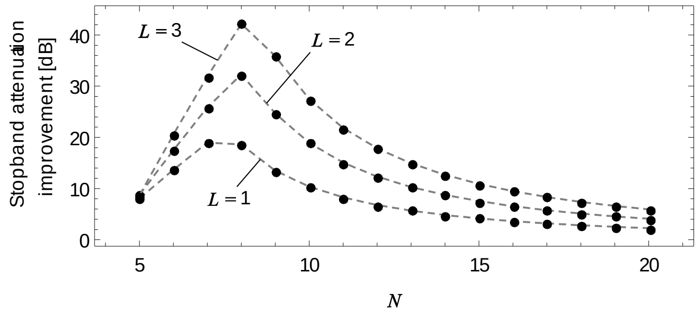


Fig. 10 Stopband attenuation improvement versus parameter *N*.

For higher number of cascades, the attenuation valleys are more uniformly distributed in terms of their attenuation values, and this is an indication that the filter has finer balance and better stopband characteristics. Numerical values of stopband attenuation, as well as stopband cut-off values are shown in the Fig. 9, which shows zoomed areas of interest from the Fig. 8. The stopband improvement here ranges again from about 19 dB for $L = 1$, over 32 dB for $L = 2$, up to 42 dB for $L = 3$.

As we have noticed, because of the complex nature of interplay between the zeroes, it is hard to predict the exact values of stopband attenuation improvement, and these can be efficiently calculated and tabulated only after the actual characteristics comparison. Therefore, we have performed detailed calculations for different filter orders and number of cascades, and we summarize the results in Fig. 10. The results indicate that the best results in improving attenuation in the stopband can be obtained when $N = 8$, for $L = 2$ and $L = 3$. When $L = 1$, most improvement is obtained for $N = 7$. As the filter order increases beyond its optimal value, attenuation improvement becomes consistently lower.

In order to compare the filter function to a similar one presented in [7], we have calculated the stopband attenuation improvement in dBs and normalized it by the total group delay (10), therefore showing how efficient is the filter function in improving the stopband attenuation with increasing number of delay elements. The results shown in Fig. 11 indicate that the proposed filter function is more efficient in this regard than the one presented in [7]. We note that $L = 2$ from [7] corresponds to the same delays as for $L = 4$ in this paper.

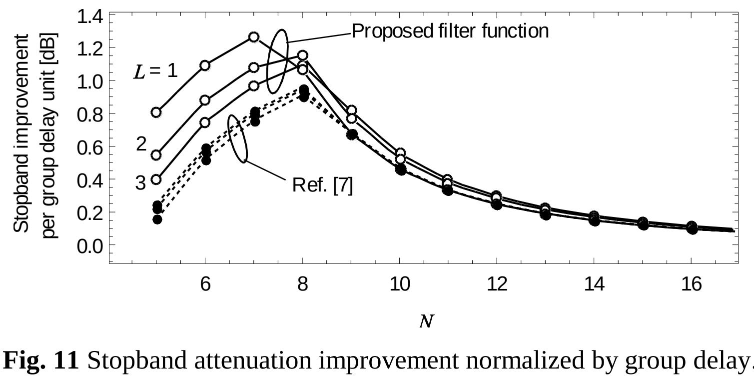


Fig. 11 Stopband attenuation improvement normalized by group delay.

4. CONCLUSION

This paper describes a new class of selective CIC filter functions in recursive and nonrecursive form. We have illustrated examples of the proposed filter function class, and shown details of the response characteristics for wide range of filter orders. We have highlighted the common points and differences in relation to classical CIC filters. Results show that normalization constant, and span of integer filter coefficients are lower than that of corresponding classical CIC filters, while the stopband characteristics are significantly improved.

Detailed comparison of response characteristics with classical CIC filters is given. The results indicate that the proposed class of CIC filter functions can have significant stopband attenuation improvement for the same digital filter complexity. Further research will be directed towards passband droop compensation while keeping the proposed technique for stopband improvement.

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REFERENCES

[1] E. Hogenauer, "An economical class of digital filters for decimation and interpolation," *IEEE Trans. Acoustics, Speech and Signal Processing*, vol. 29, no. 2, pp. 155-162, April 1981.

