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DESIGN OF MULTIPLIERLESS COMB COMPENSATORS WITH MAGNITUDE RESPONSE SYNTHESIZED AS SINEWAVE FUNCTIONS

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Abstract. *This paper presents a research on design of multiplierless comb compensators with magnitude response synthesized as sinewave functions. First, it is elaborated the importance of comb decimation filter and why we need its compensator. In continuation are presented some favorable characteristics of comb compensator. The compensators, with magnitude characteristic synthesized as sinewave functions fulfill those favorable characteristics. Next, are described some most important results on design of compensators with sinewave-based magnitude responses including single and cascaded sinewave-based functions. In all designs are presented the overall corresponding magnitude responses and the zooms in the passband. The parameters of design generally depend only on number of cascaded combs and generally do not depend on decimation factor. Design parameters are presented in tables along with the corresponding required number of adders.*

Key words: *Sigma Delta AD converters, oversampling, decimation, decimation filter, comb filter, compensation filter.*

1. INTRODUCTION

The oversampled Sigma Delta (ΣΔ) Analog-Digital Converters (ADC) samples the analog signal with a frequency much larger than the Nyquist frequency (which is the minimum required sampling frequency), usually expressed through Over Sampling Ratio (OSR) [1]. Oversampled converters have gained a lot of popularity in last two decades due to some very favorable characteristics like low power consumption, small silicon area, high resolution, among others, [2], [3]. The oversampled signal frequency must be decreased to the Nyquist frequency at the AD modulator output. This process is performed in a digital form in decimator. Therefore the principal parts of ΣΔ ADC are modulator and decimator. Our attention here is only on the decimator.

Decimation is a process of decreasing the sample rate by an integer called decimation factor *M*. Decimation introduces unwonted replicas of the main spectrum called aliasing.

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Aliasing may deteriorate the decimated signal and must be eliminated prior the decimation by a lowpass digital filter, called decimation, or antialiasing filter [4].

The most popular decimation filter is a comb filter which has all coefficients equal to unity and consequently does not require multipliers for its implementation.

This filter naturally provides the aliasing rejection in bands around the comb zeros, called folding bands. However, this attenuation is not enough and must be improved. Some recent methods for improving comb aliasing rejection are described in [5].

Additionally, the comb passband characteristic is not flat and exhibits a passband droop, which is increased with the increase of the number of cascaded combs *K*. The introduced droop in the signal band penalizes the resolution achieved by the ΣD ADC, and should be compensated [1].

In this paper we only consider the design of comb compensators. The rest of the paper is organized in the following form. Next section presents basic description of comb filters in *z*-domain and also in the frequency domain. The wideband and narrowband compensators are defined and some very desirable characteristics of comb compensator are elaborated. Section III presents compensator with magnitude characteristic synthesized as a single sinewave function. Wideband and narrowband cases are elaborated. The magnitude responses based on the cascade of single sinewave functions are described in Section IV. Finally, Section V introduces the most efficient compensator with magnitude response synthesized using fourth-order sinewave function. The parameters of design are presented for all methods, and methods are illustrated with examples.

2. COMB DECIMATION FILTER

Transfer function of the comb filter is usually presented in a recursive form as:

$$H(z) = \frac{1}{M}\left[\frac{1-z^{-M}}{1-z^{-1}}\right]^{K}, \qquad (1)$$

where *M* is the decimation factor and *K* is the number of cascaded combs.

From the recursive form (1) is derived the popular CIC (Cascaded-Integrator-Comb) structure [6], shown in Fig. 1. Due to the popularity of CIC structure some authors use also term CIC for comb filter.

