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Almost All About Audio Equalizers

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Acoustics and Audio Technology Seminar

March 6, 2017

Outline

- Brief history
- Shelving filters
- Parametric equalizers
- Graphic equalizers
- Parallel graphic equalizers
- Cascade graphic equalizers

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Brief History of Audio Equalization

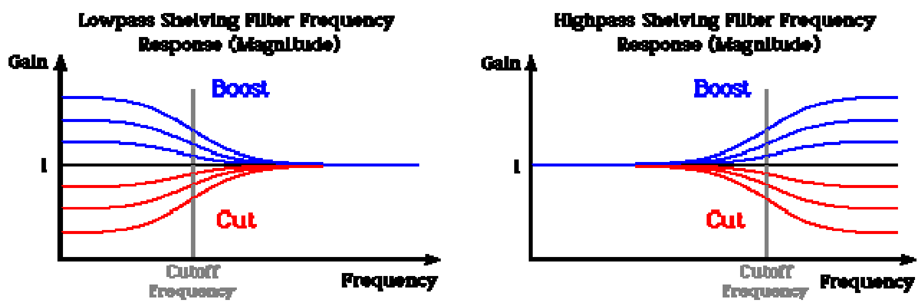
- 1870s: telegraph line signals were selected with vibrating electromechanical reeds
- 1930s: telephone line equalizers boosting of high frequencies to compensate for distance loss
  - “Equalize” the frequency response
- 1940s: Equalizing filter for gramophone players
- 1950s: RIAA correction for LP records
- 1950s: First graphic equalizer, *Cinema Engineering 7080*
- 1970s: Parametric equalizer (Massenburg, 1972)
- 1980s: Digital equalizer, *Yamaha DEQ7* (1987)

Shelving Filters and Equalizers

- Shelving filter is a bass or treble tone control
  - Control the level of low or high frequencies
  - Preserve the rest of the frequencies
- Equalizer modifies the magnitude response
  - Originally used for flattening the response of telephone systems
  - Now wide uses particularly in audio reproduction systems and recording studios (boost/cut, effects)

Shelving Filter

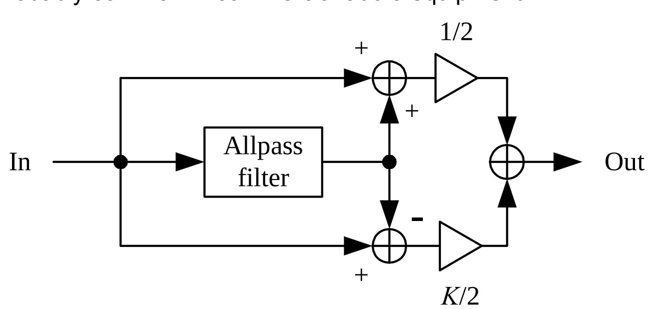
- Amplifies or attenuates low (high) frequencies without affecting the high (low) ones



(Source: http://www.harmony-central.com/Effects/Articles/Equalization/)

Structure for Shelving and EQ Filters

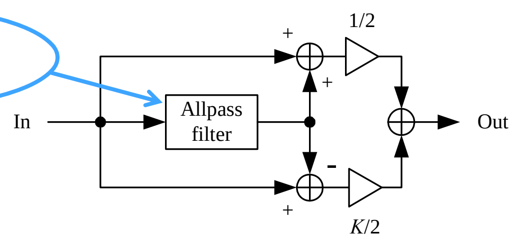
- A clever structure proposed by Regalia & Mitra (1987)
- Suitable for both shelving and equalizing filters
  - Probably common in commercial audio equipment



Shelving Filter Structure

- When *A*(*z*) is a <u>first-order</u> allpass filter, a shelving filter is obtained
  - Transition frequency is determined by the phase response of the allpass filter
  - Gain of the shelf is controlled by parameter *K*

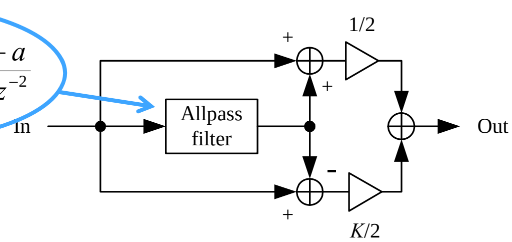
$$A(z) = -\frac{z^{-1} + a}{1 + az^{-1}}$$