[2] M. Laddomada, "Generalized comb decimation filters for ΣΔ A/D converters: Analysis and design", *IEEE Trans. on Circuits and Systems*-I, vol. 54, no. 5, pp. 994-1005, May 2007.

[3] M. Laddomada, "Comb-based decimation filters for ΣΔ A/D converters: Novel schemes and comparisons", *IEEE Trans. on Signal Processing*, vol. 55, no. 5, pp. 1769-1779, May 2007.

[4] G. Jovanović Doleček, S. K. Mitra, "A new two-stage sharpened comb decimator", *IEEE Trans. Circuits Syst. I: Regular Papers*, vol. 52, no. 7, pp. 1414-1420, July 2007.

[5] M. Nikolić, M. Lutovac, "Sharpening of the multistage modified comb filters", *Serbian Journal of Electrical Engineering*, vol. 8, no. 3, pp. 281-291, 2011.

[6] J.O. Coleman, "Chebyshev stopbands for CIC decimation filters and CIC-implemented array tapers in 1D and 2D", *IEEE Trans. Circuits Syst. I*, vol. 59, no. 12, pp. 2956-2968, December 2012.

[7] D. Milić, V. Pavlović, "A New Class of Low Complexity Low-Pass Multiplierless Linear-Phase Special CIC FIR Filters", *IEEE Signal Processing Letters*, vol. 21, no. 12, pp. 1511-1515, Dec. 2014.

[8] V. Pavlović, D. Milić, B. Stošić, „Characteristics of Novel Designed Class of CIC FIR Filter Functions Over Classical CIC Filters", IcETRAN 2014, Proceedings of the 1st International Conference on Electrical, Electronic and Computing Engineering, Vrnjačka Banja, Serbia, June 2-5, 2014.

[9] M. Lutovac, V. Pavlovic, M. Lutovac, "Efficient recursive implementation of multiplierless FIR filters", In Proceedings of the 2nd Mediterranean Conference on Embedded Computing (MECO), 15-20 June 2013, pp. 128-131.

[10] V. Pavlovic, M. Lutovac, M. Lutovac, "Efficient implementation of multiplierless recursive lowpass FIR filters using computer algebra system", In Proceedings of the 11th International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS), 16-19 Oct. 2013, vol. 1, pp. 65-68.

[11] M. Laddomada, D. E Troncoso, G. J. Doleček, "Design of Multiplierless Decimation Filters Using an Extended Search of Cyclotomic Polynomials", *IEEE Trans. Circuits Syst. II*, vol. 58, no. 2, pp. 115-119, Feb. 2011.

[12] W. A. Abu-Al-Saud, G. L. Stuber, "Modified CIC filter for sample rate conversion in software radio systems" *IEEE Signal Processing Letters*, vol. 10, no. 5, pp. 152-154, May 2003.

[13] G. J. Doleček, F. Harris, "Design of wideband CIC compensator filter for a digital IF receiver", *Digital Signal Processing*, vol. 19, pp. 827-837, September 2009.

[14] A. Fernandez-Vazquez, G. J. Doleček, "Maximally flat CIC compensation filter: Design and multiplierless implementation", *IEEE Trans. Circuits Syst. II*, vol. 59, no. 2, pp. 113–117, Feb. 2012.

[15] G. J. Doleček, A. Fernandez-Vazquez, "Trigonometrical approach to design a simple wideband comb compensator", *Int. J. Electron. Commun. (AEÜ)*, vol. 68, no. 5, pp. 437-441, May 2014.

[16] G. J. Doleček, A. Fernandez-Vazquez, "Novel droop-compensated comb decimation filter with improved alias rejections", *Int. J. Electron. Commun. (AEÜ)*, vol. 67, no. 5, pp. 387-396, May 2013.

[17] J. Le Bihan, "Impulse response and generating functions of $sinc^N$ FIR filters", In Proceedings of the Sixth International Conference on Digital Telecommunications ICDT 2011, 2011, pp. 25-29.

[18] S.C. Dutta Roy, "Impulse response of $sinc^N$ FIR filters", *IEEE Trans. Circuits Syst. II*, vol. 53, no. 3, pp. 217-219, March 2006.

[19] B. Stošić, D. Milić, V. Pavlović, "New CIC Filter Architecture: Design, Parametric Analysis and Some Comparisons", *IETE Journal of Research*, vol. 61, no. 3, pp. 244-250, Mar. 2015.