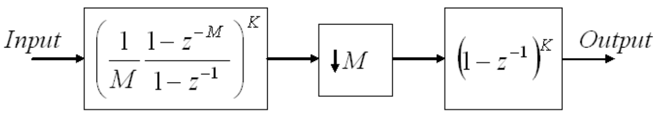


Fig. 1 CIC structure

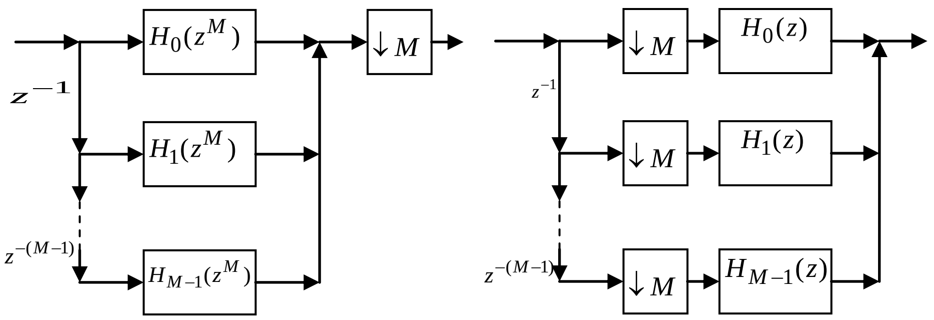
The nonrecursive transfer function is given as [4]:

$$H(z) = \left[\frac{1}{M}\sum_{k=0}^{M-1} z^{-k}\right]^{K}. \qquad (2)$$

The recursive structure is area efficient, while the nonrecursive structure is a power efficient [4]. Using the polyphase decomposition the nonrecursive structure may be more power efficient because all filtering is moved to the lower rate. In a polyphase decomposition the polyphase components are introduced [4]:

$$H(z) = \frac{1}{M} \sum_{k=0}^{M-1} z^{-\lambda} H_{\lambda}(z^{M}) \,, \tag{3}$$

where $H_{\lambda}(z^M)$, λ=1,….,M-1, are the polyphase components.
The polyphase decomposition is shown in Fig. 2 a. Using the multirate identities [4] we get more efficient structure, shown in Fig. 2b.



a. Comb polyphase decomposition b. Moving filtering to lower rate

Fig. 2 Polyphase decomposition

The magnitude characteristic of comb filter has the following form:

$$\left|H(e^{j\omega})\right| = \left|\frac{1}{M}\frac{\sin(\omega M/2)}{\sin(\omega/2)}\right|^{K} . \tag{4}$$

The passband edge frequency ω_p is defined as:

$$\omega_p = \pi / RM \,, \tag{5}$$

where R is an integer.

For R=2, it is considered wide passband, while for R<2 is considered a narrowband.

The magnitude characteristic (4) should be flat in the passband in order to preserve the decimated signal.

The stopband is defined in bands around comb zeros, called folding bands, where aliasing occur:

$$\frac{2k\pi}{M} - \omega_p \le \omega \le \frac{2k\pi}{M} + \omega_p \,, \quad k = \begin{cases} 1,....M/2 & \text{for} \quad M \text{ even} \\ 1,..., (M-1)/2 & \text{for} \quad M \text{ odd} \end{cases} . \tag{6}$$

In order to eliminate aliasing, comb should have enough attenuation in folding bands. Figure 3 shows overall comb magnitude characteristics for M=15 and K=1,…,5. The wideband passband zoom is also shown.

We can easily note that by increasing the comb parameter K, the aliasing rejection is improved. However, the passband droop is increased.

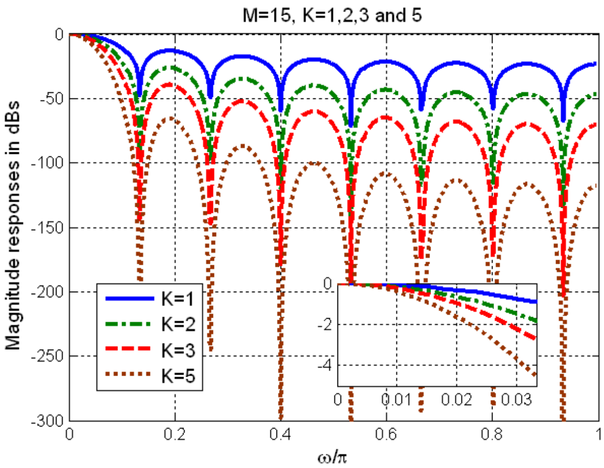


Fig. 3 Overall comb magnitude responses and passband zoom, for different values of *K*

The passband droop of comb *H*(*z*) must be corrected by the filter called comb compensator filter *C*(*z*), which works at low rate i.e. after decimation, as shown in Fig.4.

