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Application of Linear-Phase Digital Crossover Filters to Pair-Wise Symmetric Multi-Way Loudspeakers Part 1: Control of Off-Axis Frequency Response

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Outline

Traditional Crossover Alignments

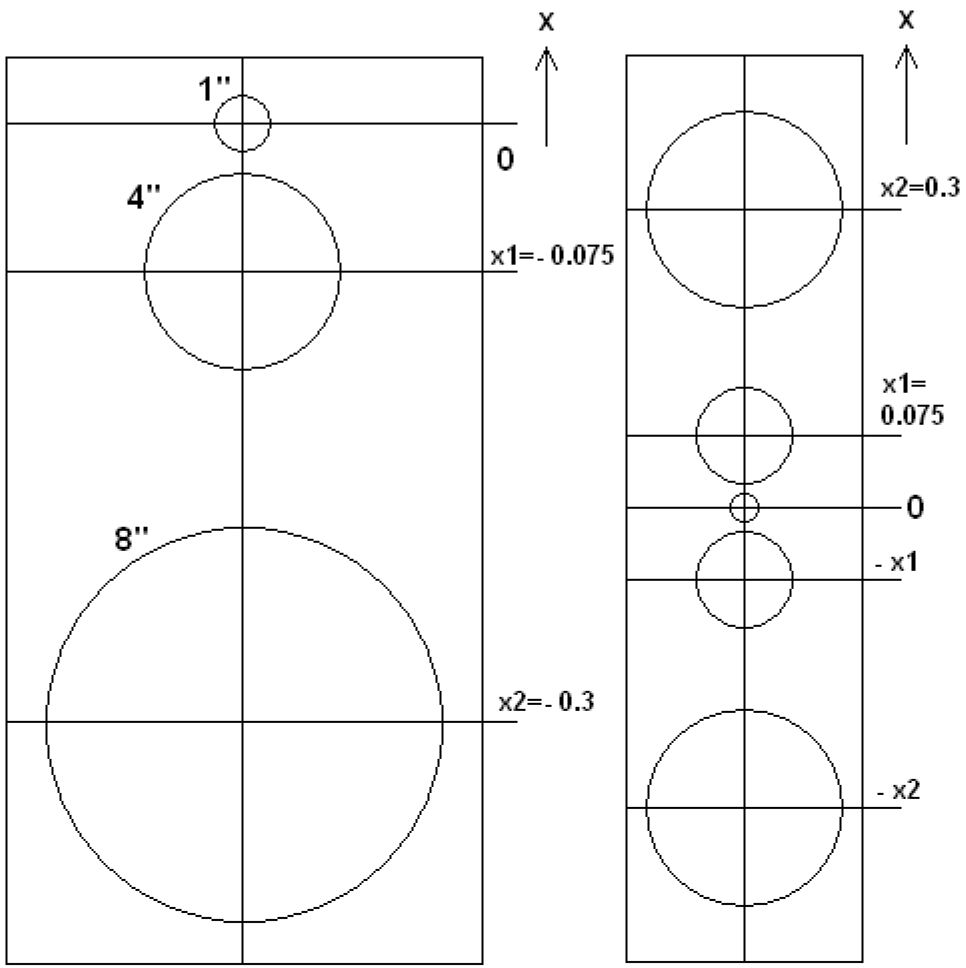
New Design Technique

- basic design
- control of low- and high frequency responses
- variation of design parameters

Implementation

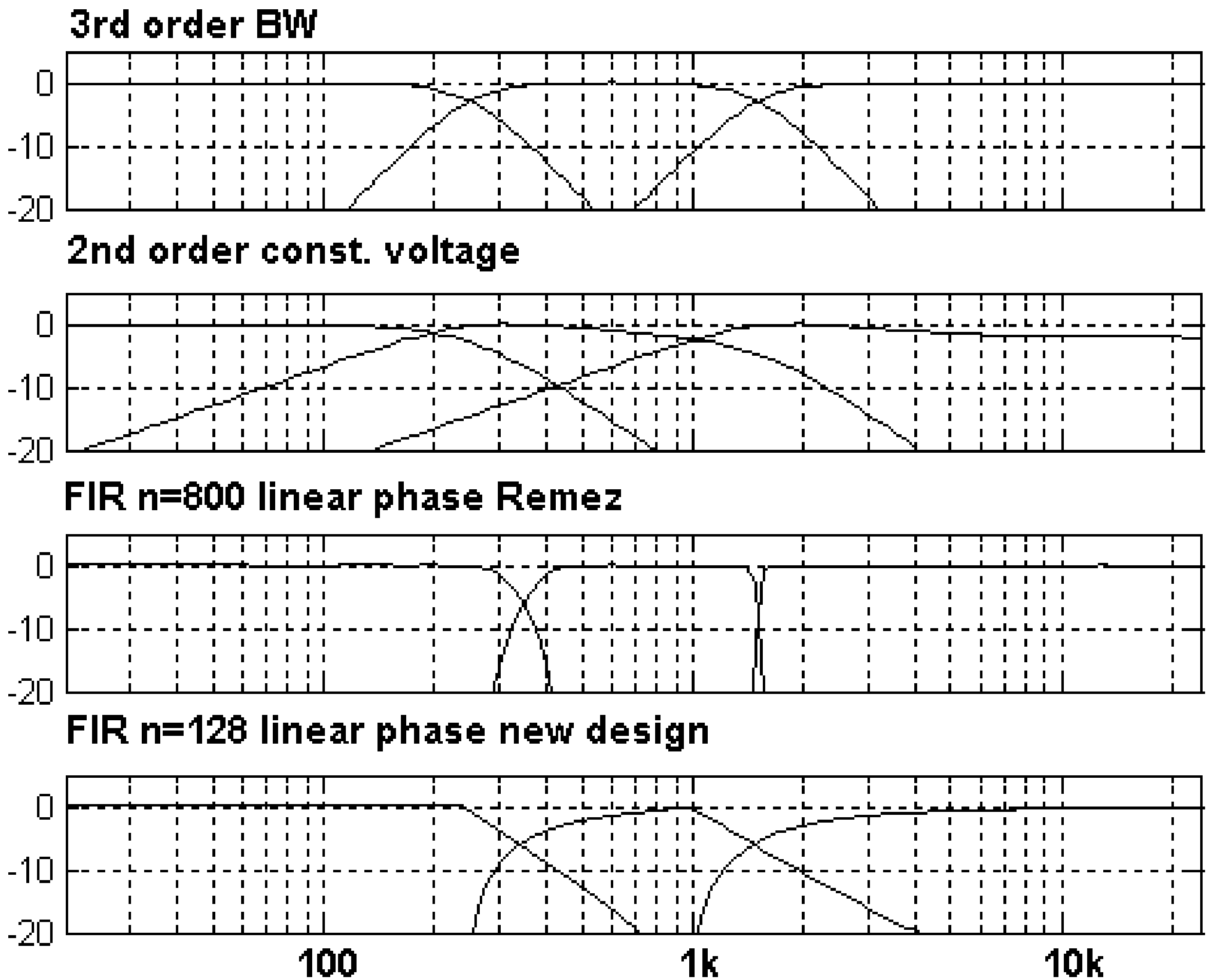
- examples: 3,4,6 - way
- filter approximation
- driver equalization
- baffle diffraction effects