Equalizing Filter Structure

- When *A*(*z*) is a <u>second-order</u> allpass filter, a peak or notch filter is obtained
  - Parameter *a* controls bandwidth, *b* controls center frequency
  - Gain of the peak/notch is controlled by parameter *K*

$$A(z) = -\frac{z^{-2} + b(1+a)z^{-1} + a}{1 + b(1+a)z^{-1} + az^{-2}}$$



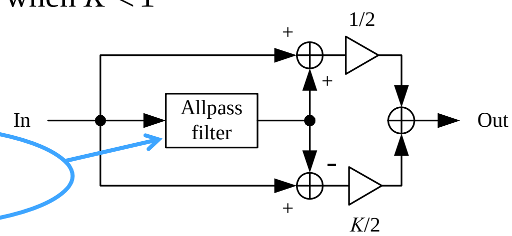
Bass Shelving Filter Design

- Parameter a depends on cutoff frequency f_0 (in Hz) and gain G (in dB) (Regalia & Mitra 1987; Zölzer 1997)

$$a = \begin{cases} \dfrac{\tan(\Omega/2) - 1}{\tan(\Omega/2) + 1}, \text{ when } K \geq 1 \\ \dfrac{\tan(\Omega/2) - K}{\tan(\Omega/2) + K}, \text{ when } K < 1 \end{cases}$$

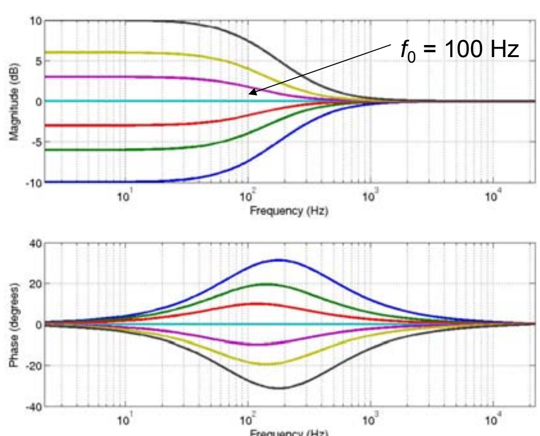
where $\Omega = \dfrac{2\pi f_0}{f_s}$

and $K = 10^{G/20}$



$$A(z) = -\frac{z^{-1} + a}{1 + az^{-1}}$$

Bass Control With Shelving Filter



Original

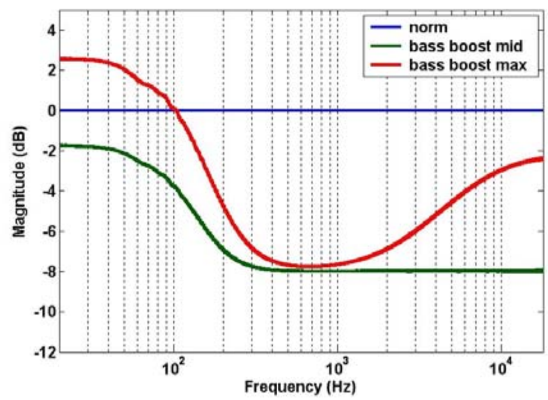
+10 dB

-10 dB

Arttu Siukola, Antti Kelloniemi, TKK, 2004

Practical Example of Tone Control

- Sony D-345 portable CD player has 3 options



Arttu Siukola, Antti Kelloniemi, TKK, 2004

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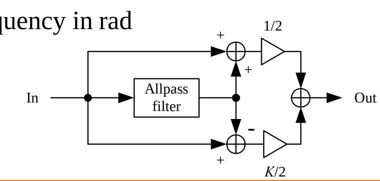
How to Design the Equalizer

