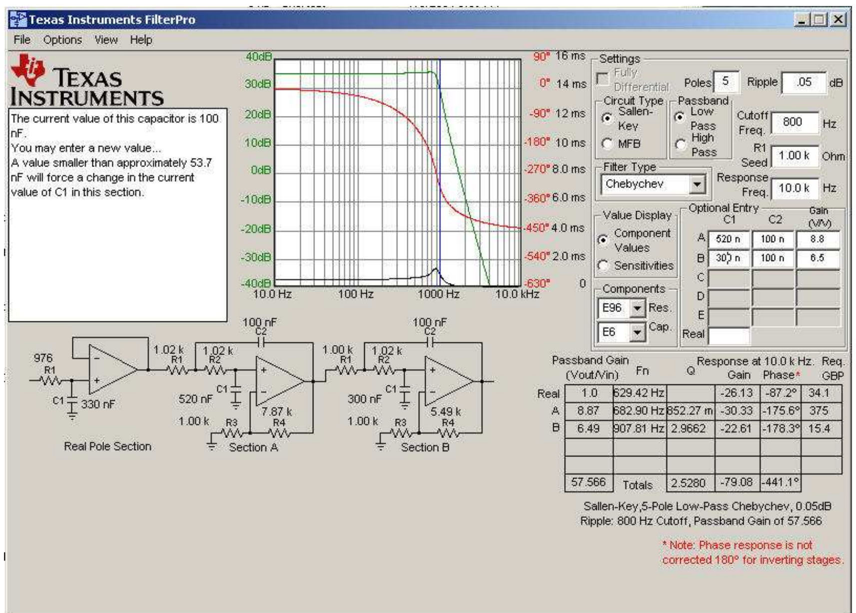
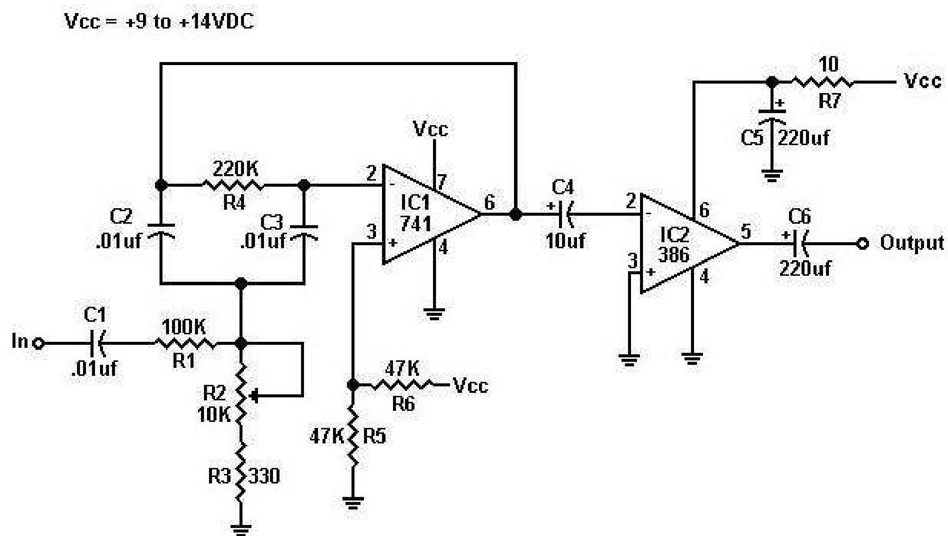
Receiver Audio Filter Design