Traditional Crossover Alignments



- ❑ asymmetric vs. symmetric
- ❑ compute frequency responses using circular piston models
- ❑ goal: smooth off-axis responses => constant directivity

Traditional (and new) Crossover Alignments



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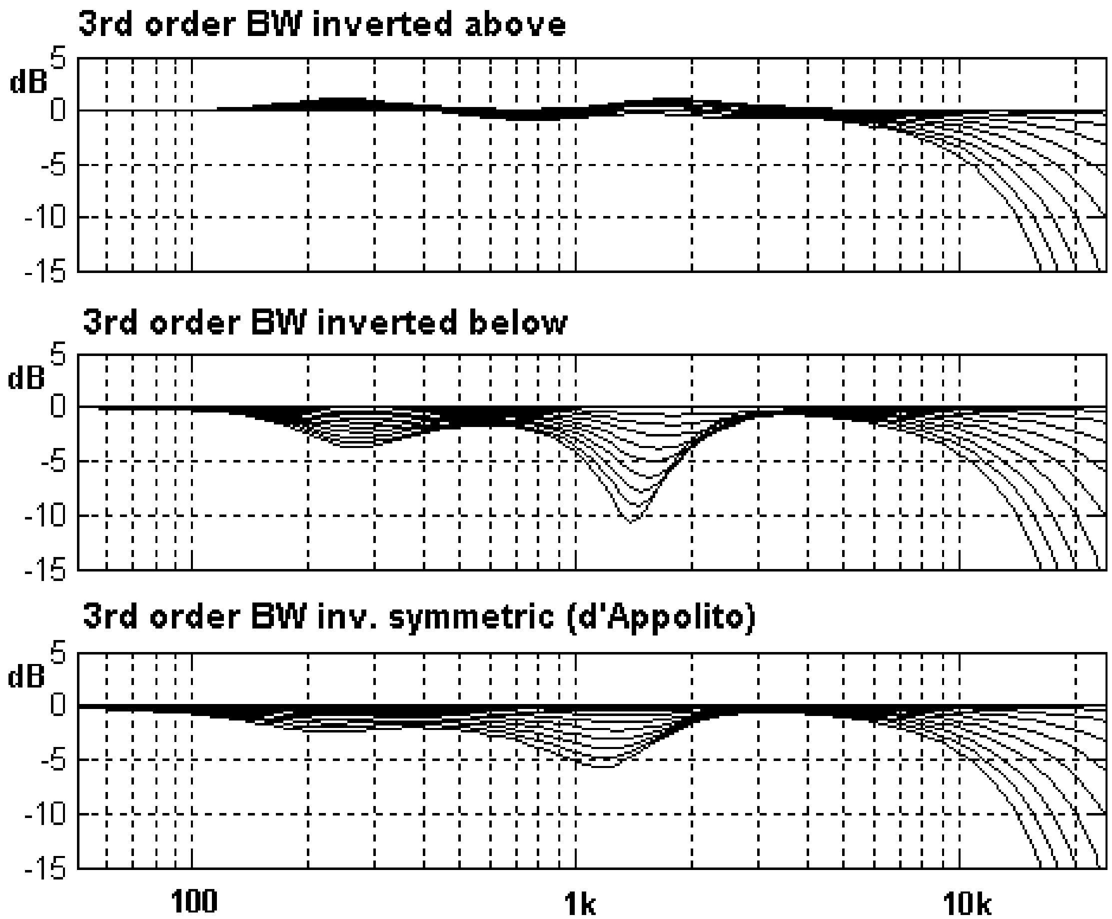
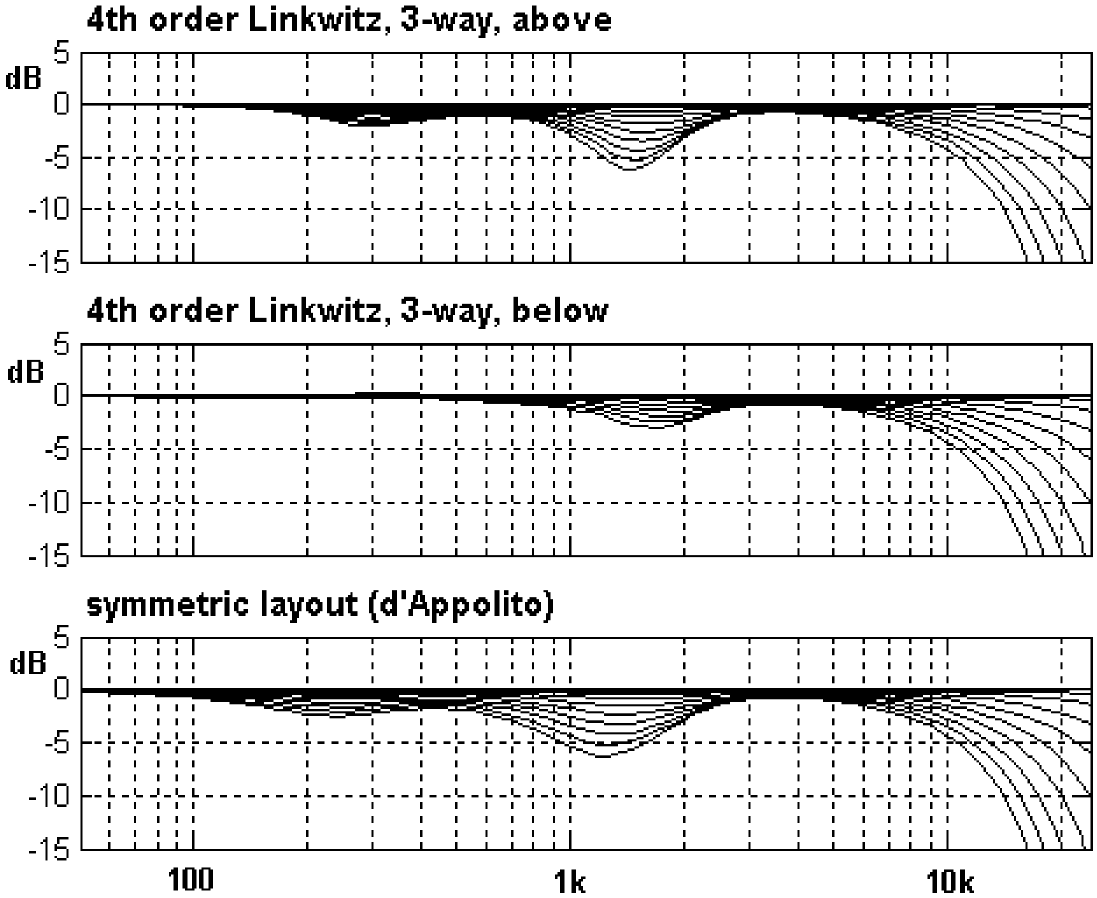
Traditional Crossover Alignments