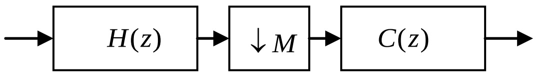


Fig. 4 Compensated comb

We consider here only comb compensators.

Some desirable characteristics of the .compensator are listed in the continuation:

- Like comb, the compensator structure does not require multipliers.
- The multiplierless compensator has a low number of adders.
- Compensator design is simple and defined only by the comb parameter *K*, and generally does not depend on the decimation factor *M*.
- Compensated comb has a low absolute value of the passband deviation.
- Compensator should not deteriorate alias rejection in comb folding bands.

Generally, there is a trade-off between the number of adders and the absolute value of the passband deviation of the compensated comb.

The compensator magnitude characteristic should approximate inverse comb characteristic:

$$\left|H_i(e^{j\omega})\right| = \left|\frac{M\sin(\omega/2)}{\sin(\omega M/2)}\right|^K, \tag{7}$$

in the passband:

$$\left|C(e^{jM\omega})\right| \approx \left|H_i(e^{j\omega})\right| \text{ for } 0 \le \omega \le \omega_p, \tag{8}$$

where ω_p is the passband frequency edge and $C(e^{jM\omega})$ is the compensator frequency response at high rate.

Different methods have been proposed for design of narrowband and wideband multiplierless compensators.

In this paper we consider only compensators with magnitude characteristic synthesized using sinewave forms, since those types of compensators truly satisfy all compensator desirable characteristics, previously mentioned. In all examples we consider the same values of comb parameters, i.e., M=16 and 25, and K=5.

3. Single Sinewave Function-Based Magnitude Response

3.1 Wide band compensator [7]

The magnitude response of compensator presented in [7] has a sinewave-squared form:

$$\left|C(e^{j\omega M})\right| = 1 + B\sin^2(\omega M/2)\,, \tag{9}$$

where B is amplitude of sine-squared function, M is a comb parameter.

The magnitude characteristic of the compensated comb is:

$$\left|H_c(e^{j\omega})\right| = \left|H(e^{j\omega})C(e^{j\omega M})\right| = \left|\frac{1}{M}\frac{\sin(\omega M/2)}{\sin(\omega/2)}\right|^K [1 + B\sin^2(\omega M/2)]\,, \tag{10}$$

where K is the order of comb filter.

The values of parameter B depend on the given value of comb parameter K and do not depend on the comb parameter M, (for M>10), and are given in the first column of Table 1, [7]. The resulting maximum absolute value of passband deviation of the compensated comb, is equal to 0.4dB.

Using a well known trigonometrical relation,

$$\sin^2(\beta) = [1 - \cos(2\beta)]/2\,, \tag{11}$$

the transfer function of compensator, at low rate, is given as:

$$C(z) = 2^{-2}[-B + (2^2 + 2B)z^{-1} - Bz^{-2}] = 2^{-2}B[-1 + 2z^{-1} - z^{-2}] + z^{-1}\,. \tag{12}$$

The compensator is a second order filter. The number of required adders S is shown in the second column of Table 1. Note that the compensator coefficients can be presented using shifts and adders, and consequently the compensator is a multiplierless filter.

Table 1 Values of parameter B and adders S for K=1,…, 5

K	B	S
1	2^{-2}	3
2	2^{-1}	3
3	$2^{-1}+2^{-2}$	4
4	1	3
5	$1+2^{-2}$	4

The values in Table 1, can be used for the same value of K and different values of M, as shown in the following example.