Approaches for Improved
Receiver Audio Performance





Dan Tayloe, N7VE

Outline

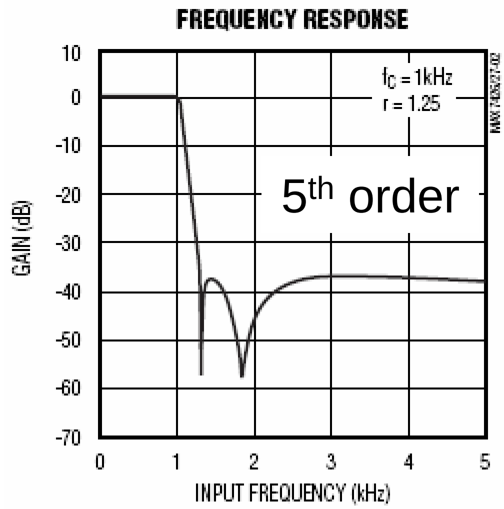
- Types of audio filters and applicability
- The impact of filter “Q”
- Active R/C design
- Hearing protection
- Broad skirt/sharp skirt filter tandem
- Impact of op-amp distortion characteristics

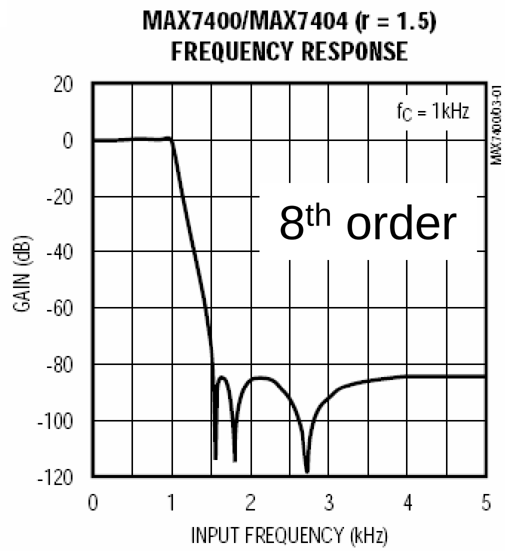
Types of audio filters and applicability

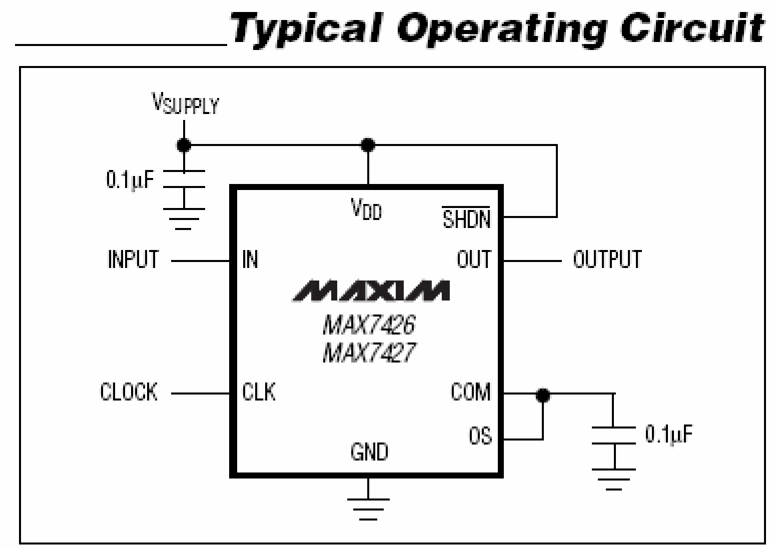
- Useful audio filters can be grouped into four main groups:
  - Passive L/C
    - *Wide dynamic range* useful in all receiver stages, compact, but *susceptible to external magnetic fields* (60 Hz AC hum, TV flyback)
  - Switched Capacitor Filters
    - Compact, *effective and cheap*, but *noisy* – good for end-of-audio chain applications
  - DSP
    - Can provide *superior filter* results, but *expensive* and typically good for *end-of-audio chain* applications
  - Active and passive R/C
    - *Wide dynamic range* useful in all receiver stages, but can have a *high parts count* depending on the number of stages

=> Main focus will be on the design of active R/C filters

Switched Capacitor Filters (SCAF)