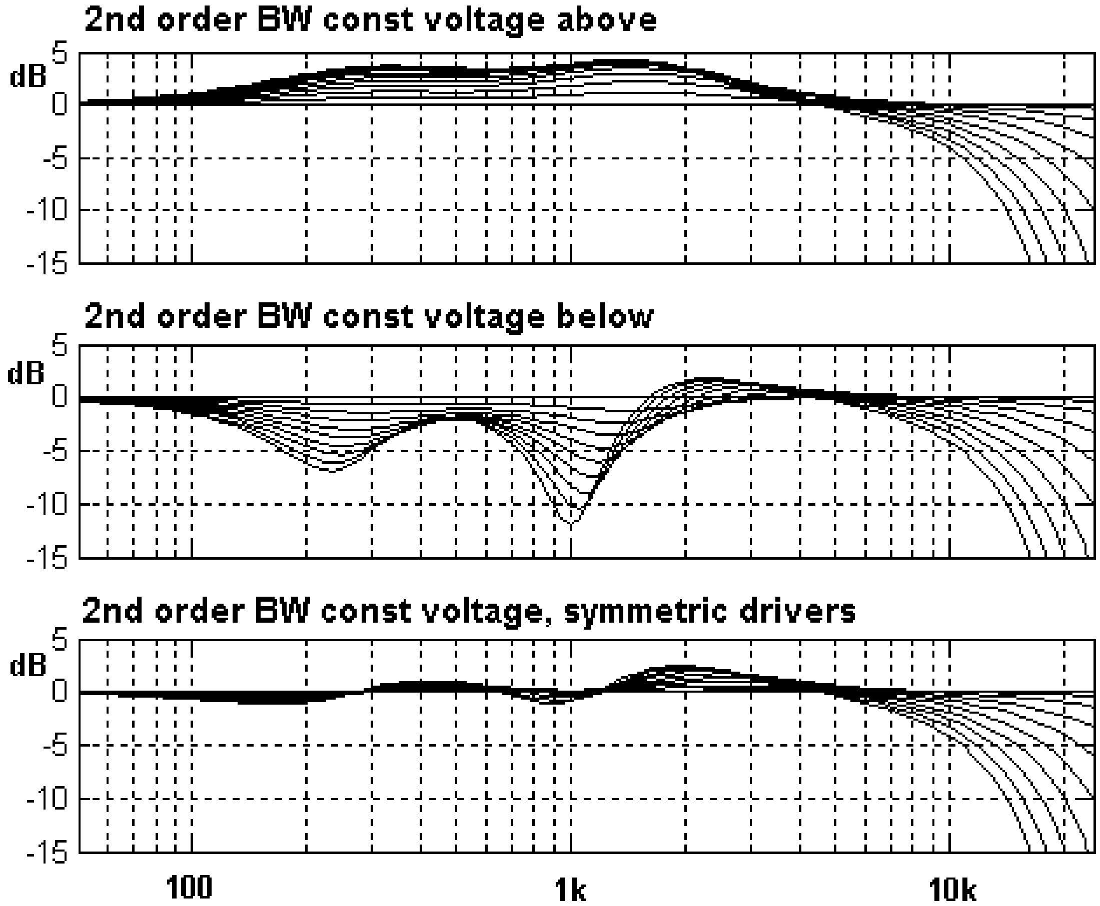
- 3rd order BW with inverted midrange
- vertical 0…45° above/ below tweeter axis/ symmetric layout

Traditional Crossover Alignments



- ❑ 4th order Linkwitz
- ❑ not strictly symmetric because of woofer
- ❑ no flat off-axis responses