- Closed form formulas are available for *a* and *b* (Regalia & Mitra 1987; Zölzer 1997)

$$a = \begin{cases} \dfrac{1-\tan(\Omega/2)}{1+\tan(\Omega/2)}, & \text{when } K \geq 1 \\ \dfrac{K-\tan(\Omega/2)}{K+\tan(\Omega/2)}, & \text{when } K < 1 \end{cases}, \text{ where } \Omega \text{ is normalized } -3 \text{ dB bandwidth and } K \text{ is gain}$$

$$b = -\cos(\omega_0), \text{ where } \omega_0 \text{ is the center frequency in rad}$$

$$A(z) = -\frac{z^{-2} + b(1+a)z^{-1} + a}{1 + b(1+a)z^{-1} + az^{-2}}$$



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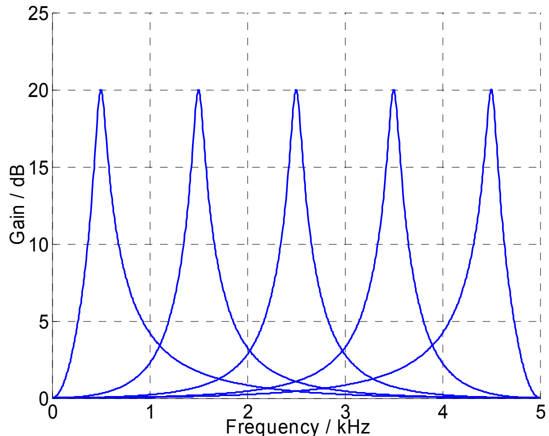
Continuous Control of Center Frequency



K = 7, BW = 100 Hz

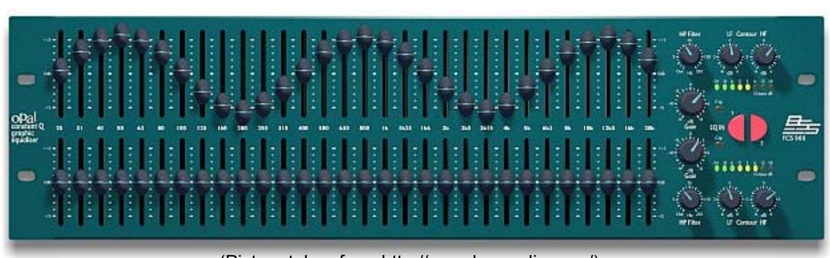
White noise:

f_0 = 300 Hz…6.5 kHz …300 Hz:

Markus Lehtonen, Martti Viljainen, TKK, 2003

Graphic Equalizer

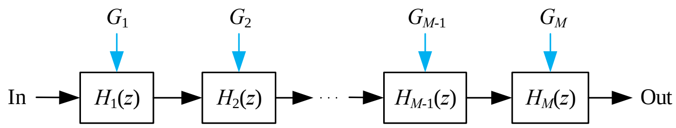
- A set of equalizers with fixed center freq. and Q value
  - One equalizing filter per band for each channel
  - Octave graphic EQ: 10 bands per channel
  - 1/3-oct graphic EQ: ~30 bands per channel



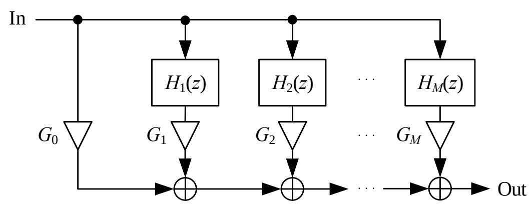
(Picture taken from http://www.bssaudio.com/)

Graphic Equalizer Types

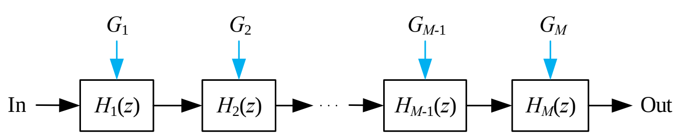
- Cascade structure



- Parallel structure



Cascade Graphic Equalizer

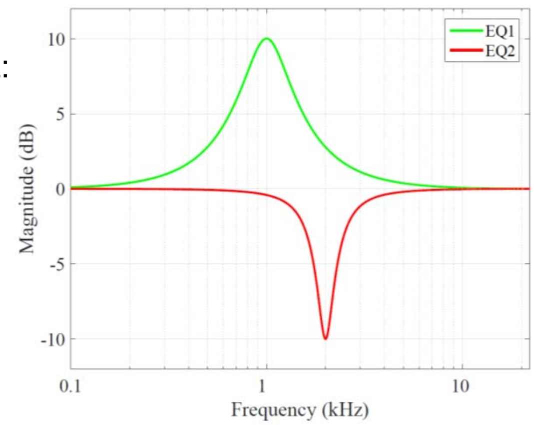


- Each subfilter is an equalizing filter with fixed f_c and Q: Gain *G* at peak, 0 dB elsewhere
- Problem: **interaction** between bands…