- Pro: Sharp cut off, simple, cheap
  - MAX7426 5th order low pass filter ($1 each; 8th order $2)
  - Cap is used on clock input to set the corner freq
    - 250 pf cap on clock line sets filter to ~ 700 Hz cut off
  - Used in NC2030 as variable audio output “comfort filter”

Switched Capacitor Filters (SCAF)

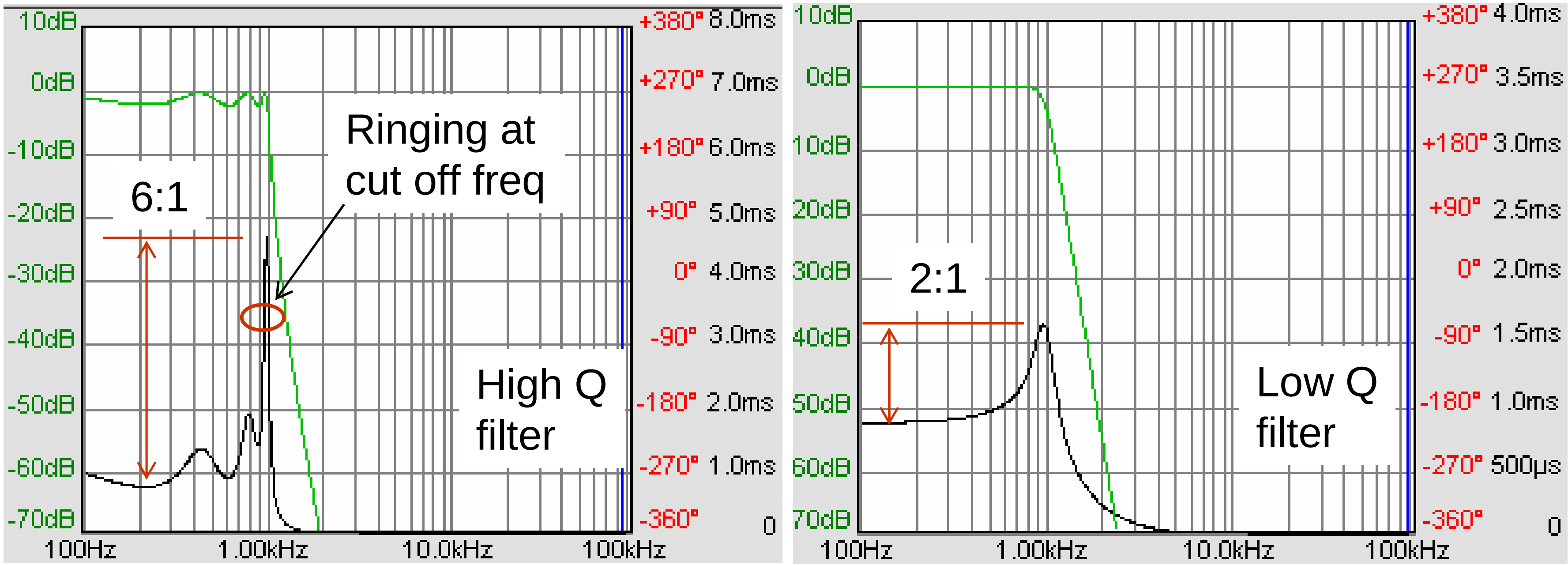
- Con: Very noisy!
  - Typical noise 80 dB down with a 4v pk-pk input
  - Only *34 dB* down at *20 mV headphone level*
  - Cannot afford to have much audio gain after a switched capacitor filter
  - Not useful as an early gain stage in a receiver