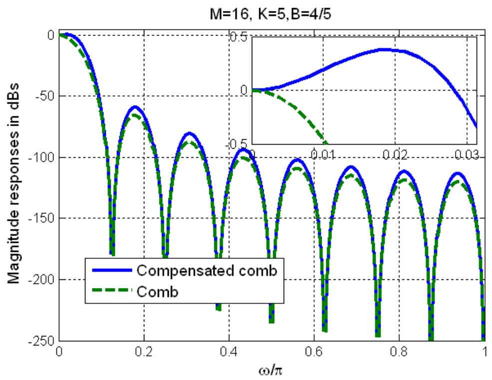
Example 1: We consider the value of $K = 5$ and two different values for M, 16 and 25. From Table 1, the parameter $B = 5/4=1+2^{-2}$. From (10), the magnitude responses of compensated combs are given as:

$$\left|H_{c_1}(e^{j\omega})\right| = \left|\frac{1}{16}\frac{\sin(8\omega)}{\sin(\omega/2)}\right|^5 [1+5/4\sin^2(8\omega)], \quad (13)$$

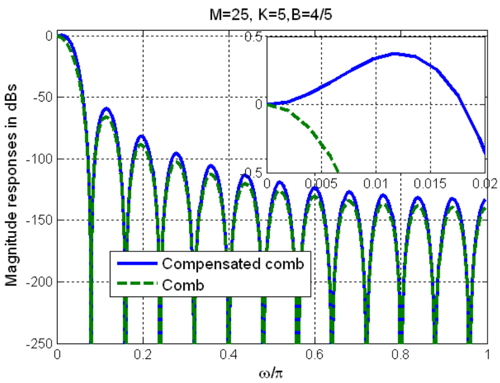
$$\left|H_{c_2}(e^{j\omega})\right| = \left|\frac{1}{25}\frac{\sin(25\omega/2)}{\sin(\omega/2)}\right|^5 p[1+5/4\sin^2(25\omega/2)], \quad (14)$$

where sub indexes 1 and 2 are for M=16, and 25, respectively.

The overall magnitude responses of the compensated comb and comb are shown in Fig. 5, along with the passband zoom.



a. M=16, K=5



b. M=25, K=5

Fig. 5 Magnitude responses of comb and compensated comb in [7]

3.2 Narrowband compensator [8]

In [8] was proposed a narrowband compensator with the following magnitude characteristic:

$$\left|C(e^{j\omega M})\right| = 1 + 2^{-b}\sin^2(\omega M/2)\,, \tag{15}$$

where b is parameter and the passband edge is equal:

$$\omega_p = \pi/8M\,. \tag{16}$$

The transfer function is given as:

$$C(z) = -2^{-(b+2)}[1-(2^{b+2}+2)z^{-1}+z^{-2}]\,. \tag{17}$$

The parameter b depends only on comb parameter K. The values of b for K=2,…,6, are given in Table 2.

Considering values of the parameter b and (17), it follows that the compensator needs only S= 3 adders, for all values of K, as shown in third column of Table 2.