Cascade Graphic Equalizer, Ex. #1

- Two EQ filters with at 1 kHz and 2 kHz:

  +10dB and -10dB



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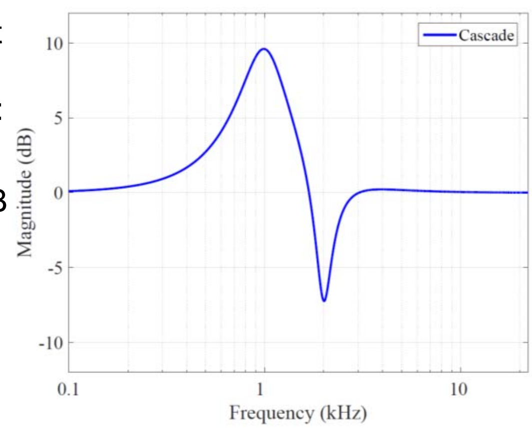
Cascade Graphic Equalizer, Ex. #1

- Responses interact so the overall response is biased:

  +9.6dB and -7.1dB



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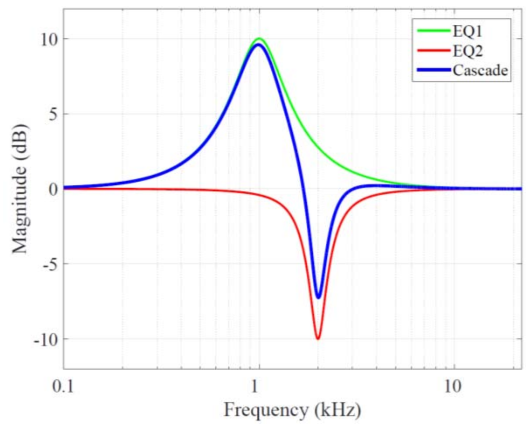
Cascade Graphic Equalizer, Ex. #1

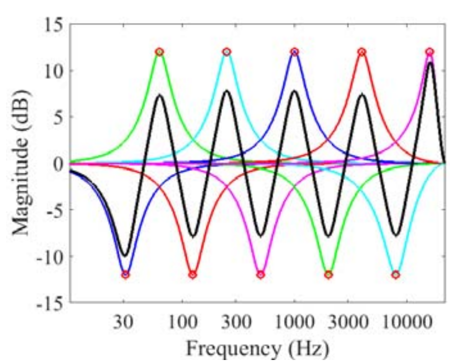
- Interaction problem:

1. Gain of EQ1 at center freq. of EQ2 > 0 dB
2. Gain of EQ2 at center freq. of EQ1 < 0 dB



Cascade Graphic EQ for Octave Bands

- Naïve design leads to severe approximation problems
  - Filter gains = command gains



How to Fix the Graphic Equalizer?

1. Try to change the bandwidth (Q value) of band filters
   – Q should vary with G, but it's complicated…
2. Use higher-order equalizing filters!
   – Get a steeper transition between bands
   – Easy to optimize for cascade GEQ (Rämö & Välimäki, IEEE SPL 2014)
3. Solve the filter gains by accounting for the interaction!
   – Set of linear equations (Abel & Berners, ICMC2004; Oliver & Jot, AES 2015)
   – Very high accuracy with tuning (Välimäki and Liski, 2017)
4. Use a novel parallel graphic EQ design!
   – Very high accuracy, but fairly complicated (Rämö *et al*. 2014)