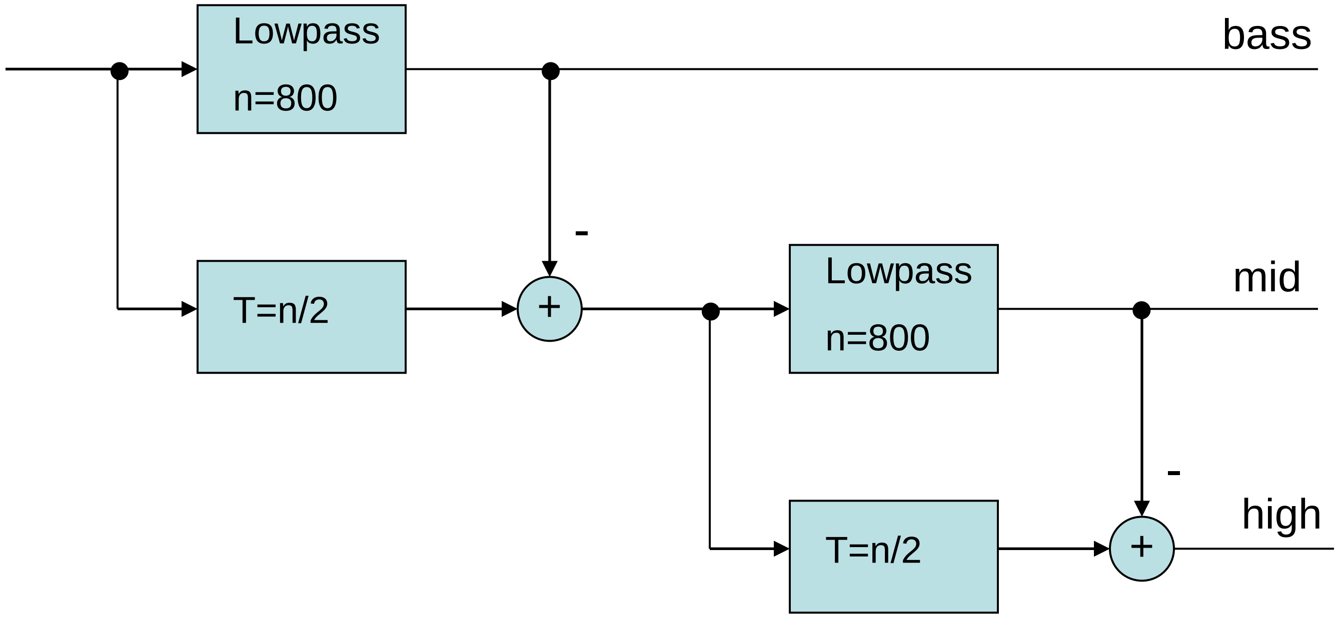
Traditional Crossover Alignments



- 2nd order constant voltage
- works quite well in the symmetric case

Traditional Crossover Alignments

- digital FIR crossover
- latency 16msec



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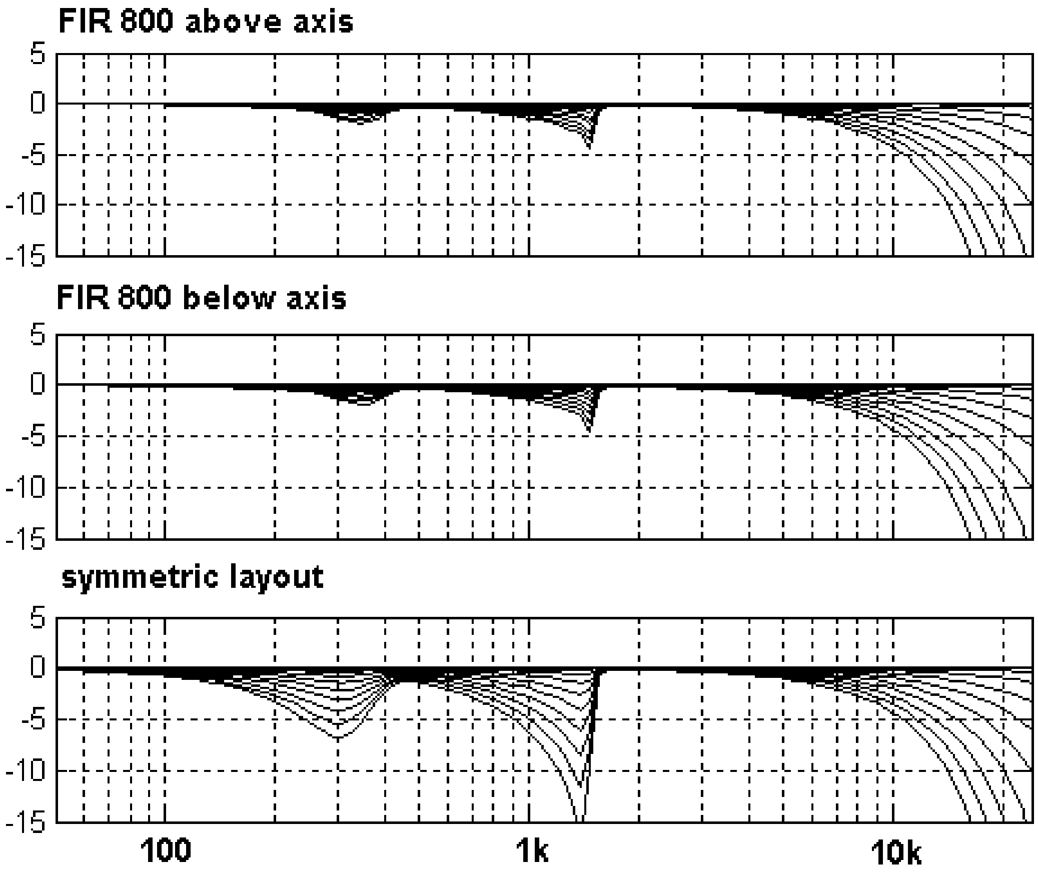
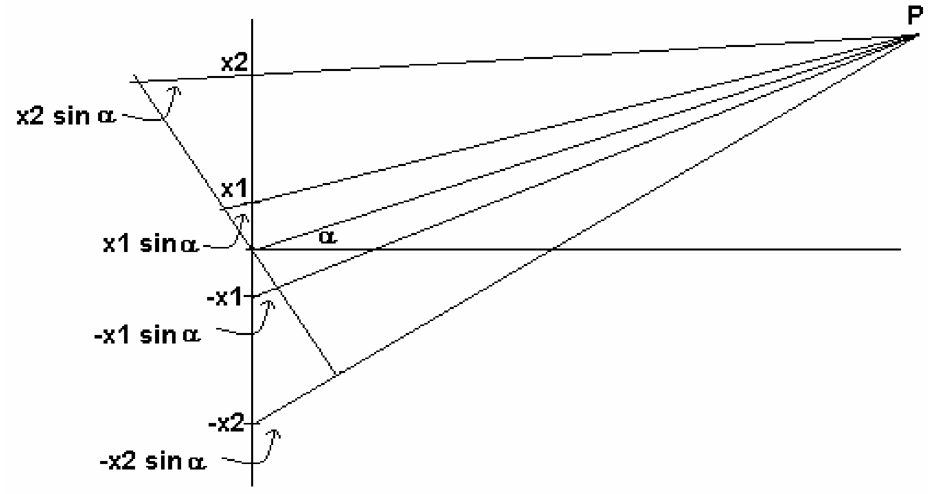
Traditional Crossover Alignments



- ❑ n=800 but still not perfect
- ❑ time smearing likely with effects present that cause non-ideal acoustic sum
- ❑ symmetric layout not applicable