=> Filter application is suited to headphone or speaker level audio filtering

Impact of Q in Audio Filter Design

- High Q designs tend to have sharp roll off
  - Sharp frequency roll off is a good thing
- Disadvantages of high Q
  - Component values become *very critical*
  - High Q causes large delay variations across the bandwidth
    - *Filters with low delay variation tend to "sound" better (key point)*
  - A high Q filter tends to "ring" in the presence of impulse noise
    - Think of tapping a leaded crystal glass with a fork
      - Tap is the impulse, ringing tone is the result
    - *Ringing during poor band conditions produces audio that is very fatiguing to listen to*
      - Ringing "covers up" weak signals

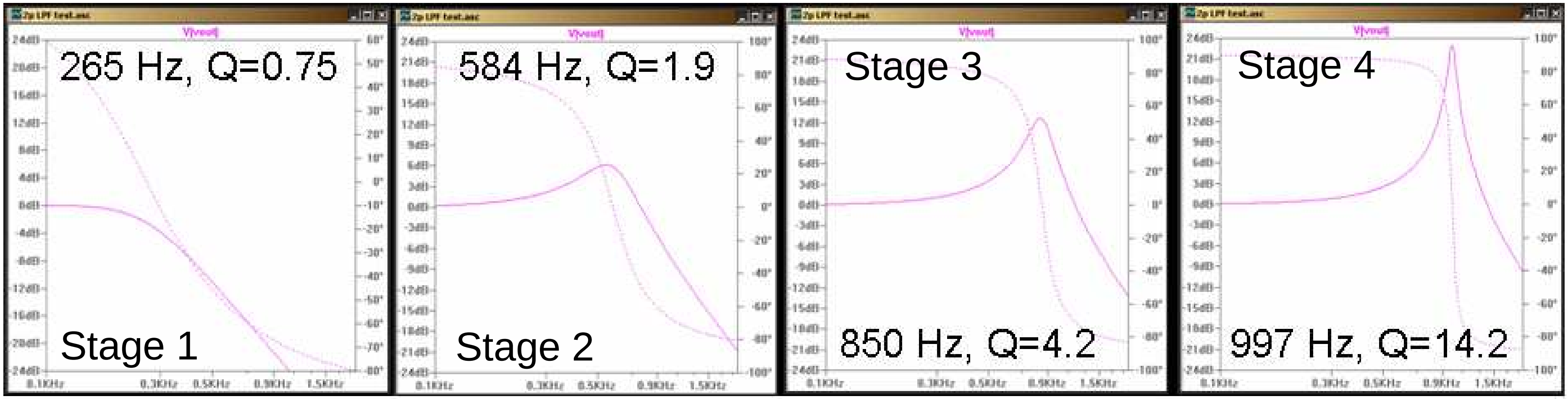
Freq, Delay Response of Two Filters

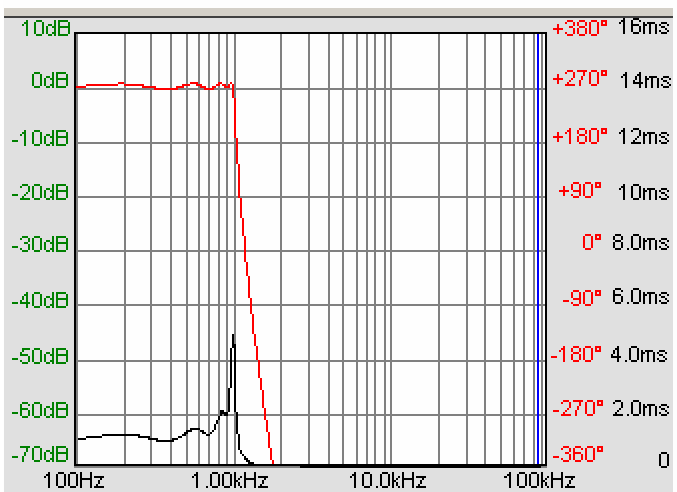


- Filter 1 shows 6:1 delay variation, filter 2 2:1
  - Filter 1 has Q=14 for highest Q stage
  - Filter 2 has Q =3 for highest Q stage