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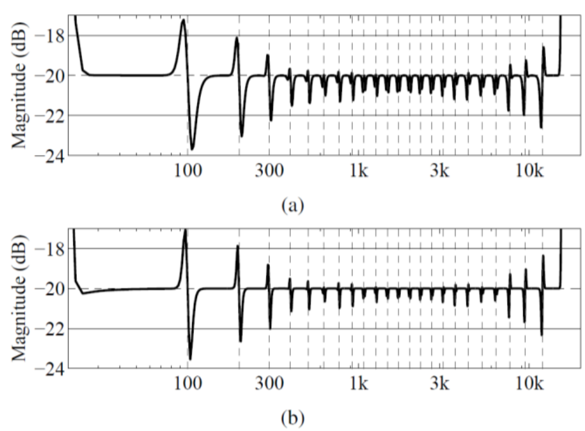
High-Order Cascade Graphic EQ

- Bark-band graphic EQ
  (a)16th-order EQ filters (total order: 384)
  (b) 28th-order EQ filters (672)
- **No interaction** between band filters!
- A new problem: **Ripple** at band edges



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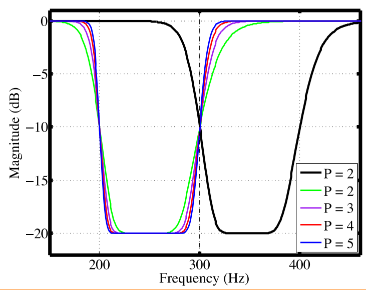
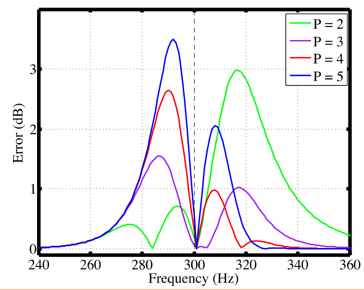
Optimizing High-Order Graphic EQ

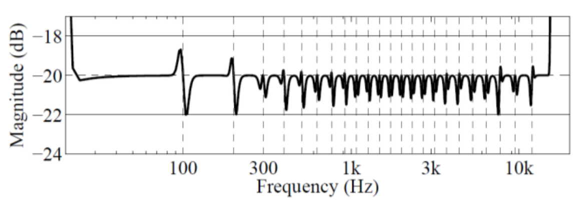
- Ripple between bands is reduced, if the neighboring filters are symmetric (Rämö & Välimäki 2014)
- Iteratively choose the best orders *P*, e.g. *P* < 5
  - In this case, *P* = 3 gives the smallest ripple





Optimized High-Order Cascade GEQ

- Different filter order *P* selected for each band: 28, 20, 16, 12, 12, 12, …, 12, 16, 20
  (24 bands, total order 328)
- **Ripple** reduced to < 2 dB



(Rämö &Välimäki 2014)

Octave Cascade Graphic EQ Design (1)

- It is possible to measure the interaction and form an interaction matrix (Abel & Berners 2004; Oliver & Jot 2015)
- Interaction matrix **B** shows how much each band filter leaks to neighboring bands:
  - Normalized so it shows how much 1 dB of gain affects other bands

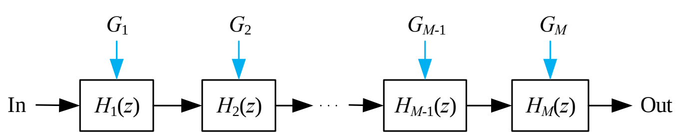
$$\mathbf{B} = \begin{bmatrix} 0.80 & 0.23 & 0.02 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.19 & 1 & 0.21 & 0.04 & 0.01 & 0 & 0 & 0 & 0 & 0 \\ 0.04 & 0.21 & 1 & 0.20 & 0.04 & 0.01 & 0 & 0 & 0 & 0 \\ 0.01 & 0.04 & 0.20 & 1 & 0.20 & 0.04 & 0.01 & 0 & 0 & 0 \\ 0 & 0.01 & 0.04 & 0.20 & 1 & 0.20 & 0.04 & 0.01 & 0 & 0 \\ 0 & 0 & 0.01 & 0.04 & 0.20 & 1 & 0.20 & 0.04 & 0.01 & 0 \\ 0 & 0 & 0 & 0.01 & 0.04 & 0.20 & 1 & 0.20 & 0.03 & 0 \\ 0 & 0 & 0 & 0 & 0.01 & 0.04 & 0.21 & 1 & 0.18 & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 0.01 & 0.06 & 0.25 & 1 & 0.10 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & 0.14 & 0.94 \end{bmatrix}$$

