

# EFFICIENT DIGITAL FREQUENCY DOWN CONVERTER STRUCTURE USING CIC FILTERS AND INTERPOLATED FOURTH-ORDER POLYNOMIALS

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Keywords: DFDC, CIC, ISOP, IFOP.

Abstract: In this paper, we propose an efficient digital frequency down converter (DFDC) structure using CIC (Cascaded Integrator-Comb) decimation filters and interpolated fourth-order polynomials (IFOP). Typical DFDC with high decimation factors consist of a CIC filter and a halfband filter. By inserting the proposed IFOP between the CIC and halfband filters, it is shown that passband droop and aliasing band attenuation characteristics are simultaneously improved. Since the IFOP requires only three multiplications, the proposed DFDC can be used in intermediate frequency blocks of the high-speed communication systems.

## 1 INTRODUCTION

Since DFDCs (Digital Frequency Down Converters) with narrow bandwidth require high orders, power consumption and implementation area should be considered. To save on implementation cost, conventional VLSI chips for DFDCs utilize CIC filters followed by halfband filters and a Programmable Finite Impulse Response (PFIR) filter. For example, a DFDC chip with a 16384 decimation ratio consists of CIC, halfband, and PFIR stages, where the decimation factors of the CIC, halfband and PFIR stages are 32, 32 and 16, respectively. CIC filters are widely used in the first stage of the DFDC since they do not require multiplications (Hogenauer, 1981). Studies to improve CIC filter characteristics have been undertaken (Yang, 1996) (Gao, 1999). In (Kwentus, 1997), a sharpening technique using a combination of three filters (Kaiser, 1977) is applied to a CIC filter. By using this method, the ripple in the passband and attenuation in the aliasing band can be mitigated, but the implementation cost is quite high. In (Oh, 1999), ISOP (Interpolated Second Order Polynomial) is inserted between CIC and halfband filters. This method reduces the ripple in the passband, but attenuation in the aliasing band is

worsened. In this paper, we propose an efficient IFOP technique to reduce ripple in the passband and attenuation in the aliasing band simultaneously.

## 2 PROPOSED METHOD USING IFOP

The system function of the CIC filters, which do not require multiplications, is expressed as

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

where M, L, and R represent the decimation factor, filter order, and differential delay, respectively. When L is increased in equation (1), the stopband attenuation is improved but passband ripple is exacerbated, as shown in Fig. 1. In general, L should be determined to satisfy the desired stopband attenuation specification.

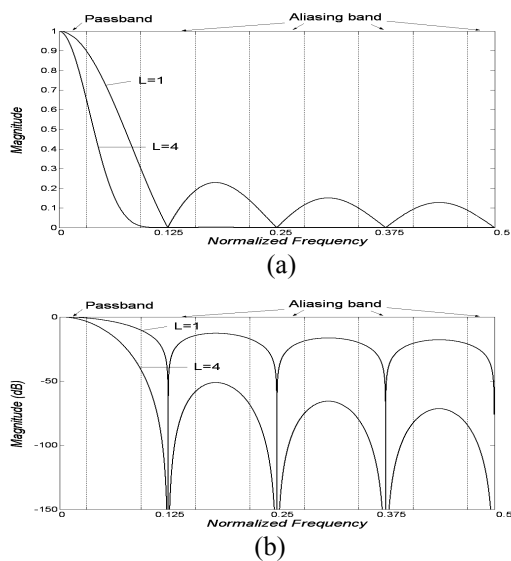


Figure 1: Frequency response and aliasing band of CIC filter (M=8, R=1, one halfband filter).

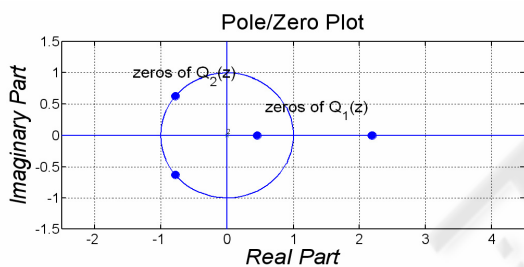


Figure 2: Zeros location of the proposed IFOP filter in z-plane.

After the stopband attenuation specification is satisfied, methods for dealing with the passband ripple can be applied. In a DFDC using CIC filters, halfband filters usually follow the CIC section, and therefore aliasing bands are considered instead of a stopband. When a halfband filter is used, the aliasing band is determined, as shown in Fig. 1. When two halfband filters are used, the aliasing band and passband become narrower by half. To reduce ripple in the passband and attenuation in the aliasing bands, we propose the following IFOP

$$P_1(z) = \frac{1 + p_1 z^{-1} + p_2 z^{-2} + p_1 z^{-3} + z^{-4}}{2 + 2p_1 + p_2} \quad (2)$$

In equation (2), the absolute value of the denominator is for DC increase proportionally to 1, and I is the interpolation factor. Excluding scaling and interpolation factors, the basic equation is represented as

$$P(z) = 1 + p_1 z^{-1} + p_2 z^{-2} + p_1 z^{-3} + z^{-4} \quad (3)$$

To design an optimal IFOP filter, the above basic equation is factored as

$$P(z) = Q_1(z)Q_2(z) \quad (4)$$

$$= (1 + q_1 z^{-1} + z^{-2})(1 + q_2 z^{-1} + z^{-2})$$

As shown in Fig. 2, the IFOP filter is controlled for two zeros to place on the real axis, and is used to improve the passband ripple of the CIC filter. The filter is determined for two zeros to place on the unit circle, and used to improve aliasing band attenuation of the CIC filter. The overall proposed DFDC structure is shown in Fig. 3.