New Technique – Basic Design



Sound pressure of two monopole pairs at point *P*, crossed over using a filter pair with frequency responses w_1, and $(1-w_1)$:

$$H(f) = w_i(f) \cdot C_{i+1}(f) + (1 - w_i(f)) \cdot C_i(f), \quad i = 1,$$

$$C_i = \cos(2\pi\, d_i / \lambda), \quad d_i = x_i \sin\alpha, \quad \lambda = c / f, \quad i = 1,2$$

New Technique – Basic Design

Prescribe an attenuation ***a*** at an off-axis angle $\boldsymbol{\alpha_0}$:

$$H(f) = a \quad at \quad \alpha = \alpha_0$$

Compute the crossover function:

$$w_i(f) = \frac{a - C_i(f)}{C_{i+1}(f) - C_i(f)}$$

Setting

$C_i(f) = a$ yields the frequencies where the lowpass reaches zero,

$$f_i = \frac{c \cdot \arccos(a)}{2\pi \cdot x_i \cdot \sin\alpha_0},$$ that are called “critical frequencies”

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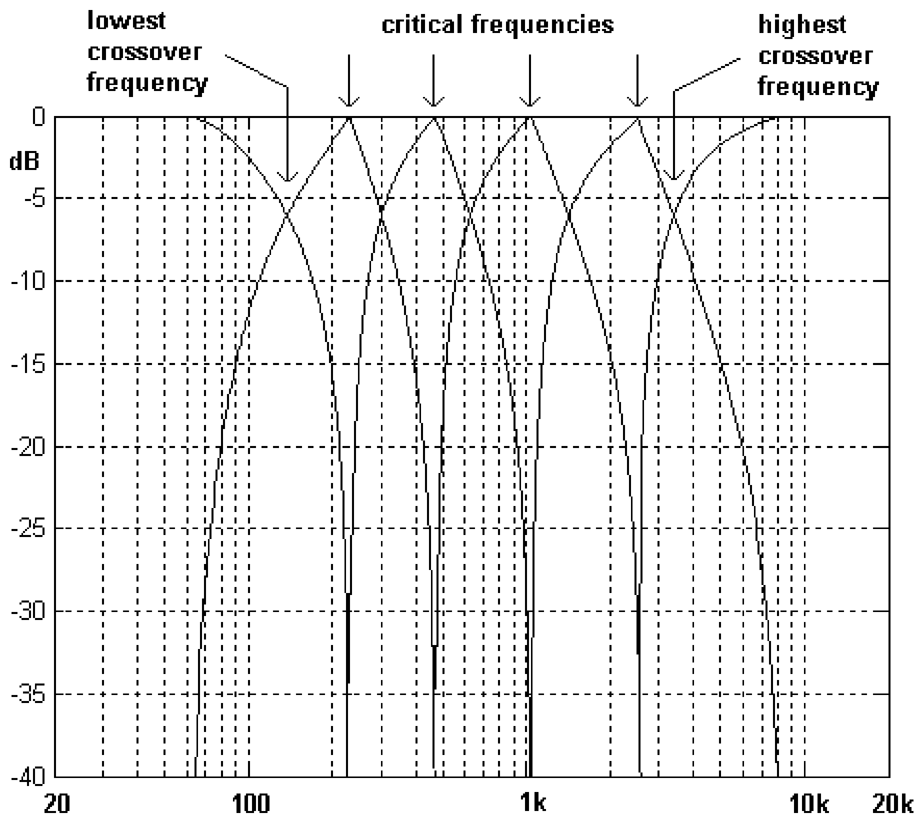
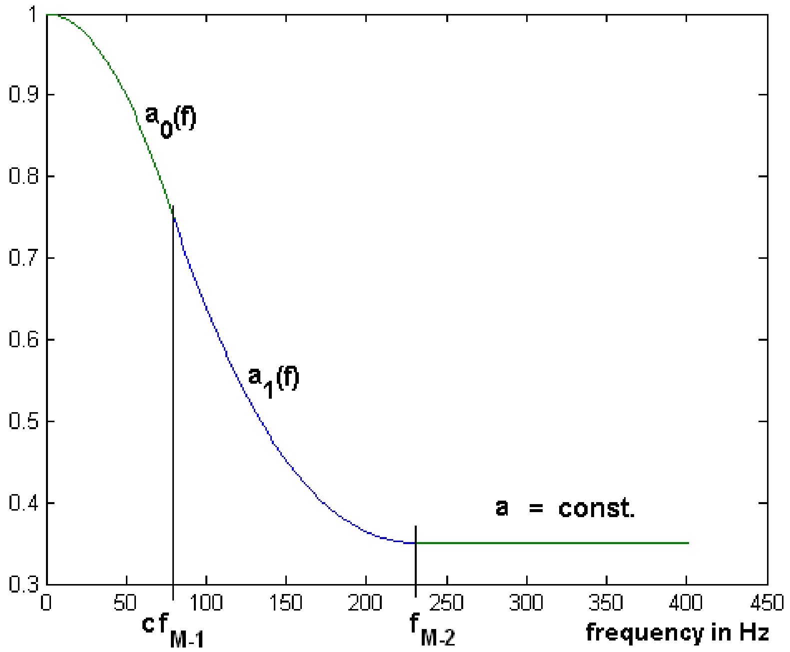
New Technique – Basic Design



- 6-way design example
- crossover frequencies result from driver location data and prescribed attenuation at desired angle
- max. two pairs of transducers are active at a given frequency point

New Technique – Control of Low Frequency Responses

- the frequency response below the lowest critical frequency is that of a pair of monopoles $a_0(f)$, approaching one at DC
- prescribe a transitional frequency response $a_1(f)$ using a spline function



$$w(f) = \frac{a_1(f) - C_{M-2}(f)}{C_{M-1}(f) - C_{M-2}(f)}$$

(M – way design)

