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A pre-distortion based design method for digital audio graphic equalizer

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ABSTRACT

The traditional design method for digital audio graphic equalizer using infinite impulse response filters usually has some deficiencies, including center frequency shift, narrower bandwidth at high frequency and inaccurate gain. In this paper, an improved method based on the modified bilinear transformation is proposed to design a digital audio graphic equalizer. The new bilinear mapping can compensate the center frequency shift, and pre-distorting the quality factors and optimizing the gains can correct the bandwidth and gain of each sub-band respectively. Experimental results reveal that both center frequency and bandwidth of the proposed digital graphic equalizer are strictly equal to the desired ones, and the average gain error decreases at least 2 dB.

1. Introduction

The audio equalizer (EQ) is one of the most important audio effects and is widely used in many audio systems, such as broadcasting studio, sound console, audio workstation, sound recording, audio player, smart phone and mobile terminal [1–6]. By mainly changing the amplitude of audio signals in sub-bands, an EQ can emphasize or attenuate some frequency components, and thus render many special effects [7]. Most of the EQs can be divided into two basic types: parametric equalizer and graphic equalizer (GEQ). A parametric EQ usually has some adjustable parameters, including center frequency, bandwidth and gain, thus it is more flexible than a GEQ and can meet the professional application. Nevertheless, the parametric EQ is very difficult to operate for a lay person due to its complex configuration. As for the GEQ, the whole audio frequency band is divided into some sub-bands. Usually the number of sub-bands is 3, 5, 10, 15 or 31, and the gain of each sub-band is the only parameter which can be adjusted independently. Because the GEQ is simple and intuitive, it is widely used in many audio equipments, such as PDA, tablet PC, smart phone, MP3 player.

Though designing a perfect digital GEQ is a challenging task, a few valuable methods have still be given. A GEQ can be considered as a kind of filter bank, but it is special one. Due to the variable band width, computational complexity, algorithm delay and user's demand, the perfect reconstruction filter bank is scarcely ever used in designing a digital GEQ. Most of the design methods for a digital GEQ derive from the analog filter design techniques. In 1983, based on the Hurwitz polynomial properties, Greiner and Schoessow applied positive and real functions to design a GEQ [8]. In 1986, Bohn proposed the constant-Q GEQ, including design requirement and trade-offs of constant-Q circuitry [9]. Park designed a high-speed continuous-time CMOS analog adaptive equalizer [10] for equalization in the read channels of magnetic recording in 1998. The GEQ is implemented as the combination of several bandpass filters covering different frequency bands. The above-mentioned three methods are suitable for designing an analog prototype EQ. So far the design methods of digital equalizer are as follows. In 2005, Lee et al. proposed an adjusted-Q digital GEQ employing the opposite filters [11]. By gracefully increasing the Q-factor of the opposite filters with increasing gain, the inter-band interference can be reduced effectively in all frequency range. In 2006, Holters proposed a digital GEQ design method based on developed higher-order band shelving filters [12]. The amplitude deviation in the transitional region between two neighbor bands is very low by Holters's method. In 2007, Gerdes et al designed battery powered three-band GEQ [13] and amplifier for portable MP3 player. In 2009, Cecchi and Stefania proposed an approach comprising the fixed and adaptive GEQ [14], and applied it to an automobile.

The infinite impulse response (IIR) filter is often employed to design the GEQ due to its low computational complexity and algorithm delay [15]. For an analog GEQ, the traditional design methods are good enough; but for a digital GEQ, they will result in an unexpected adjacent band interference and obvious deviations of center frequency, bandwidth and gain, especially in the sub-bands located in the high frequency region. To remedy these problems, an improved design method of the GEQ based on the modified bilinear transformation is proposed. This method combines

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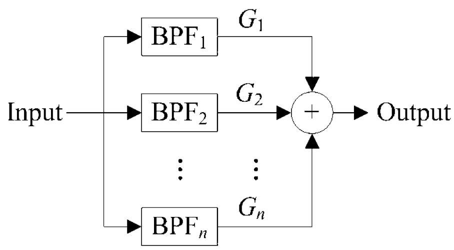

Fig. 1. Diagram of graphic equalizer.

the pre-distortion and optimization techniques to make the center frequencies and bandwidths of the GEQ equal to the desired ones, and its amplitude–frequency response is more accurate than the traditional design methods. As for the GEQ implementation, the program based on the proposed method is run on a personal computer, and the proper coefficients of GEQ are generated. These coefficients are then downloaded to a digital signal processor (DSP) to implement the audio equalization.

The paper is organized as follows: The traditional design method of digital GEQ is described in Section 2. The improved design method is proposed in Section 3. Some simulations are given in Section 4. Finally, some conclusions are drawn in Section 5.

2. The traditional design method for digital audio graphic equalizer

The schematic diagram of a digital audio GEQ is shown in Fig. 1 [5]. Without loss of generality, we only discuss the case of bandpass filter (BPF), because the result for bandstop filter (BSF) is similar [14]. In Fig. 1, the input signal is first separately filtered with the BPF_k, $k = 1, 2, \ldots, N$, then multiplied by the gain G_k, $k = 1, 2, \ldots, N$, and finally merged them as output signal.