Octave Cascade Graphic EQ Design (2)

- Use inverse matrix of **B** to solve the optimal dB gains in the least squares (LS) sense:

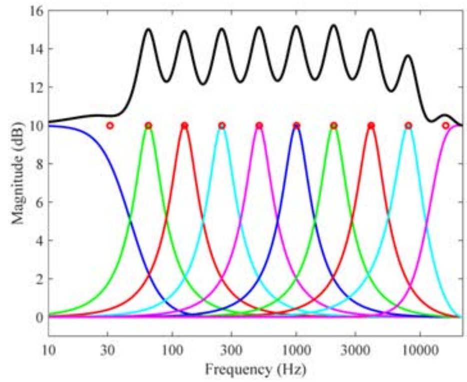
$$\mathbf{g}_{\text{opt}} = \mathbf{B}^{-1}\mathbf{g}$$

- After optimization: filter gains ≠ command gains
- In the next example, 8 peak/notch filters and two 1st-order shelf filters are cascaded (Välimäki & Reiss 2016)



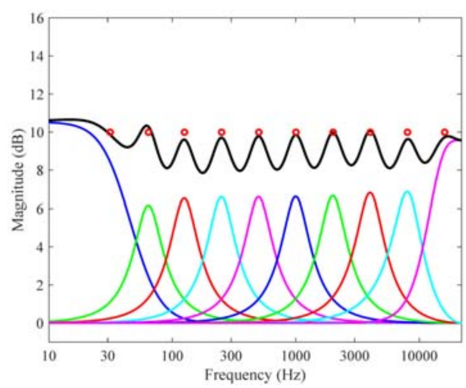
Unoptimized Octave Cascade Graphic EQ

- Maximum error about 5 dB



Optim. Octave Cascade Graphic EQ, 1st try

- Maximum error about 2 dB

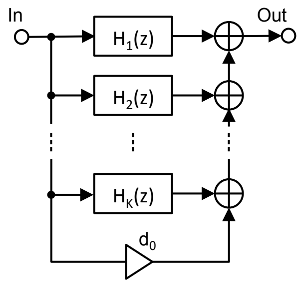


New Graphic EQ Design Methods

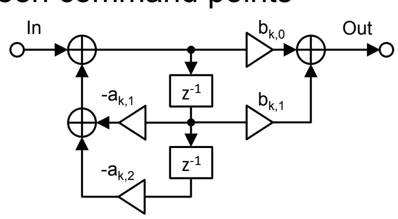
- The previous design method is ok for some applications, but it doesn't fulfill the hi-fi requirement (max 1 dB error)
- Alternative #1: a novel **parallel** graphic EQ design
  - Very high accuracy, but requires optimization (Rämö *et al*. 2014)
- Alternative #2: a novel **cascade** graphic EQ design
  - Even more accurate (Välimäki & Liski 2017)

Novel Parallel Graphic EQ Structure

- Use the parallel IIR filter structure, with fixed poles, proposed by B. Bank (2008)
- Use extra band filters between command points