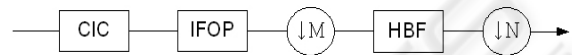


Figure 3: Overall proposed DFDC structure.

To examine the effect of the proposed IFOP, the DFDC structure using one or two halfband filters was investigated. Passband ripple and aliasing band attenuation of the proposed DFDC with IFOP are compared with three other structures which are ISOP structure [4], CIC only structure[1], and Sharpened structure[2], respectively. Results are summarized in Table 1. As shown in Table 1, ripple in the passband and attenuation in the aliasing band of the proposed IFOP are improved simultaneously. In the case of L=4, R=1, and one halfband filter, the passband ripple and aliasing band attenuation of the CIC-only structure are 3.593dB and 41.314dB, respectively. And those of the ISOP structure are 0.416dB and 38.138dB, respectively, where it is shown that the passband ripple is improved, but aliasing band attenuation is worsened. However, those of the proposed IFOP structure are improved to 0.308dB and 62.256dB, representing better results than those of the ISOP method. In a two-halfband case simulation, Table 1 shows that the proposed structure provides better performance. The proposed structure shows better passband ripple and aliasing band attenuation results. From the given specifications, the proposed DFDC design procedure can be summarized as

- (1) CIC and halfband filters specification decision
  - 1-1 M, R, L decision for CIC filter
  - 1-2 Number and specification decision for halfband filters
- (2) CIC and halfband filters design
  - 2-1 Observation of frequency responses
  - 2-2 Target frequency decision of stopband or aliasing band
- (3) IFOP design
  - 3-1 Value of I decision
  - 3-2 Minimization of aliasing band attenuation through adjusting the  $q_2$

3-3 Minimization of passband ripple through adjusting the  $q_1$

3-4 From the and  $q_1, q_2$  IFOP decision

Table 1: Passband droop and aliasing attenuation of the CIC-only, Sharpened, ISOP, and IFOP(one halfband:  $1/(4M)$ , two half band:  $1/(8M)$ ).

		$fc = 1/(4M)$		$fc = 1/(8M)$	
		passband ripple	aliasing attenuation	passband ripple	aliasing attenuation
Proposed IFOP	L=4, R=1	0.3081	62.2555	0.0234	102.09
	L=4, R=2	2.2805	56.7509	0.1682	94.416
	L=6, R=1	0.5417	82.9282	0.0316	136.85
	L=6, R=2	6.3643	80.2976	0.339	128.61
ISOP	L=4, R=1	0.4162	38.138	0.04	67.04
	L=4, R=2	4.5393	42.26	0.2615	67.27
	L=6, R=1	0.752	57.334	0.0652	100.56
	L=6, R=2	8.7786	65.361	0.555	101.07
CIC-only	L=4, R=1	3.5926	41.314	0.8751	67.758
	L=4, R=2	15.634	53.355	3.5988	70.518
	L=6, R=1	5.3889	61.971	1.3127	101.63
	L=6, R=2	23.450	80.033	5.3983	105.78
Sharpened	L=2, R=1	0.84	32.33	0.062	58.40
	L=4, R=1	2.692	73.14	0.231	126.10

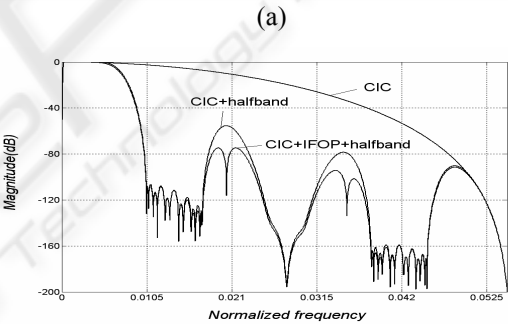
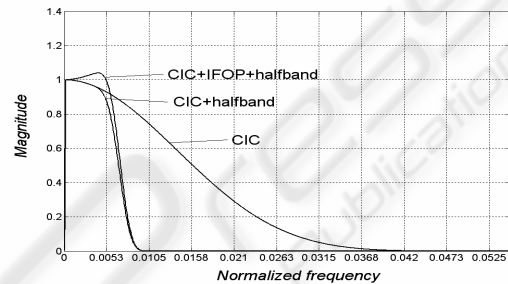
### 3 DESIGN EXAMPLES