=> Suggest using Q of 3 or less for low ring, low delay spread and cleaner sounding audio

Stage by Stage Freq Response of Sharp Filter

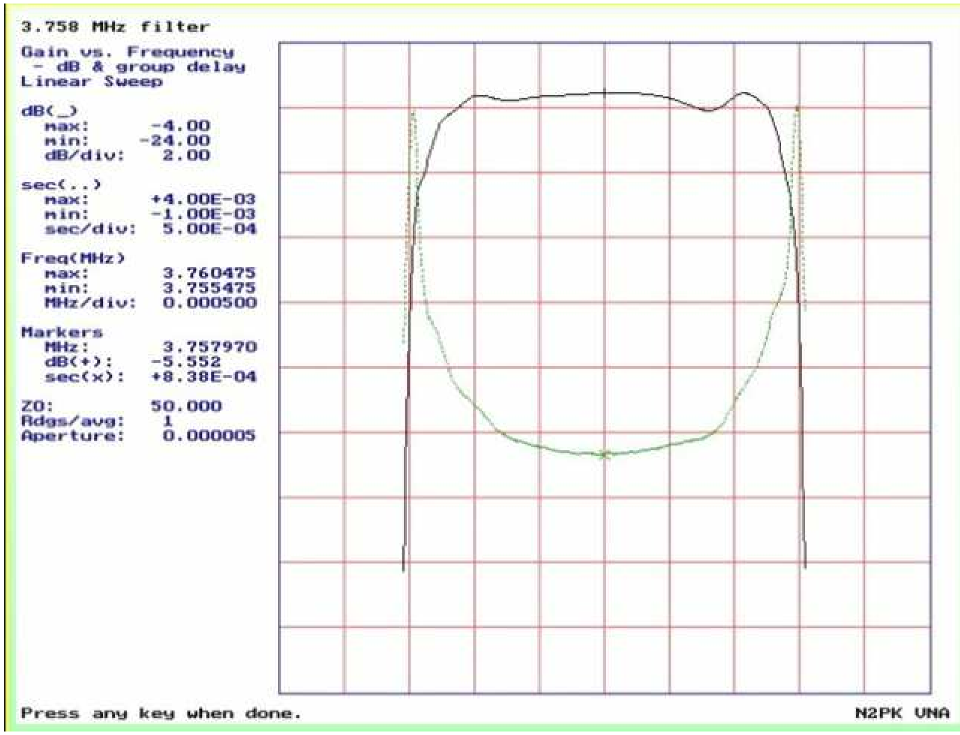




- Composite 4 stage response
- Note ripples are the peaks from stages seen above

- Sharp spike of Q=14 stage causes ringing, but provides fast frequency roll off
- The first three stages start *rolling off early* to even out *1 KHz gain spike* by the last stage
- Notice the first stage is down 24 dB at 1 KHz
  - *Cancels 24 dB peak gain of fourth stage*

