Simple wideband CIC compensator

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A simple design for wideband compensation of a cascaded-integrator-comb (CIC) decimation filter is presented. The proposed multiplierless linear phase finite impulse response compensator works at a low sampling rate and requires only three additions/subtractions. The structure of the filter is independent of the decimation factor and the number of the cascaded CIC filters K. However, the proposed filter requires K or $K-1$ stages, depending on the parameter K of the CIC filter.

Introduction: A commonly used decimation filter is the cascaded-integrator-comb (CIC) filter [1] with the transfer function

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

where M is the decimation ratio, and K is the number of stages. The corresponding magnitude characteristic has a highpass band droop that causes degradation of the decimated signal. Several schemes have been proposed to compensate for the passband droop of CIC filters, for the narrow passband [2–4] and the wide passband [5].

The motivation behind this work is to appropriately modify the original CIC characteristic in the passband defined with the passband frequency $\omega_p = \pi/2M$, such that the compensator filter has the following characteristics: 1. It has only three coefficients; 2. It works at the low rate; 3. Multiplierless design; 4. No need for redesign for different values M and K.

Cosine-based compensator: Consider the transfer function of the three coefficient FIR filter

$$G(z^M) = bz^{-M} + az^{-2M} + bz^{-3M} \tag{2}$$

with the corresponding magnitude characteristic

$$|G(e^{jM\omega})| = |2b\cos(M\omega) + a| \tag{3}$$

The condition that the magnitude characteristic (3) has the value 1 for $\omega = 0$, gives

$$a = 1 - 2b \tag{4}$$

Replacing (4) into (3) we arrive at

$$|G(e^{jM\omega})| = |2b[\cos(M\omega) - 1] + 1| \tag{5}$$

The value of b is estimated minimising the squared error in the passband

$$\min_b \int_0^{\omega_p} E^2(\omega)d\omega \tag{6}$$

where

$$E^2 = \left(\left|\frac{\sin(M\omega/2)}{M\sin(\omega/2)}\{[2b\cos(M\omega) - 1] + 1\}\right| - 1\right)^2 \tag{7}$$

The estimated value of b is rounded using the rounding constant $r = 2^{-6}$ resulting in

$$b = -4 \times 2^{-6} \tag{8}$$

From (4) and (8) we have

$$a = 72 \times 2^{-6} \tag{9}$$

Using (2), (8) and (9), we arrive at

$$G(z^M) = 2^{-6}[-4z^{-M} + 72z^{-2M} - 4z^{-3M}] \tag{10}$$

Finally from (10) the proposed filter is given as

$$G(z^M) = -2^{-4}[z^{-M} - (2^4 + 2)z^{-2M} + z^{-3M}] \tag{11}$$

Characteristics: The proposed filter (11) is multiplier-free with only three adders and can be implemented at a lower rate after down sampling by M by making use of the multirate identity. The corresponding magnitude characteristic approximates the inverse magnitude characteristic of (1), for $K = 1$, in the passband, as shown in Fig. 1. The same is confirmed for $K > 1$ applying the following cascade of the filters (11):

$$H_{comp}(z^M) = \begin{cases} G^K(z^M) & \text{for} \quad 1 < K \le 3 \\ G^{K-1}(z^M) & \text{for} \quad K > 3 \end{cases} \tag{12}$$

where K is the CIC parameter. Fig. 1 illustrates the cases for $K = 3$ and 5. The total number of additions depends on K, as given by

$$N_{add} = \begin{cases} 3K & \text{for} \quad K \le 3 \\ 3K - 3 & \text{for} \quad K > 3 \end{cases} \tag{13}$$

The method is illustrated in the following example. We compensate for the CIC filter with parameters $M = 16$ and $K = 5$. According to (12) and (13), the compensator needs four stages requiring a total of 12 adders. Magnitude characteristic zoom in the passband is shown in Fig. 2, thus confirming the good passband compensation.

