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One Method For Design of Lowpass Narrowband Filters

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ABSTRACT

This paper presents a lowpass narrowband filter design method with a small number of products per output sample (MPS). The method is based on the use of a sharpened Cascade Integrator-Comb (CIC) filter and an Interpolated Finite Impulse Response (IFIR) structure.

INTRODUCTION

In many communications and signal processing systems it is necessary to isolate a very narrow band signal from a very wide band signal. The use of a Finite Impulse Response (FIR) digital filter has the advantages of guaranteed stability, absence of limit cycles, and linear phase, if desired.

The main disadvantage of FIR filters in narrowband filtering is that the large filter length is required. This implies a large number of arithmetic operations per output sample in the filter implementation. The number of multipliers per output sample (MPS) is equal to or half of the length of the filter in the nonlinear and linear phase cases, respectively.

Several FIR design methods have been proposed to reduce the number of arithmetic operations. The interpolated FIR (IFIR) filter proposed by Y. Neuvo at al., 1984, is one of the computationally efficient realizations for narrowband FIR filters. The IFIR filter is a cascade of two filters

$$H(z)=G(z^M)I(z), \tag{1}$$

where $G(z^M)$ is an expanded shaping or model filter, I(z) is an interpolator or images suppressor and M is the interpolator factor. The advantage of this structure is based on the design of a narrowband FIR prototype filter H(z) by using smaller order filters, G(z) and I(z). For more details of the IFIR structure see Y. Neuvo at al., 1984.

The minimum number of MPS in an IFIR structure is computed for a chosen interpolator factor M such that the orders of the filters G(z) and I(z) are equal or close to each other. Hence, an increment in the interpolator factor means an exponential grow in the interpolation filter order. We can notice that fewer MPS would be needed if the interpolator filter is implemented with fewer products. This idea was used by D. Pang, at al., 1991, where a low order B-spline filter is used as the interpolator filter.

In this paper we propose to use the sharpened Cascaded Integrator-Comb (CIC) filter as the interpolator in the IFIR structure for narrowband filtering. A CIC filter uses only one product per output sample. In this way the number of MPS is considerably reduced. The filter sharpening technique, proposed by J. F. Kaiser and R. W. Hamming, 1984, and generalized by R. J. Hartnett, and G. F. Boudreaux, 1995, is used to improve the frequency domain response of the CIC filter.

The CIC filter characteristics are reviewed in section II. In section III the filter sharpening technique is described. The proposed method and an illustrative example are presented in section IV.

CASCADED INTEGRATOR-COMB FILTER

The Cascaded Integrator-Comb (CIC) structure was proposed by E. B. Hogenauer, 1981, as an efficient structure for multirate filtering. A CIC decimation filter consists of two sections

- Cascade of L integrators operating at the high rate

$$H_I(z)=\left(\frac{1}{N}\frac{1}{1-z^{-1}}\right)^L. \tag{2}$$

- Cascade of L comb filters operating at the low rate

$$H_c(z)=\left(1-z^{-1}\right)^L. \tag{3}$$

These two sections are separated by a decimator with a decimation factor N. The CIC decimation filter can be viewed as a single rate filter preceding the decimator, with a transfer function given as

$$H_{CIC}(z)=\left(\frac{1}{N}\frac{1-z^{-N}}{1-z^{-1}}\right)^L=\left(\frac{1}{N}\sum_{k=0}^{N-1}z^{-k}\right)^L. \tag{4}$$

This filter is a cascade structure with L stages. Each stage is an N length FIR filter with a rectangular window shaped impulse response. The frequency response of the CIC filter is given by

$$\left|H_{CIC}(\omega)\right|=\left\{\frac{sin\left(\frac{N\omega}{2}\right)}{Nsin\left(\frac{\omega}{2}\right)}e^{-j\omega[(N-1)/2]}\right\}^L, \tag{5}$$

This is a linear-phase low pass filter with a very wide transition band, whose passband is only a small portion of the resulting bandwidth. The frequency response has nulls at integer multipliers of $(2\pi)/N$. The CIC filter has only two control parameters: number of stages L, and its length N.