New Technique – Control of High Frequency Responses

minimize *n* errors at *n* frequency points

$$e_n = \sum_k (H(f_{n-1}, \alpha_k) - a(k))^2$$

for *k* angles, with

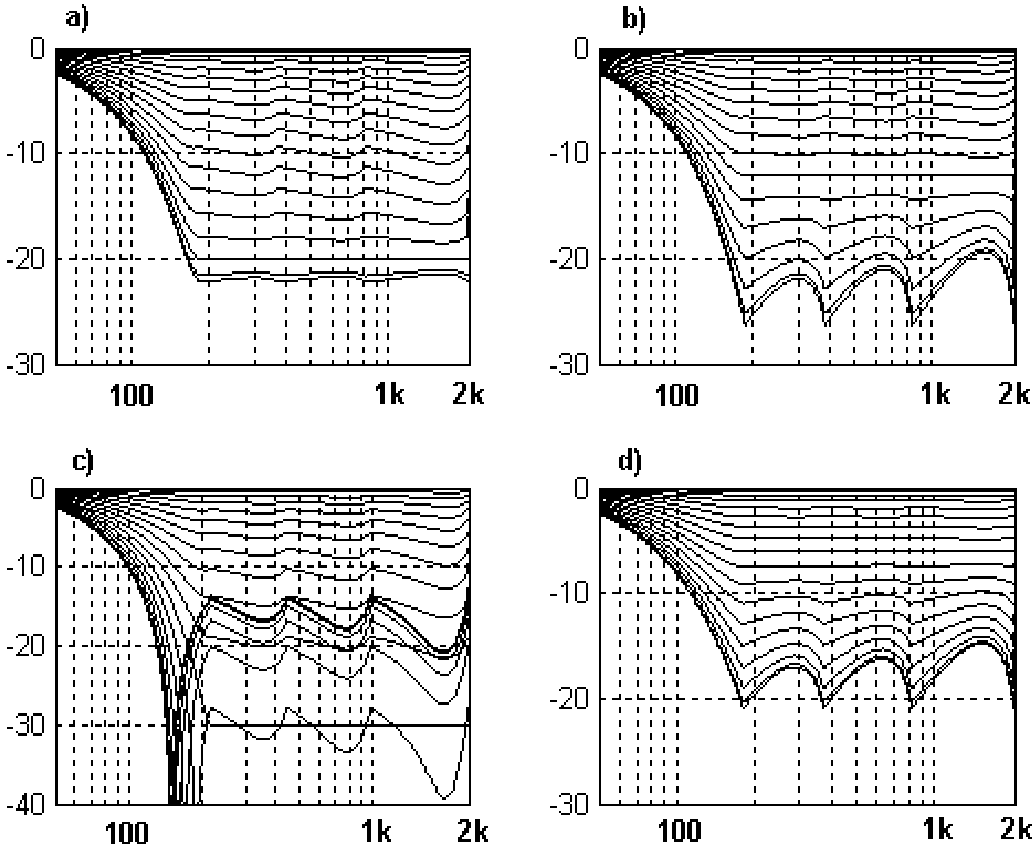
$$H(f_n, \alpha_k) = x(n) \cdot C_1(f_n) + (1 - x(n)) \cdot H_{Tw}(f_n, \alpha_k)$$

- one-parameter crossover filter optimization *x(n)* per frequency point n
- includes a measured tweeter magnitude response H_{TW}

New Technique: Variation of Design Parameters

$$a_\alpha = \cos\left(\frac{\sin\alpha}{\sin\alpha_0} \arccos(a) \right)$$

attenuation at an arbitrary angle is the same at all critical frequency points



6-way design

0…(5°)…90° shown

a) α=80°, a=-20dB

b) α=60°, a=-12dB

c) α=60°, a=-30dB

d) α=45°, a=-6dB

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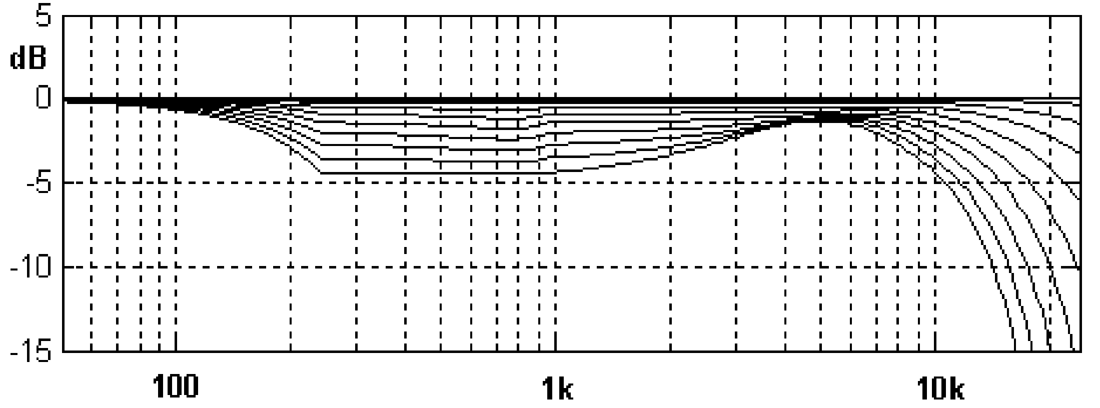
Implementation examples: 3/ 4-way

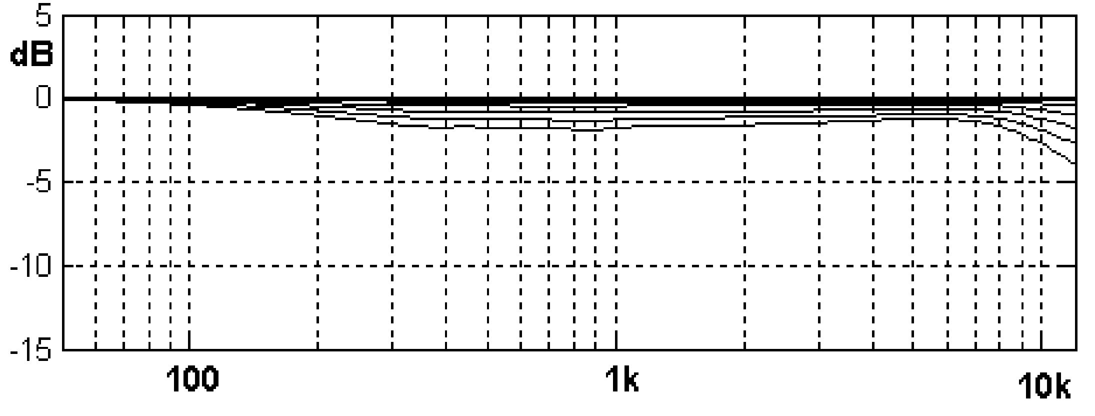


shown 0…5°…45°

x=[.3, .075]

