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# Optimized Comb Filter using Simplex Algorithm with Improved Attenuation

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**Abstract—***Comb filters are multiplier less FIR filters, which are used for the purpose of decimation. The main issues with Comb filters are low attenuation in stop-band and high droop in pass-band. This paper explains the design of multiplierless filter connected in cascade with comb filter. The designed multiplierless filter is based on the decimation factor. This research work deals with the simplex algorithm of optimization to improve attenuation around the folding bands of comb filter. The attenuation at folding-band and at side lobes so obtained is higher than that obtained with similar stages of comb filter.*

## 1. INTRODUCTION

Comb filters are the simplest filters used for the process of decimation or interpolation process as the first stage of decimation or interpolation as they don't require any multiplier in hardware implementation. The Cascaded integrator Comb filters are proposed by Hogenaur[1]. The recursive architecture of Comb filters has transfer function as given by equation (1). The recursive structure is an IIR filter acting as an integrator and Comb filter acting as a differentiator. The IIR and Comb filters are separated by a down-sampler. The non-recursive architecture have transfer function given by equation (2). The transfer function of K stages of recursive architecture of comb filter with decimation factor M is given by:

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

Putting $z=e^{j\omega}$ in equation (2), the frequency response of Comb filters is given by:

$$H(e^{j\omega}) = e^{-j(M-1)K\omega/2} H(\omega) \quad (2)$$

The frequency response of resulting non-recursive Comb filters is given by:

$$H(\omega) = \left[\frac{1}{M}\left(\frac{\sin\left(\frac{\omega M}{2}\right)}{\sin\frac{\omega}{2}}\right)\right]^K \quad (3)$$

The pass-band frequency is defined by:

$$\omega_p = \frac{\pi}{\nu M} \quad (4)$$

where, $\nu$ is the decimation of further stages in multistage architecture

The first folding band edge frequency in [26] of comb filter is defined by:

$$\Omega = \left[\frac{2\pi}{M} - \omega_p : \frac{2\pi}{M} + \omega_p\right] \quad (5)$$

Thus from equation (3) it can be stated that Comb filters have linear phase.

The issues of comb filters can be stated as low droop in pass-band and higher attenuation in stop-band. A lot of research work during last few years has been done to improve the characteristics (droop in pass-band and attenuation around the folding bands where worst case of aliasing occurs)of Comb filter An extra compensator can be used in cascade with original filter to improve droop in pass-band. To improve attenuation simplest way is to increase the number of stages of filter. On increasing the number of stages of Comb filter also increases droop in pass-band region of Comb filter.

Dolecek(2009) et al. approached a general method [6] to design a compensation filter. Linear equations are used to solve the coefficients of design filter. Jimenez (2013) et al. approached a generalized sharpening technique [5] and is applied to second stage of comb filter to improve droop introduced by first stage of comb filter. The compensator filter is designed based on the approach of filter sharpening proposed by Kaiser and Hamming. Dolecek (2014) et al. approached a compensation filter which provides better droop in wideband region of cascaded integrator comb filter. A second order sine based compensation filter using trigonometric approach is presented [7]. Kalpana Devi et al. (2015) presented a design of sharpened maximally flat cascaded third order and fourth order sharpened compensated Cascaded integrator comb filters are shown in [28].

The goal of paper is to increase attenuation around the folding band of comb filter in stop-band. The goal is achieved by designing linear equations and solving the linear equations using an optimization technique known as Simplex algorithm and hence provides improved stop-band attenuation around the folding bands of comb filters. The overall optimized Comb filter provides better attenuation around the folding bands and side lobes of comb filter without affecting pass-band droop.

The paper is organized as follows. In Section 2 a set of linear equations with a brief introduction to multiplierless filter and flowchart of proposed work is presented. In Section 3 results are discussed in the paper. In Section 4, finally a conclusion is discussed.

## 2. PROPOSED WORK

### 2.1 Multiplierless Filter

This section explains the design of multiplierless filter connected in cascade with comb filter. The designed multiplierless filter is of length depending upon the decimation factor of comb filter. Consider the magnitude response of multiplierless filter, given as:

$$H_1(z)=\sum_{k=1}^{\frac{M+1}{2}} z^{-k} \quad (6)$$

The overall comb filter connected in cascade with designed filter has magnitude response H $_2$(z), given as:

$$H_2(z)=H(z)^* H_1(z) \quad (7)$$

### 1.2 Flowchart

The flowchart of proposed work is shown in fig.1 which explains the proposed work as follows:

a) Connect desired stages of comb filter in cascade.
b) Three equations are designed obtain a feasible solution using simplex algorithm in MATLAB in the following manner:

$$x_1+x_2+x_3H(e^{j\omega})+ x_3[H(e^{j\omega})]^2 \leq 0.5 \quad (8)$$

$$x_2=0,\ x_2+x_3+x_4=1 \quad (9)$$

$$\text{CostFunction: } x_1 + x_2+x_3+x_4 \quad (10)$$

where, H $(e^{j\omega})$ is the DFT of equation (2)

c) Cascade Comb filter with designed multiplierless filter.
d) Multiply coefficients obtained in step c) with feasible point obtained in step b) using Simplex algorithm.
e) Plot overall magnitude response, plot for folding band attenuation, phase response, and pole-zero plot coefficients obtained in step d) and in step a)
f) Compare the results for values obtained from above plots.