#### 3.1 Example 1

Using the proposed method, we demonstrate an example of a DFDC design with a decimation factor of 36. Overall specifications of the passband frequency and ripple are 0.00525 and 0.2dB, respectively. The specifications of the stopband frequency and attenuation are 0.0105 and 70dB, respectively. Since the decimation factor is 36, we choose a factor of 18 for the CIC and a factor of 2 for the halfband filter to satisfy these specifications. Desired parameters of the CIC filter are  $R=1$ ,  $M=18$  and  $L=5$ . The halfband filter used in this design example is typical. The combined frequency response of the CIC and halfband section is shown in Fig. 4. As shown, the passband ripple and stopband attenuation are 1.07dB and 55.42dB, respectively. Since the weak points of the stopband

attenuation are  $\omega = 0.02$  and  $\omega = 0.035$ , parameter I of the IFOP is determined with 18. Adjusting value of the  $q_2$ , zeros of  $Q_2(z)$  are placed in  $\omega = 0.02$  and  $\omega = 0.035$ . We then adjust  $q_1$  to minimize the passband ripple. Overall improved passband ripple and stopband attenuation are 0.1995dB and 74.71dB, respectively, as shown in Fig. 4. From the obtained  $q_1$  and  $q_2$ , system function of the IFOP in this example is expressed as

$$P_{18}(z) = 0.2053 - 0.4367z^{-18} - 0.5374z^{-36} - 0.4367z^{-54} + 0.2053z^{-72} \quad (5)$$



DFDCs	passband ripple(dB)	stopband attenuation(dB)
CIC+HBF	1.07	55.42
CIC+IFOP+HBF	0.1995	74.71

(c)

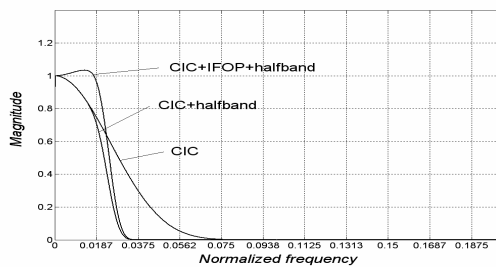
Figure 4: Frequency response improved by proposed IFOP in the design example 1.

#### 3.2 Example 2

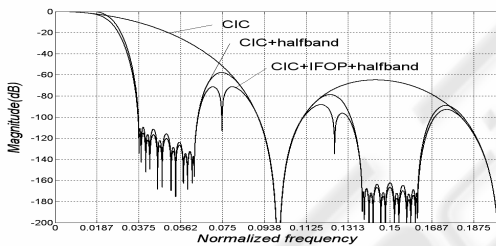
The second example is a design for a DFDC with a decimation factor of 10. Overall specifications of the passband frequency and ripple are 0.01875 and 0.3dB, respectively. And the specifications of the stopband frequency and attenuation are 0.0375 and 70dB, respectively. Since the decimation factor is 10, we choose a factor of 10 for the CIC and a factor of

1 for the halfband filter to satisfy these specifications. Chosen parameters of the CIC filter are  $R=1$ ,  $M=10$  and  $L=5$ . The halfband filter used in this design example is also the typical one as in the previous example. The combined frequency response of the CIC and halfband section is shown in Fig. 5. Fig. 5 shows that the passband ripple and stopband attenuation of the CIC and halfband filter are 2.94dB and 57.86dB, respectively.

Since the weak points of the stopband attenuation are  $\omega = 0.075$  and  $\omega = 0.125$ , parameter I of the IFOP is determined with 5. Adjusting the value of the  $q_2$ , zeros  $Q_2(z)$  are placed in  $\omega = 0.075$  and  $\omega = 0.125$ .



(a)



(b)

DFDCs	passband ripple(dB)	stopband attenuation(dB)
CIC + HBF	2.94	57.86
CIC+IFOP+HBF	0.289	71.27

(c)

Figure 5: Frequency response improved by proposed IFOP in the design example 2.

We then adjust  $q_1$  to minimize the passband ripple. Overall improved passband ripple and stopband attenuation are 0.289dB and 71.27dB, respectively, as shown in Fig. 5. System function of the IFOP in this example is expressed as:

$$P_3(z) = 0.4418 - 0.5571z^{-5} - 0.7695z^{-10} - 0.5571z^{-15} + 0.4418z^{-20} \quad (6)$$

## 4 CONCLUSIONS

We propose a DFDC structure that can improve the passband ripple and aliasing band attenuation simultaneously. By adjusting the zero position of the two polynomials repeatedly, the overall frequency response in the passband and aliasing band is improved, and the coefficients of the IFOP can be obtained. The implementation cost of the structure is competitive. Since the proposed DFDC satisfies linear phase characteristics and needs only three more multiplications, it can be widely used in IF(Intermediate Frequency) blocks of the high-speed communication systems.

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