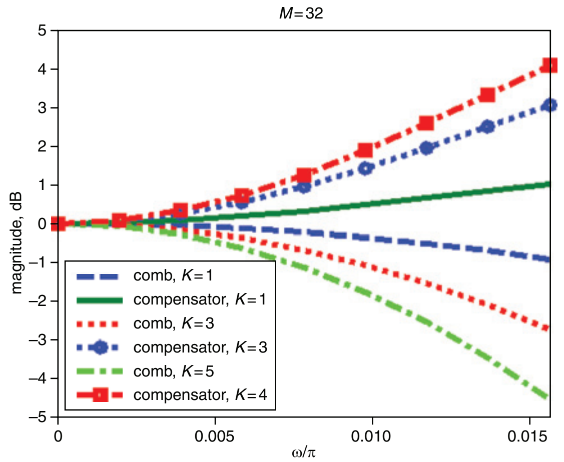

Fig. 1 *Passband zoom: comb filters and compensators*

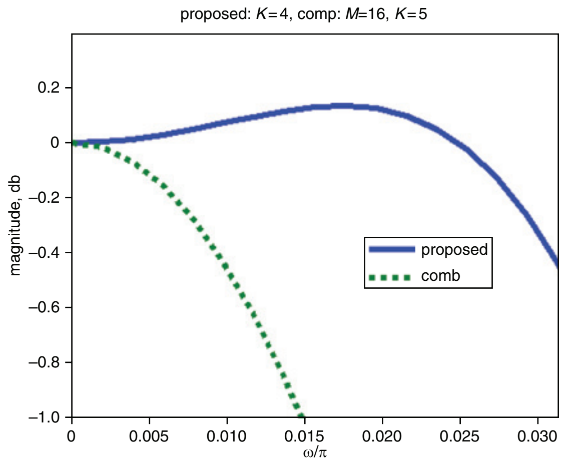

Fig. 2 *Passband zoom: compensation of comb filter with $M = 16$ and $K = 5$*

Comparison: We now compare the performance of the proposed compensation filter with the method [5] for wideband compensation recently reported in literature.

Method of Kim et al. [5]: The coefficients of the compensation filter [5] are given by

$$[-a/(1-2a), 1/(1-2a), -a/(1-2a)] \tag{14}$$

The performance of the compensation filter depends on the value a, obtained by minimising the corresponding error function for the given values of M and K. We compare the performance of our proposed filter with that of [5] for $K = 5$ and the decimation rates equal to 14 and 20. The corresponding values of the parameter a for $M = 14$ and 20 are 0.1803 and 0.1806, respectively [5]. According to (12), the same compensation filter is used for both values of M. The proposed filter is multiplier-free and requires 12 adders. Method [5] requires two different compensation filters, one for $M = 4$, and another for

$M = 20$, both with two multipliers and two adders. The results shown in Figs. 3*a* and *b* demonstrate that the proposed filter provides better compensation.

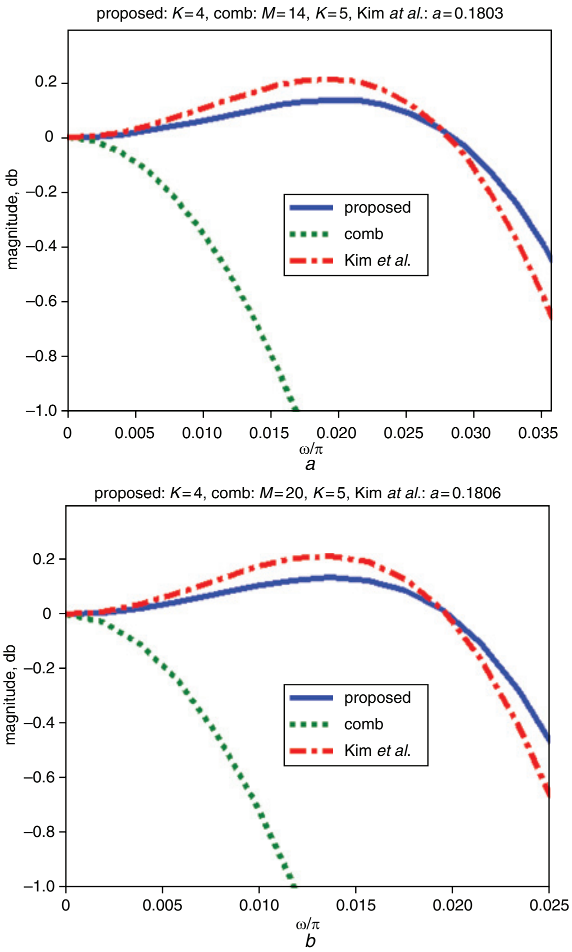

Fig. 3 *Passband zoom: comparison with method [5]*

a $M = 14$
b $M = 20$

Conclusion: A simple multiplier-free cosine-based compensator for a CIC filter with only three adders is proposed. This structure remains the same for all CIC parameters M and K. However, the number K of the cascaded CIC filters defines the number of the compensator stages. For $K \leq 3$ and $K > 3$, the numbers of compensator stages are K and $K-1$, respectively, requiring the total number of adders, $3K$ and $3K-3$, respectively. Comparison with known methods demonstrates that the proposed method provides a slightly better compensation and a less complex alternative to existing solutions.

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