Freq, Delay Response of a Crystal Filter



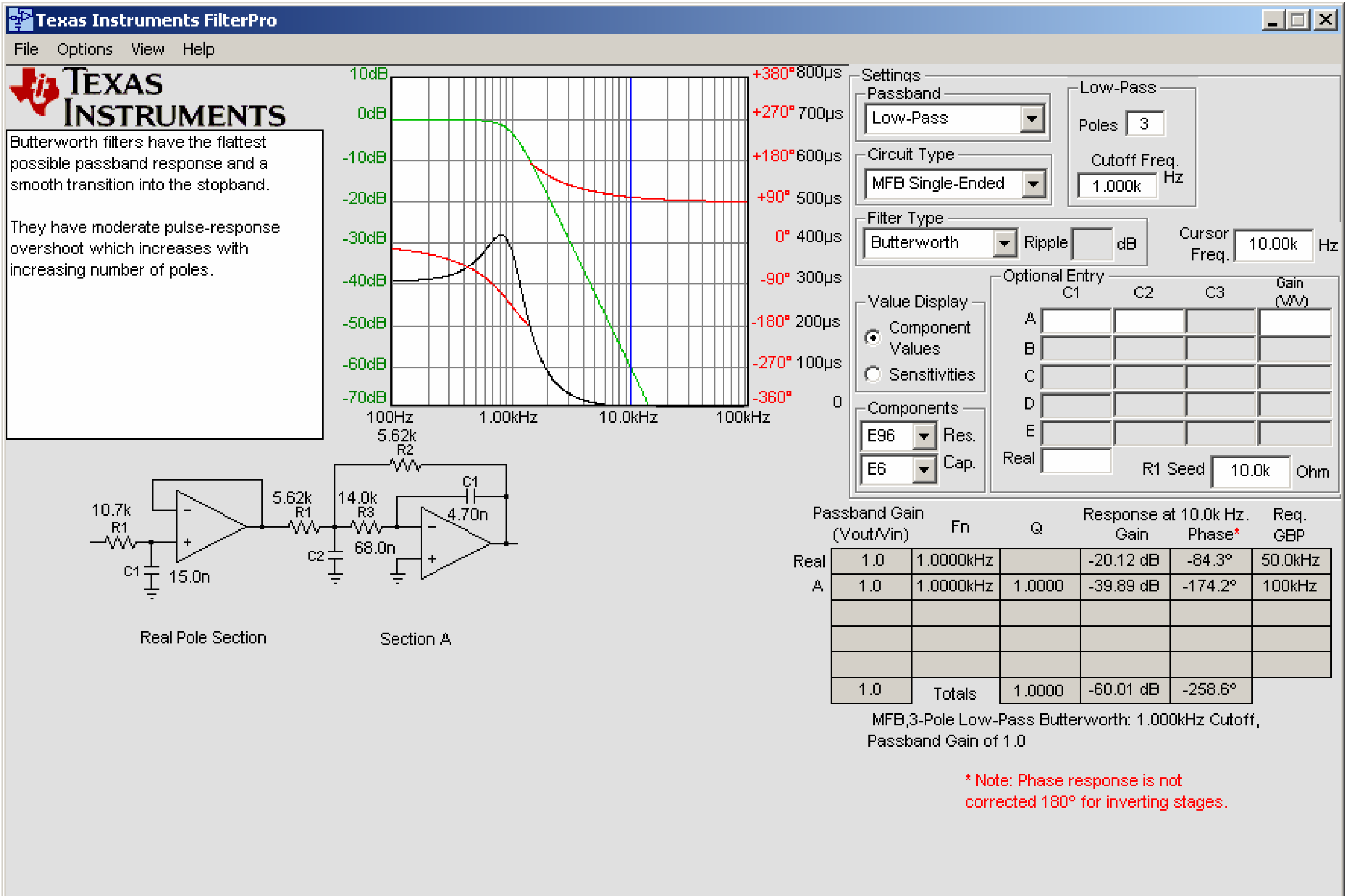
Solid line: Frequency response
Dotted line: Group delay "ears"

4.5:1 group delay variation

=> Sharp roll off filters tend to have large group delay variations and significant ringing

- Crystal filters have *two* sharp edges,
  - 500 Hz cw filter has one at 300 Hz and 800 Hz
- Filter rings at both *300 and 800 Hz* edges