Table 2 Values of parameter b and adders S, for K = 2,…,6

K	b	S
2	2	3
3	2	3
4	1	3
5	0	3
6	0	3

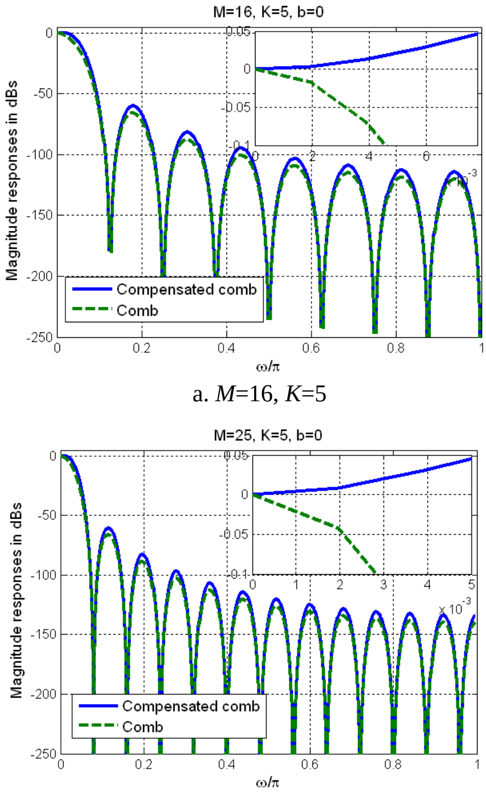
Example 2: We consider again M = 16 and 25, and K = 5. From Table 2, in both cases b = 0 and the magnitude characteristics of the compensated combs are:

$$\left|H_{c_1}(e^{j\omega})\right| = \left|\frac{1}{16}\frac{\sin(8\omega)}{\sin(\omega/2)}\right|^5 [1+\sin^2(8\omega)]\,, \tag{18}$$

$$\left|H_{c_2}(e^{j\omega})\right| = \left|\frac{1}{25}\frac{\sin(25\omega/2)}{\sin(\omega/2)}\right|^5 [1+\sin^2(25\omega/2)]\,, \tag{19}$$

where sub indexes 1 and 2 are for M=16, and 25, respectively.

The corresponding magnitude responses are shown in Fig. 6.



a. M=16, K=5

b. M=25, K=5

Fig. 6 Magnitude responses of comb and compensated comb in [8]

4. Magnitude Response Synthesized as Cascade of Sinewave Functions

4.1. Method in [9]

In order to decrease maximum absolute passband deviation of compensated comb, in [9] was proposed the magnitude response of compensator as a cascade of two sinewave functions with different parameters B:

$$\left|C(e^{j\omega})\right| = \left|1 + B_1 \sin^2(\omega/2)\right| \times \left|1 + B_2 \sin^2(\omega/2)\right| \ . \tag{15}$$

The proposed compensator has an interesting feature, i.e. the parameter B_1 remains the same for all values of K, and B_2 is linearly related with the comb parameter K:

$$B_1 = 2^{-3}; B_2 = \frac{1+4(K-1)}{2^4} \text{, for } K=1,\ldots.5. \tag{16}$$

The parameters and number of adders S are summarized in Table 3.

The method is illustrated in next example, taking the same comb parameters as in previous examples.

Table 3 Values of parameters B_1 and B_2 and adders S, for K=1,…,5

K	B_1	B_2	S
1	2^{-3}	2^{-4}	6
2	2^{-3}	$2^{-4}+2^{-2}$	7
3	2^{-3}	$2^{-4}+2^{-1}$	7
4	2^{-3}	$2^{-4}+2^{-2}+2^{-1}$	8
5	2^{-3}	$2^{-4}+2^{0}$	7

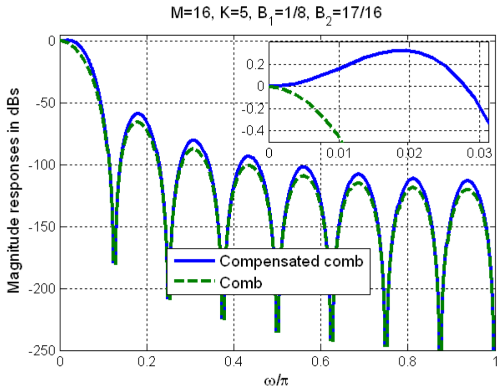
Example 3: From (16) we get $B_1=2^{-3}$, and $B_2=17/16=1+2^{-4}$, for both values of M.