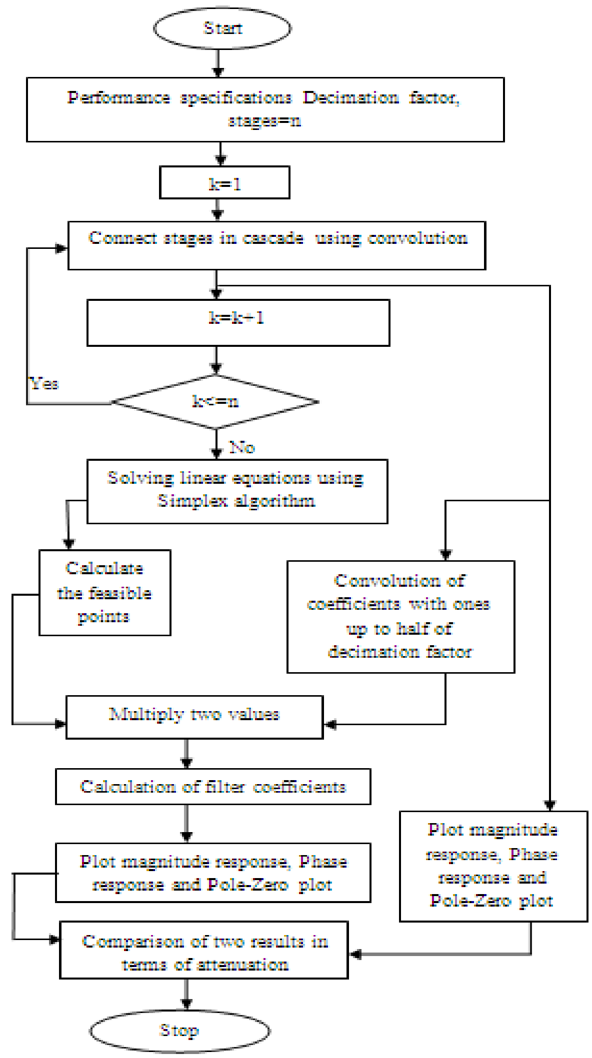



**Fig. 1: Flowchart of proposed work**

## 3. RESULTS

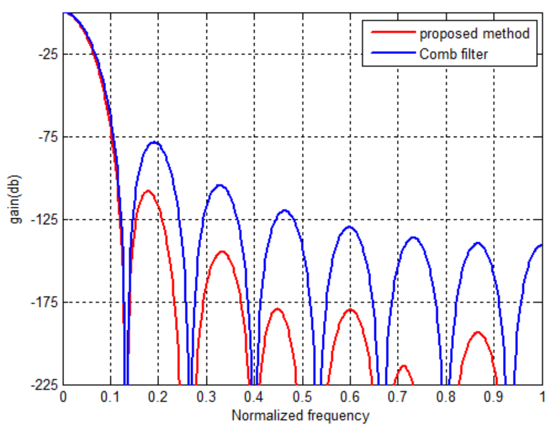
The MATLAB7.5 (R2007b) is used to achieve the objectives using some specified parameters such as: M =15, K= 6 and v=4. The various responses of Comb filter are demonstrated with blue line while Optimized Comb filters phase response is demonstrated with red line.

The fig.2 (a) illustrates the magnitude response of Comb filter and Optimized Comb filter. The fig. shows an increase in attenuation around first side-lobes of optimized comb filter and comb filter is approximately by 30dB with a very small increase in pass-band distortion with pass-band ripples of -0.4143dB.

Folding band zoom of Comb filter and Optimized Comb filter is shown in fig 2(b). The fig. illustrates the values of attenuation around first folding band ($\Omega$=0.1167$\pi$:0.15$\pi$) is 104.3dB and 114.7dB respectively for optimized comb filter and comb filter.