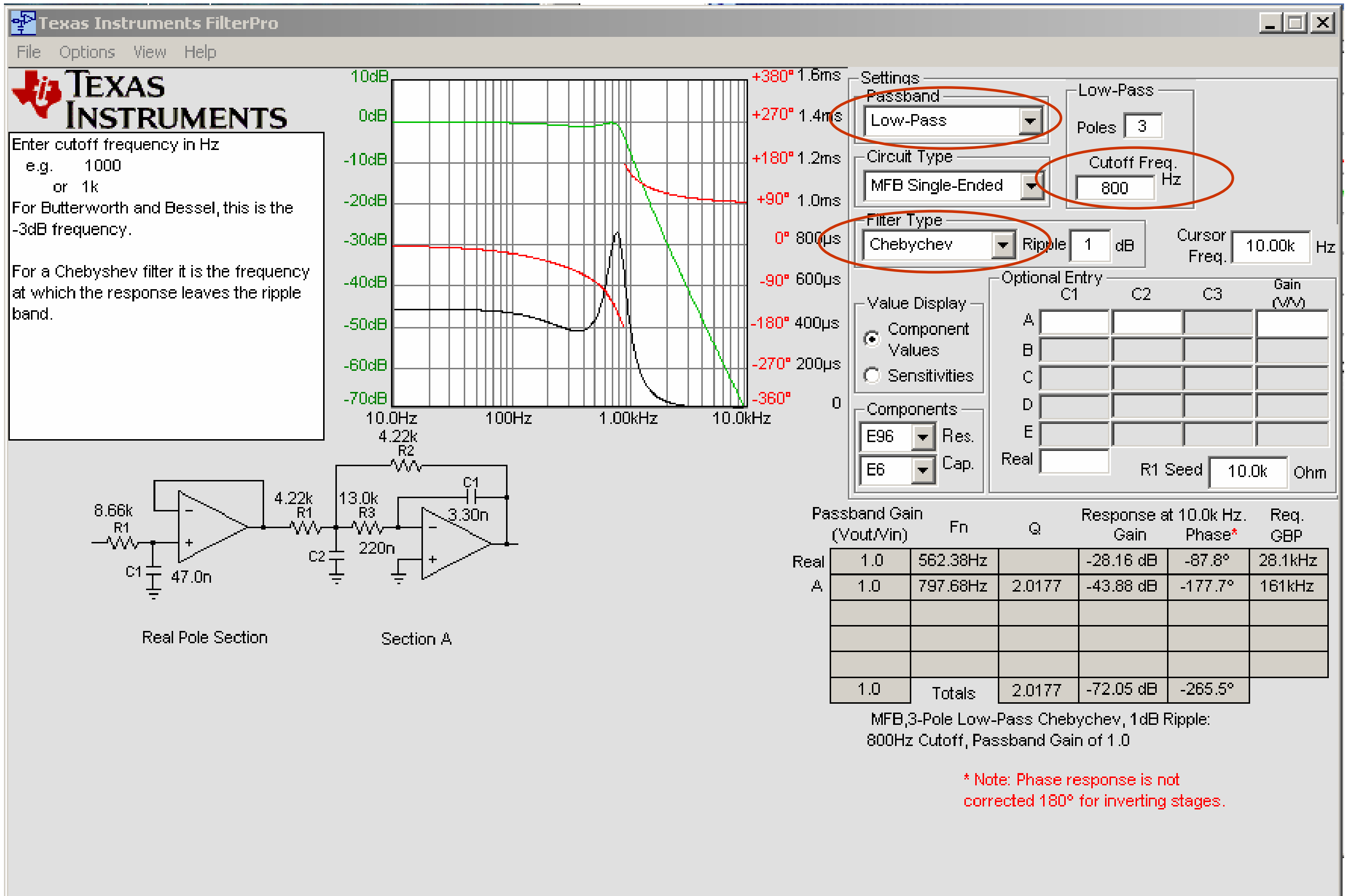
R/C Active Filter Design Tools



- Texas Instruments *Filter Pro v2.0*
- Freeware available at: http://focus.ti.com/docs/toolsw/folders/print/filterpro.html

=> In the top five of the most valuable design tools I have!