The magnitude responses of compensated combs for M=16 and 25, respectively, are:

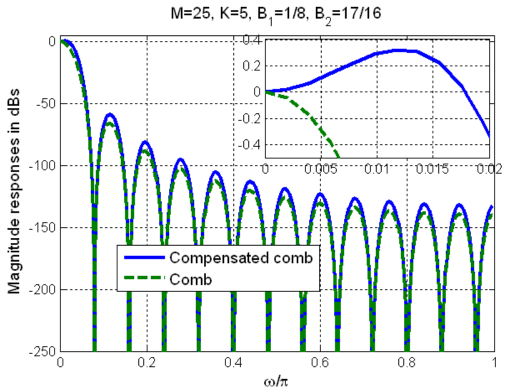
$$\left|H_{c_1}(e^{j\omega})\right| = \left|\frac{1}{16}\frac{\sin(8\omega)}{\sin(\omega/2)}\right|^5 [1+1/8\sin^2(8\omega)][1+17/16\sin^2(8\omega)]\,. \qquad (17)$$

$$\left|H_{c_2}(e^{j\omega})\right| = \left|\frac{1}{25}\frac{\sin(25\omega/2)}{\sin(\omega/2)}\right|^5 [1+1/8\sin^2(25\omega/2)][1+17/16\sin^2(25\omega/2)]\,. \qquad (18)$$

The overall magnitude responses and the passband zooms for both cases are shown in Fig. 7.



a. M=16, K=5



b. M=25, K=5

Fig. 7 Magnitude responses of comb and compensator in [9]

Note that the maximum absolute passband deviation of the compensated combs is slightly decreased and it is lesser than 0.3 dB.

4.2. Cascade narrowband and wideband compensators [10]

In [10] is proposed the cascade of narrowband compensator (17) from [8]

$$C_1(z) = -2^{-(b+2)}[1-(2^{b+2}+2)z^{-1}+z^{-2}], \tag{19}$$

and the wideband compensator from [11]:

$$C_2(z) = [-2^{-4}[z^{-1}-(2^4+2)z^{-2}+z^{-3}]]^{K_1}, \tag{20}$$

where K_1 is the parameter.

The transfer function of compensator is:

$$\begin{aligned} &C(z) = C_1(z)\times C_2(z) = \\ &-2^{-(b+2)}\times[1-(2^{b+2}+2)z^{-1}+z^{-2}]\times[-2^{-4}[z^{-1}-(2^4+2)z^{-2}+z^{-3}]]^{K_1}. \end{aligned} \tag{21}$$

The parameters of compensator, b and K_1, depend only on the comb parameter K, and are shown in Table 4 along with the corresponding number of adders S for values of K=2, …,5.

Table 4 Values of parameters b and K_1 and adders S, for values of K=2,…, 5.

K	K_1	b	S
2	1	1+2	6
3	2	1+2	9
4	3	1+2	12
5	4	2^2	15
6	5	$1+2^2$	18

The maximum absolute passband deviation of the compensated comb is decreased, as shown in the following example. However, the number of the required adders is increased, as given in last column of Table 4.

Example 4: We again consider the decimation factors 16 and 25 and K=5. From Table 4 we have the compensator parameters K_1=4 and b=22. The required number of adders is 15. The magnitude response of compensated comb for M=16:

$$\left|H_{c_1}(e^{j\omega})\right| = \left|\frac{1}{16}\frac{\sin(8\omega)}{\sin(\omega/2)}\right|^5 \left|C(e^{j16\omega})\right|, \tag{22}$$

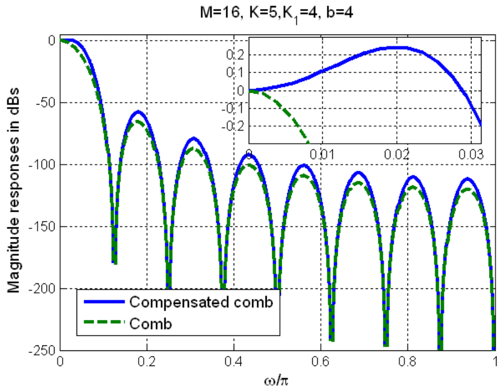
where $C(e^{j16\omega})$ is the magnitude response of compensator (21) at high rate.