α=45°, a=-4.5dB

f_c= 340/ 1500 Hz



x=[.4, .16, .06]

a=60°, a=-4.5dB

f_c= 160/ 500/ 1700 Hz

Implementation examples: 6-way

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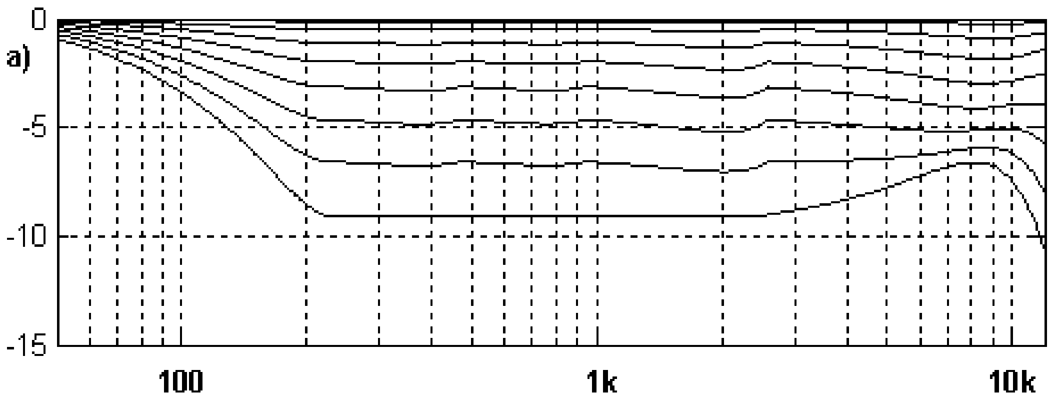
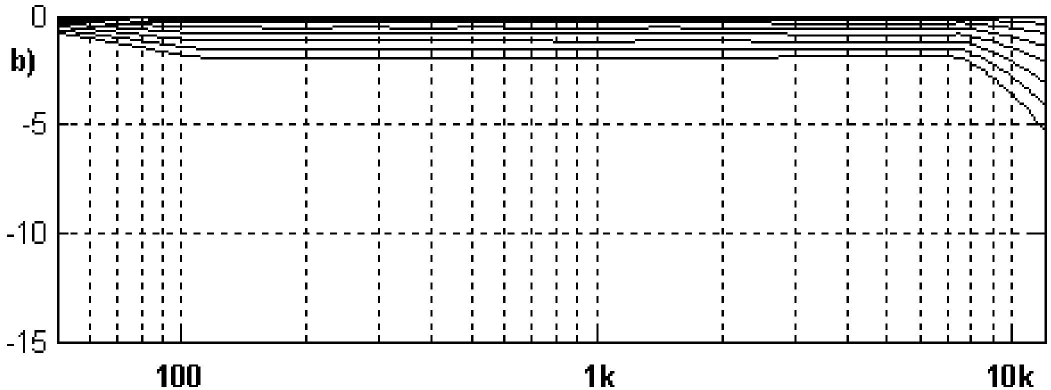


shown 0…5°…40°

x=[.7 .45 .22 .11 .048]

α=40°, a=-9dB

f_c= 160/ 300/ 600/ 1250/ 3200 Hz



α=40°, a=-2dB

f_c= 90/ 160/ 320/ 660/ 1600 Hz

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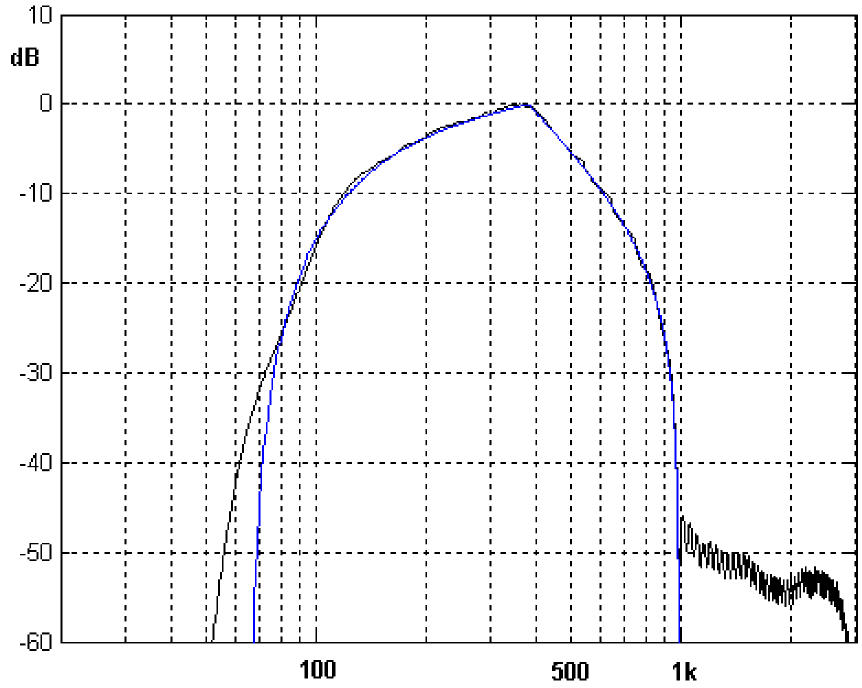
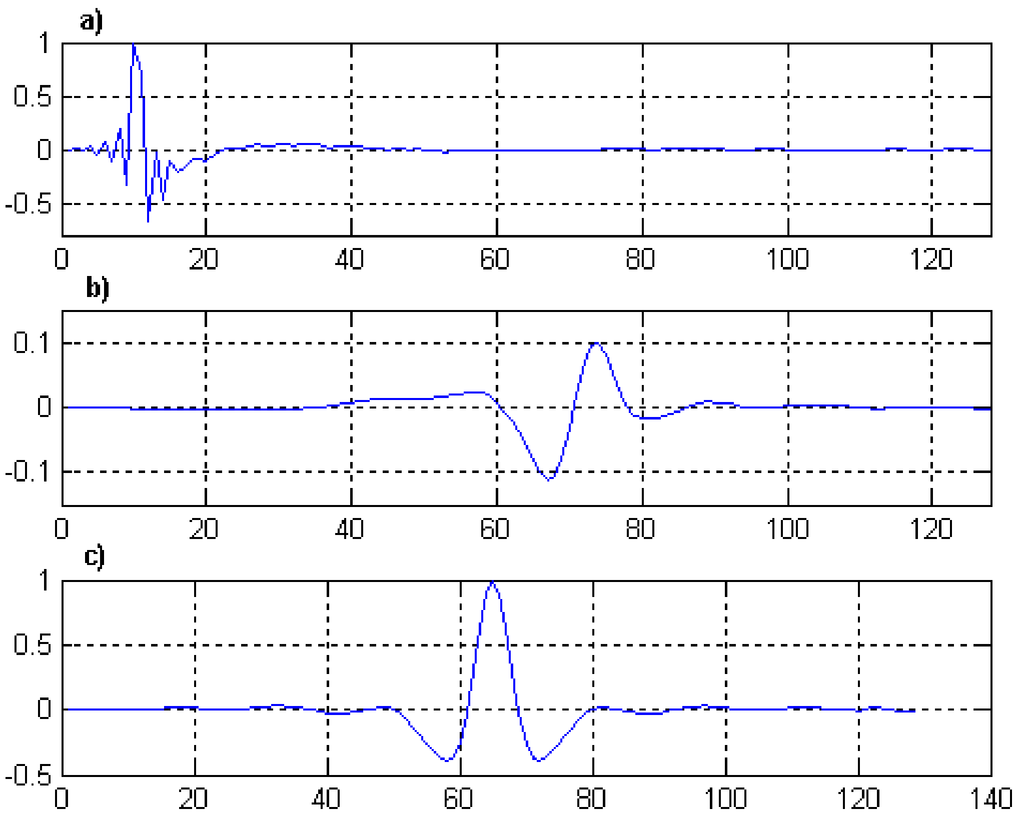
Implementation: Filter approximation and driver EQ