In order to improve the frequency domain behavior of the CIC filter we utilize the filter sharpening technique, which is described next.

FILTER SHARPENING

This section briefly describes the filter sharpening technique. For more details see R. J. Hartnett, and G. F. Boudreaux, 1995. This technique was first proposed by J. F. Kaiser and R. W. Hamming, 1984. It is used for simultaneous improvement of both passband and stopband characteristics of a linear-phase FIR digital filter.

It is based on the use of polynomials to approximate a piecewise constant desired Amplitude Change Function (ACF). The ACF maps a transfer function amplitude before sharpening, $H(\omega)$, to an amplitude value after sharpening, $P[H(\omega)]$. The method assumes $|H(\omega)|$ approximates unity in the passband and zero in the stopband.

A general piecewise linear desired ACF was proposed by R. J. Hartnett, and G. F. Boudreaux, 1995, with the constraints on the approximating polynomial $P[H(\omega)]$ given as

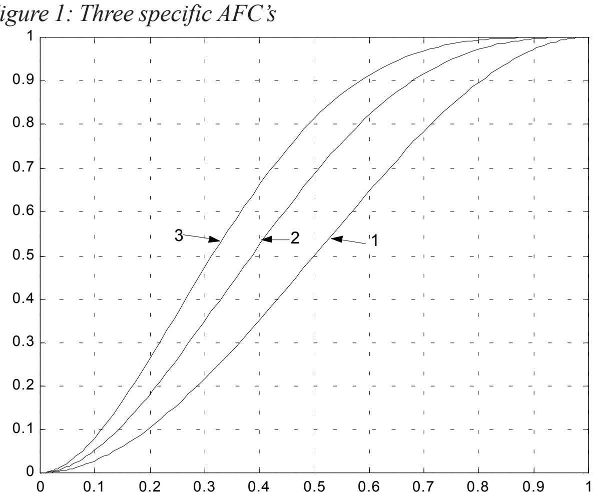
- n^{th} order tangency at $\{H(\omega),P[H(\omega)]\}=(0,0)$ to the line of slope δ.
- m^{th} order tangency at $\{H(\omega),P[H(\omega)]\}=(1,1)$ to the line of slope σ.

In this fashion, there are more control parameters available for achieving the desired ACF. Later S. Samadi, 2000, derived a closed formula for any value of control parameters. As an example Figure 1 shows the plot of the following ACF's

$$\begin{aligned}
&1.\ P[H(\omega)]=3H^2(\omega)-2H^3(\omega) && (\sigma=0,\ \delta=0,\ n=1,\ m=1).\\
&2.\ P[H(\omega)]=6H^2(\omega)-8H^3(\omega)+3H^4(\omega) && (\sigma=0,\ \delta=0,\ n=1,\ m=2). \qquad (6)\\
&3.\ P[H(\omega)]=10H^2(\omega)-20H^3(\omega)+15H^4(\omega)-4H^5(\omega) && (\sigma=0,\ \delta=0,\ n=1,\ m=3).
\end{aligned}$$

As we can see, with the increase of the tangency order in (1,1), the passband magnitude response is improved.

Figure 1: Three specific AFC's



PROPOSED STRUCTURE

In order to reduce the number of MPS in an IFIR structure, we use a sharpened CIC filter as the interpolator. The mirror images of the model filter can be suppressed if the CIC frequency nulls are centered at each mirror image. This implies M=N.

Given the narrowband filter specifications, the proposed structure can be designed as follows:

1. Design the model filter $G(z)$, with the interpolator factor=M .
2. Design an L-stage integrator-comb filter, $I_{cic}(z)$, with length N=M .
3. Apply filter sharpening technique to $I_{cic}(z)$ with a specific ACF to obtain the sharpened CIC filter I_{speic} (z).
4. Cascade the model filter $G(z^M)$ and the sharpened CIC filter I_{speic} (z).
5. If stopband filter specification is not met go to step two and increase the number of stages L.
6. If passband filter specification is not met go to step three and modify the ACF.