Similarly, the magnitude response of the compensated comb with M=25, at high rate is:

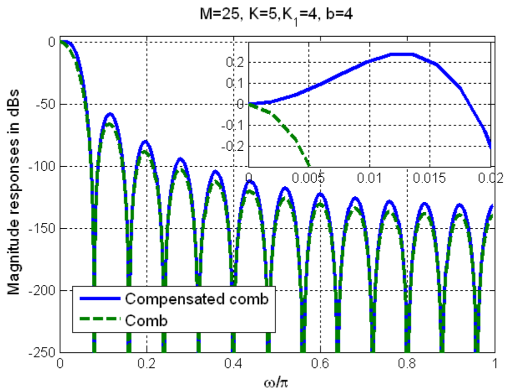
$$\left|H_{c_2}(e^{j\omega})\right| = \left|\frac{1}{25}\frac{\sin(25\omega)/2}{\sin(\omega/2)}\right|^5 \left|C(e^{j\omega 25})\right|, \tag{23}$$

where $C(e^{j25\omega})$ is magnitude response of the compensator (21) at high rate.

The overall magnitude responses of the combs and the compensated combs are contrasted in Fig. 8. The passband zooms are also shown.



a. M=16, K=5, K_1=4, b=4



b. M=25, K=5, K_1=4, b=4

Fig. 8 Magnitude responses of comb and compensated comb in [10]

5. Fourth-Order Sine-based Magnitude Response [12]

In order to get better approximation of the inverse comb characteristic in [12] was proposed to cascade the filter (9) from [7], and filter with a fourth-order sine-based magnitude response:

$$\left|C_2(e^{j\omega M})\right| = 1 + A\sin^4(\omega M/2). \tag{24}$$

The magnitude characteristic of the compensator is given as:

$$C(e^{j\omega M}) = C_1(e^{j\omega M})C_2(e^{j\omega M}) . \quad (25)$$

Using (9), (24) and (25), the magnitude characteristic of compensator at high rate, becomes:

$$\left|C(e^{j\omega M})\right| = [1 + B\sin^2(\omega M/2)] \times [1 + A\sin^4(\omega M/2)] . \quad (26)$$

Transfer function $C_2(z)$ is obtained by using the following trigonometrical relations:

$$\sin^4(\alpha) = [\cos(4\alpha) - 4\cos(2\alpha) + 3]/8 . \quad (27)$$

Using (27) and Euler's formula from (24) we get:

$$C_2(z) = 2^{-4} A[1 + z^{-4} - 4(z^{-1} + z^{-3}) + (2^2 + 2)z^{-2}] + z^{-2} . \quad (28)$$

Similarly, from (14) we have:

$$C_1(z) = 2^{-2}[-B + (2^2 + 2B)z^{-1} - Bz^{-2}] = 2^{-2} B[-1 + 2z^{-1} - z^{-2}] + z^{-1} . \quad (29)$$

Finally, from (28) and (29) we get the compensator transfer function:

$$\begin{aligned} &C(z) = C_1(z)C_2(z) = \\ &[2^{-4} A[1 + z^{-4} - 4(z^{-1} + z^{-3}) + (2^2 + 2)z^{-2}] + z^{-2}] \times . \\ &[2^{-2} B[-1 + 2z^{-1} - z^{-2}] + z^{-1}] \end{aligned} \quad (30)$$

The values of A and B are the parameters of the design which depend on the comb parameter K, and are given in Table 5 along with the required number of adders for each value of K, K=1,….,6.

Table 5 Values of parameters A and B, and adders S, for values of K=1,…, 6.

K	A	B	S
1	0	2^{-2}-2^{-5}	4
2	2^{-2}	2^{-2}+2^{-4}	10
3	2^{-1}	2^{-1}-2^{-4}	10
4	2^{-1}	2^{-1}+2^{-3}+2^{-4}	11
5	1	2^{0}-2^{-2}-2^{-5}	11
6	1	2^{0}-2^{-6}	10

The method is illustrated in Example 5.