$$H_{result} = H_{cross} / FFT(b_{driver}),$$
$$b_{result} = IFFT(H_{result})$$



- H_{cross} is real-valued (zero-phase)
- in this example *f_s=6kHz, n=128*
- no steep transition band => low filter degrees are possible

Implementation: Filter approximation and driver EQ



Measured driver impulse response

FIR crossover-EQ impulse response

resulting acoustic impulse response

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Implementation: Baffle diffraction effects

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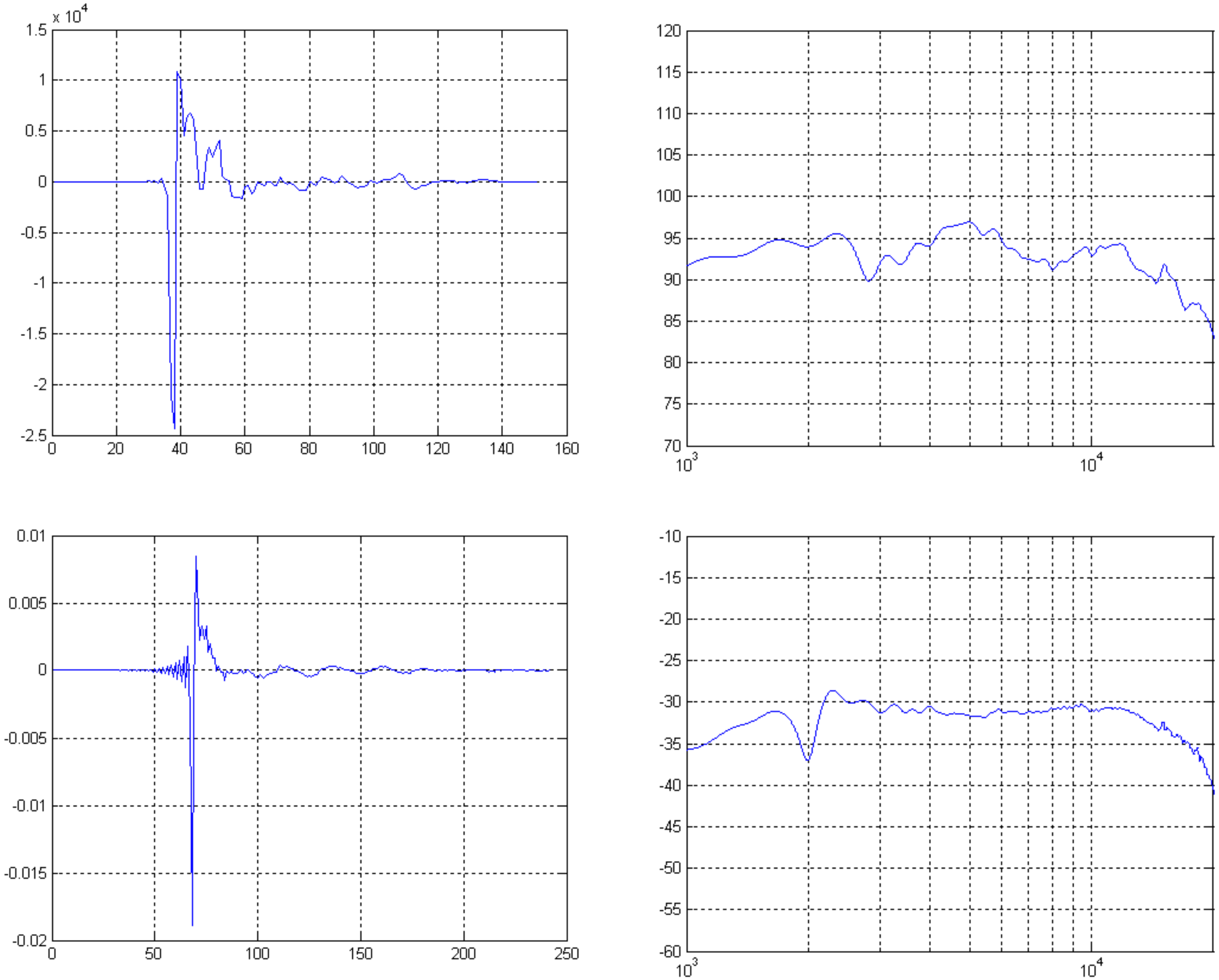

Diffraction caused by woofer cavities

with cardboard cover

angle-dependent effect => equalization is not advisable!

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Final remarks

- we presented a new class of digital crossover filters that allow the design of “perfect” multiway speaker systems
- attention needs to be paid to effects that have previously been considered second order, like baffle diffraction caused by adjacent drivers
- what has really happened in the loudspeaker industry over 30 years? See M. Tanaka *et al,* 63. AES convention, Los Angeles 1979 “An Approach to the Standard Sound Transducer”