Parallel Structure

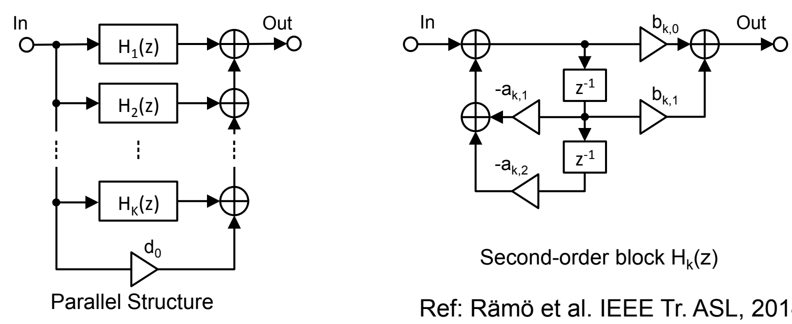


Second-order block $H_k(z)$

Ref: Rämö *et al.* IEEE Tr. ASL, 2014

Novel Parallel Graphic EQ Design

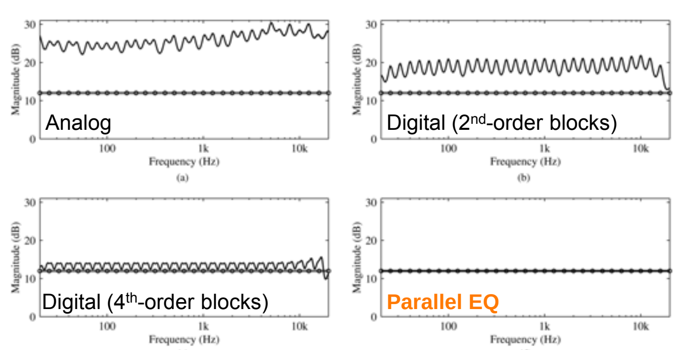
- Poles can be set first (log freq. distribution)
- Least squares design of coefficients $b_{k,0}$ and $b_{k,1}$



Ref: Rämö et al. IEEE Tr. ASL, 2014

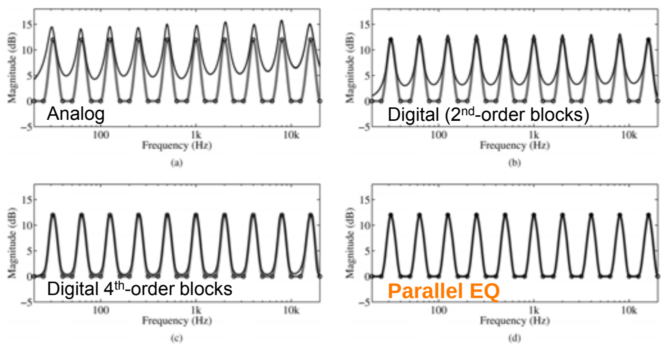
Graphic EQ Response Example #1

- Constant +12 dB command gain at all bands – surprisingly hard!



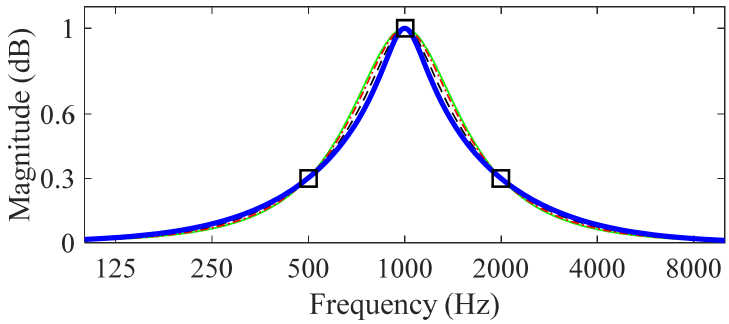
Graphic EQ Response Example #2

- Every 3rd gain at +12 dB, others at 0 dB – known to be difficult



Cascade GEQ with Variable-Q Band Filters

- It is possible to force the response ”proportional” at its f_c and the 2 neighboring f_cs (Välimäki & Liski 2017)



Orfanidis Peak Filter

- We use the following peak filter with $G_B = 0.3G$

$$H(z) = \frac{1 + G\beta - 2\cos(\omega_c)z^{-1} + (1 - G\beta)z^{-2}}{1 + \beta - 2\cos(\omega_c)z^{-1} + (1 - \beta)z^{-2}},$$

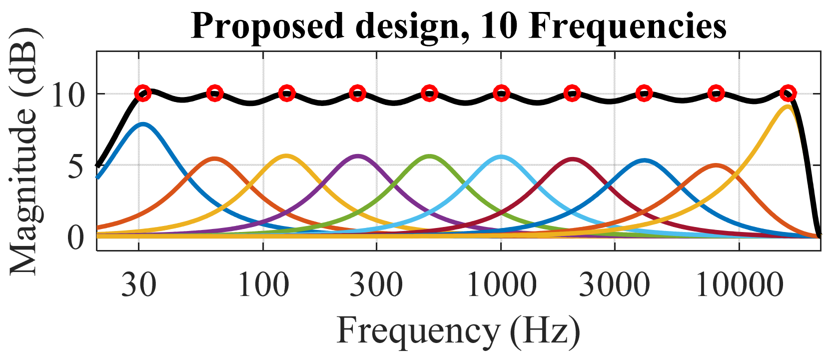
where G is the peak gain, ω_c is the center frequency,

$$\beta = \begin{cases} \tan(B/2), & \text{when } G = 1 \\ \sqrt{\frac{|G_B^2 - 1|}{|G^2 - G_B^2|}} \tan\left(\frac{B}{2}\right), & \text{otherwise} \end{cases}$$