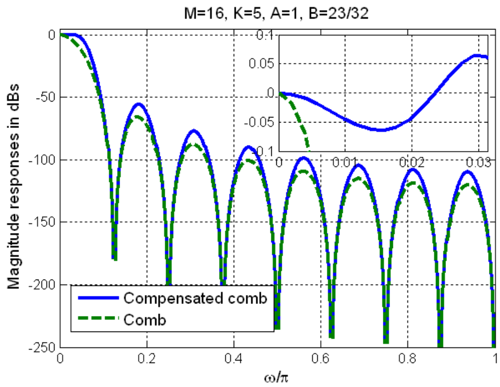
Example 5: Using the same values M=16 and 25 and K=5, as I previous examples, from Table 4, we get design parameters: A=1 and B=2^0-2^{-2}-2^{-5}=23/32.

Magnitude responses of compensated combs for M=16 and 25, respectively, are given as:

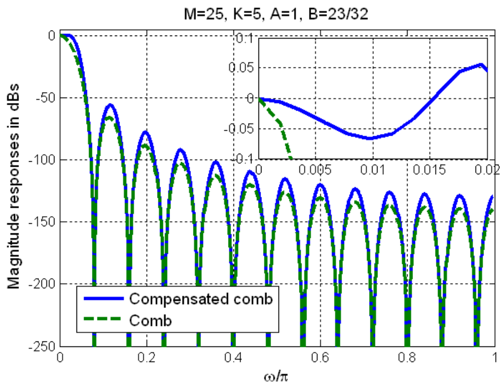
$$\left|H_{C_1}(e^{j\omega})\right| = \left|\frac{1}{16}\frac{\sin(8\omega)}{\sin(\omega/2}\right|[1 + 23/32\sin^2(8\omega)] \times [1 + \sin^4(8\omega)] . \quad (31)$$

$$\left|H_{c_2}(e^{j\omega})\right| = \left|\frac{1}{25}\frac{\sin(25\omega/2)}{\sin(\omega/2}\right|[1+23/32\sin^2(\omega 25/2)]\times[1+\sin^4(\omega 25/2)]. \quad (32)$$

Magnitude responses (31) and (32) are contrasted with the comb magntude responses in Fig. 9a and 9b, respectively. The zooms in passband are shown in both cases.



a. *M*=16, *K*=5, *A*=1, *B*=23/32



b. *M*=25, *K*=5, *A*=1, *B*=23/32

Fig. 9 Illustration of compensator in [12]

The absolute value of passband deviation of the compensated combs is lesser than 0.1 dB requiring 11 adders.

6. Conclusion

This paper addresses the different methods for comb compensator design with magnitude responses synthesized as sinewave functions. The presented methods are the result of our research in last ten years. All presented designs are multiplierless, considering that the compensator coefficients are realized using only adders and shifts. All design parameters depend only on the comb parameter *K*, and practically do not depend on the decimation factors. The design parameters are presented in tables. The presented methods are compared in Table 6 in terms of the compensation capability expressed in maximum absolute value of the passband deviation in dB, of the compensated comb, and the complexity expressed in number of adders. In all presented methods, comb compensation do not deteriorate aliasing rejection in folding bands.

Table 6 Comparisons

Method	δ[dB]	*S*
[3]	0.4	3, for *K*=1,2,4; 4, for *K*=3,5
[9]	0.3	6 for *K*=1; 7 for *K*=2,3,5; 8 for *K*=4
[10]	0.25	6 for *K*=2; 9 for *K*=3; 12 for *K*=4, 15 for *K*=5; 18 for *K*=6
[12]	0.1	4, for *K*=1, 10 for *K*=2,3; 11, for *K*=4,5; 10, for *K*=6

We can observe that the compensator in [12] exhibits best trade-off between the quality of compensation expressed in the maximum absolute passband deviation and the complexity expressed in the number of required adders.

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