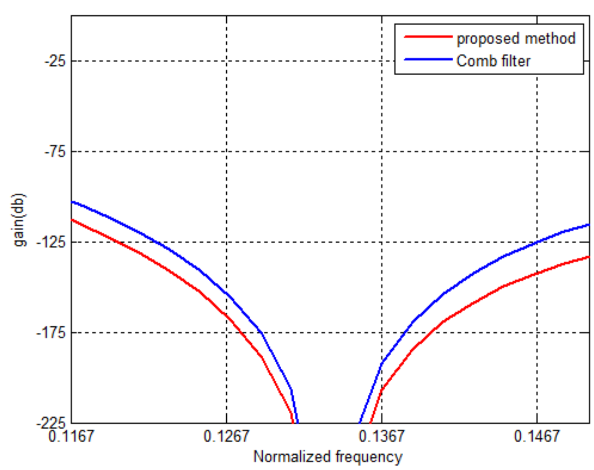
Fig.3 illustrates the phase response of Comb filter and Optimized Comb filter to indicate linear phase response of optimized Comb filter. Thus wave shape is preserved from being distorted as signal is passed through designed filter.

Fig.4 illustrates the pole-zero response of Optimized Comb filter to indicate the stability of designed optimized Comb filter in terms of location of poles and zeros. Since all zeros of designed filter are located on the unit circle while the poles are located at the centre of unit circle.




**M=15, K=6, ν=4**

a) Overall Magnitude response of Comb filter and Optimized Comb filter




b) Folding band zoom of Comb filter and Optimized Comb filter

**Fig. 2: Magnitude responses of Comb filter and Optimized Comb filter**

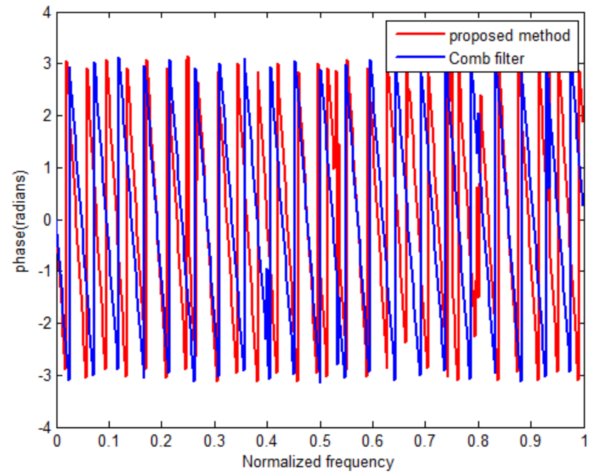



**Fig. 3: Phase response of Comb filter and Optimized Comb filter**

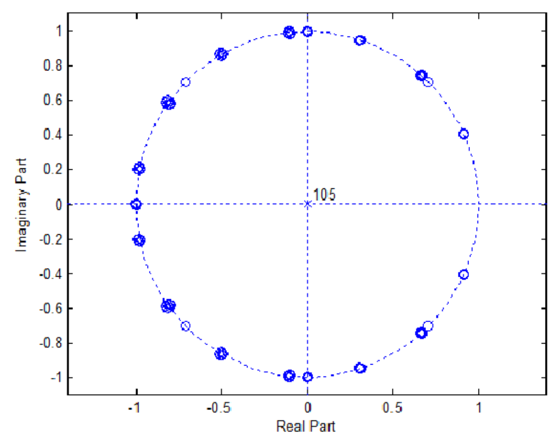



**Fig. 4: Pole-Zero plot of Optimized Comb filter**

Table I illustrates the values of attenuation of folding band at frequency 0.1167π and attenuation at side-lobes. It is illustrated in Table I that the proposed approach provides approximately 10dB higher attenuation at folding bands where worst case of aliasing occurs while attenuation at first side-lobe is approximately 30dB higher.

**Table 1: Attenuation Values for M=15, K=6 and ν=4**

| Method | Attenuation around folding band | Attenuation at side lobe |
|---|---|---|
| Using Simplex Algorithm | 104.3dB | 109dB |
| Comb filter | 114.7dB | 79dB |

Table II illustrates the values of attenuation for parameters such as: M=11, K=5 and ν=2. The folding band attenuation occurs at frequency 0.1363π. It is illustrated in Table II that the proposed approach provides an attenuation of 10dB higher at folding bands while attenuation at side-lobes is 40dB higher.

**Table 2: Attenuation Values for M=11, K=5 and ν=2**

| Method | Attenuation around folding band | Attenuation at side lobe |
|---|---|---|
| Using Simplex Algorithm | 62.19dB | 104.5 |
| Comb filter | 52.32dB | 65.69dB |

## 4. CONCLUSION

It is concluded that Simplex algorithm can be used to improve the attenuation around folding bands and side-lobes. Linear equations are solved using Simplex Algorithm. It has been shown that attenuation obtained for different stages of comb filter by using optimization algorithm is increased. The paper briefs the design of multiplierless filter. The designed work is explained by using an example by considering different values of decimation factor. The phase linearity is explained by phase plot of comb filters. The stability of designed approach is explained by pole-zero plots.

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