The number of MPS in an IFIR structure is controlled by the interpolation factor M. It is therefore important to use an appropriate M value in step one. If this value is too high, a more complex ACF in step three is needed. From step 5 we can see that the number of stages L controls the filter stopband. In step 6 the filter sharpening technique controls the filter passband. Now we present one filter design example.

Example

A linear-phase narrowband filter is designed with the following specifications:
Passband frequency $\omega_p=0.01\pi$,
Stopband frequency $\omega_s=0.015\pi$,
Maximum passband ripples $R_p=0.086$dB,
Minimum stopband attenuation $A_s=-60$ dBs.

A linear-phase FIR filter designed by Parks McClellan method would require 509 MPS (order=1017).

The minimum number of MPS for the IFIR structure is 69 with an interpolator factor M=18. The orders of G(z) and I(z) are 66 and 69 respectively.

In the proposed method, an interpolation factor of M=21 is chosen, and the CIC filter is designed with the control parameter values L=2, and N=M=21. The ACF applied in the filter sharpening for the first case shown in figure 1, is given by

$$P[H(\omega)]=3H^2(\omega)-2H^3(\omega),\quad \sigma=0,\ \delta=0,\ n=1,\ m=1.$$

In Figure 2 is shown the proposed implementation of this example. The order of G(z) is 57 and the total number of MPS is 31. A product reduction of 55% is obtained with respect to the IFIR structure. The allband and the passband magnitude responses for the IFIR structure and for the proposed method are shown in Figure 3.

Figure 2: Proposed implementation

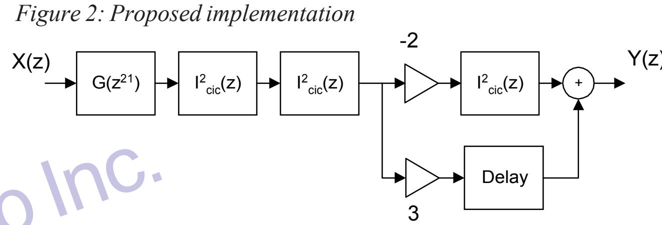
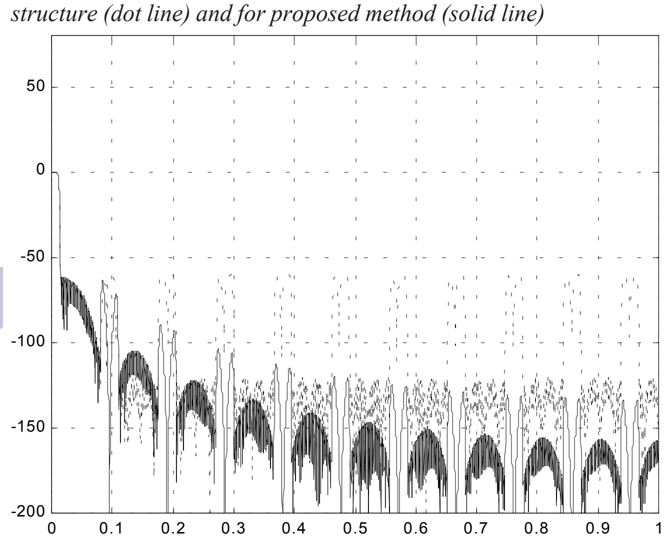


Figure 3: Allband and passband magnitude responses for IFIR structure (dot line) and for proposed method (solid line)



CONCLUSIONS

A lowpass narrowband filter design method with small number of MPS is presented. The number of multipliers is reduced by the use of a sharpened cascade integrator-comb filter (CIC) as the interpolator in an IFIR structure.

A specific amplitude change function (ACF) is applied to the CIC filter to improve its frequency domain behavior. The control parameters for the proposed method are: the interpolation factor M, number of stages L, length of each stage N, and the filter sharpening parameters s, d, n, m.

The filter sharpening controls the filter passband magnitude response. The number of stages controls the filter stopband magnitude response.

As the filter design example presented here shows, there is a notable reduction in the number of MPS in the implementation of the proposed method. Further reduction in MPS would require an increase of the interpolator factor M, which in turn would increase the implementation complexity.

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