- Original design by Orfanidis (2010)

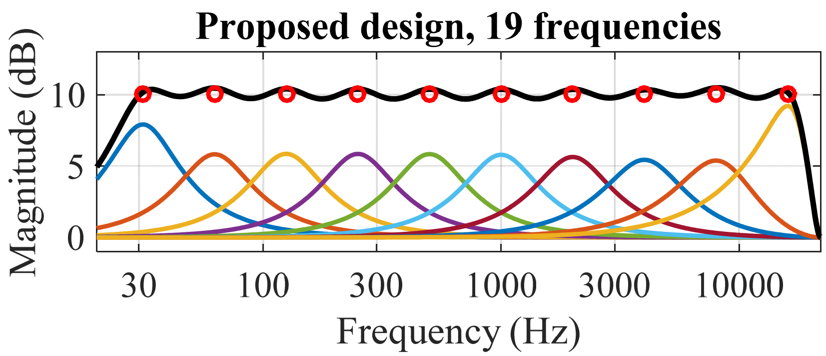
New Cascade Graphic EQ, 1st attempt

- Much better, but the response has droops between command points



New Cascade Graphic EQ, 2nd attempt

- Use more points in the matrix equations to make the ripple more symmetric (Välimäki & Liski 2017)



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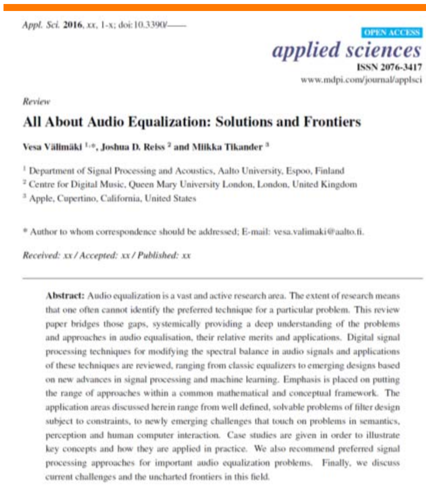
Recent Review Article



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Review

All About Audio Equalization: Solutions and Frontiers

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Abstract: Audio equalization is a vast and active research area. The extent of research means that one often cannot identify the preferred technique for a particular problem. This review paper bridges those gaps, systemically providing a deep understanding of the problems and approaches in audio equalisation, their relative merits and applications. Digital signal processing techniques for modifying the spectral balance in audio signals and applications of these techniques are reviewed, ranging from classic equalizers to emerging designs based on new advances in signal processing and machine learning. Emphasis is placed on putting the range of approaches within a common mathematical and conceptual framework. The application areas discussed herein range from well defined, solvable problems of filter design subject to constraints, to newly emerging challenges that touch on problems in semantics, perception and human computer interaction. Case studies are given in order to illustrate key concepts and how they are applied in practice. We also recommend preferred signal processing approaches for important audio equalization problems. Finally, we discuss current challenges and the uncharted frontiers in this field.

- A review paper about audio equalizers published in *Applied Sciences* in 2016
- Joint work with Dr. Josh Reiss (Queen Mary Univ. London, UK)

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Conclusion

- Basic building blocks of equalizers: shelving filters and parametric equalizing filters (peak/notch)
- Graphic equalizer design is more difficult than it seems
  - Bias caused by band interactions
  - Ripple in the magnitude response
- Several Graphic equalizer designs were discussed
  - Optimized high-order cascade graphic equalizer (Rämö & Välimäki 2014)
  - New parallel graphic equalizer (Rämö, Bank, Välimäki 2014)
  - New cascade graphic equalizer (Välimäki & Liski 2017)

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