In the Laplace domain (S-domain), the transfer function of the k-th constant-Q analog BPF is [9]

$$H_k(s) = \frac{\frac{\Omega_{dk}}{Q_{dk}} s}{s^2 + \frac{\Omega_{dk}}{Q_{dk}} s + \Omega_{dk}^2}, \quad k = 1, 2, \ldots, N \tag{1}$$

where Ω_{dk} is the desired analog center angular frequency of the k-th BPF, Q_{dk} is the desired quality factor of the k-th BPF, defined by the ratio of filter's center frequency and bandwidth.

When the bilinear mapping rule from S-domain to Z-domain is applied in Eq. (1) [14], i.e. s is replaced with the following equation

$$s = \frac{2}{T_s} \frac{1 - z^{-1}}{1 + z^{-1}} \tag{2}$$

where T_s is the sampling interval, the transfer function of the corresponding digital BPF in the Z-domain is

$$H_k(z) = \frac{2\Omega_{dk} T_s (1 - z^{-2})}{[4Q_{dk} + 2\Omega_{dk} T_s + Q_{dk}(\Omega_{dk} T_s)^2] + [2(\Omega_{dk} T_s)^2 - 8]Q_{dk} z^{-1} + [4Q_{dk} - 2\Omega_{dk} T_s + (\Omega_{dk} T_s)^2]Q_{dk} z^{-2}} \tag{3}$$

The overall transfer function of the GEQ is the sum of these $H_k(z)$

$$H(z) = \sum_{k=1}^{N} [G_{dk} H_k(z)] \tag{4}$$

Eqs. (3) and (4) are the traditional design method for a digital GEQ.

A 10-segment digital GEQ is designed as an example. The design parameters are chosen as shown in Table 1.

The amplitude–frequency responses of analog BPFs and corresponding digital BPFs are shown in Fig. 2, and the overall amplitude–frequency responses of analog GEQ, digital GEQ and desired GEQ are shown in Fig. 3. In Fig. 2 and Fig. 3, the side-effect of the design method based on bilinear mapping is obvious, especially in the high frequency region, the center frequency and bandwidth shift from its expected value. Moreover, the amplitude–frequency response of the digital GEQ seriously deviates from its expected value (5 dB) in Fig. 3. To overcome these drawbacks, a more efficient design method for the digital GEQ is expected.

Table 1
The design parameter of digital GEQ.

N, the band number of GEQ	10
f_s (kHz), the sampling rate	48
Ω_{dk} (rad), the center frequency of GEQ	$31.25\pi \times 2^k$
G_{dk}, the gain of GEQ	1.778
Q_{dk}, the quality factor of GEQ	1.414

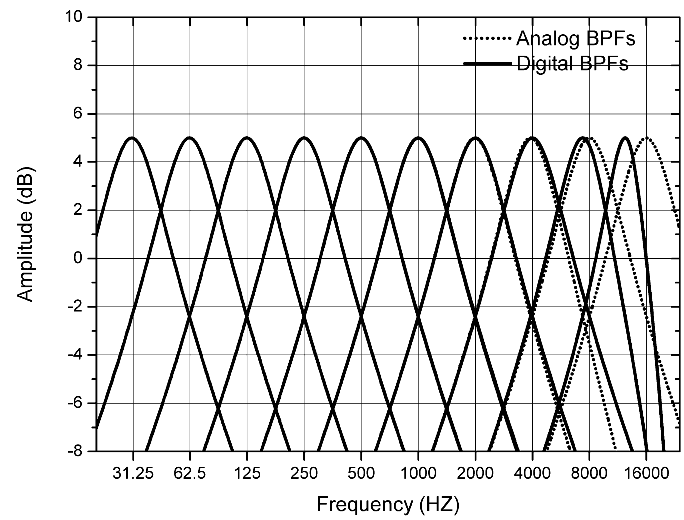

Fig. 2. The amplitude–frequency responses of analog BPFs and digital BPFs in a 10-segment GEQ.

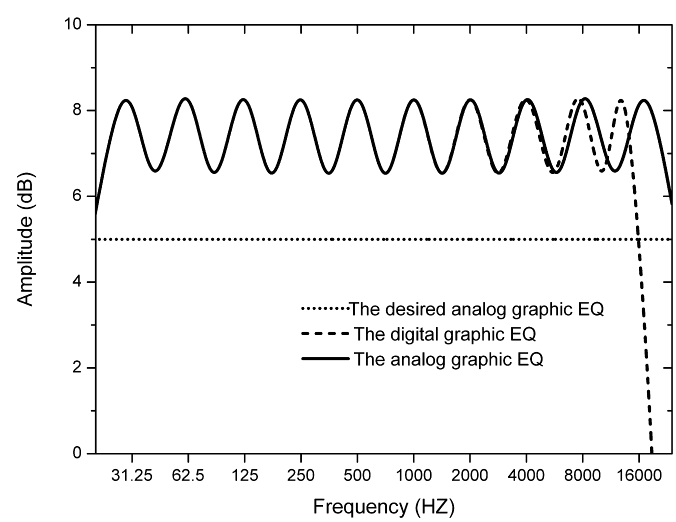

Fig. 3. The amplitude–frequency response of analog GEQ, digital GEQ and desired analog GEQ.

3. An improved design method for digital graphic equalizer

In the improved method, a modified mapping rule is introduced to make the digital center frequency correspond to the analog center frequency strictly, then the bandwidth of digital GEQ is