Design of 800 Hz CW Low Pass Filter

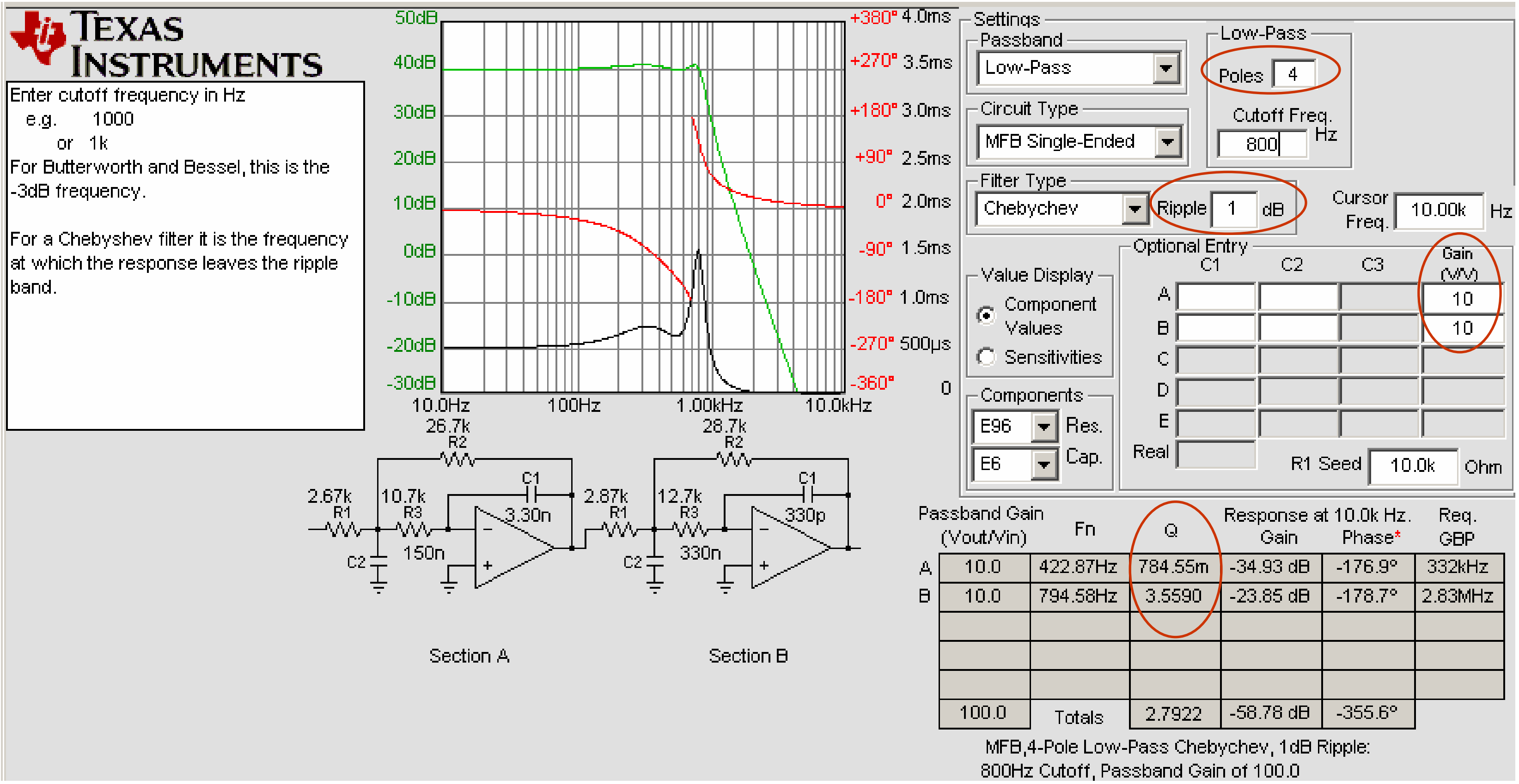


- Pick band pass type (*Low-pass*) and filter type (*Chebychev*)
- Pick the cut off frequency (*800 Hz* for a cw filter)

What is the goal of this filter?

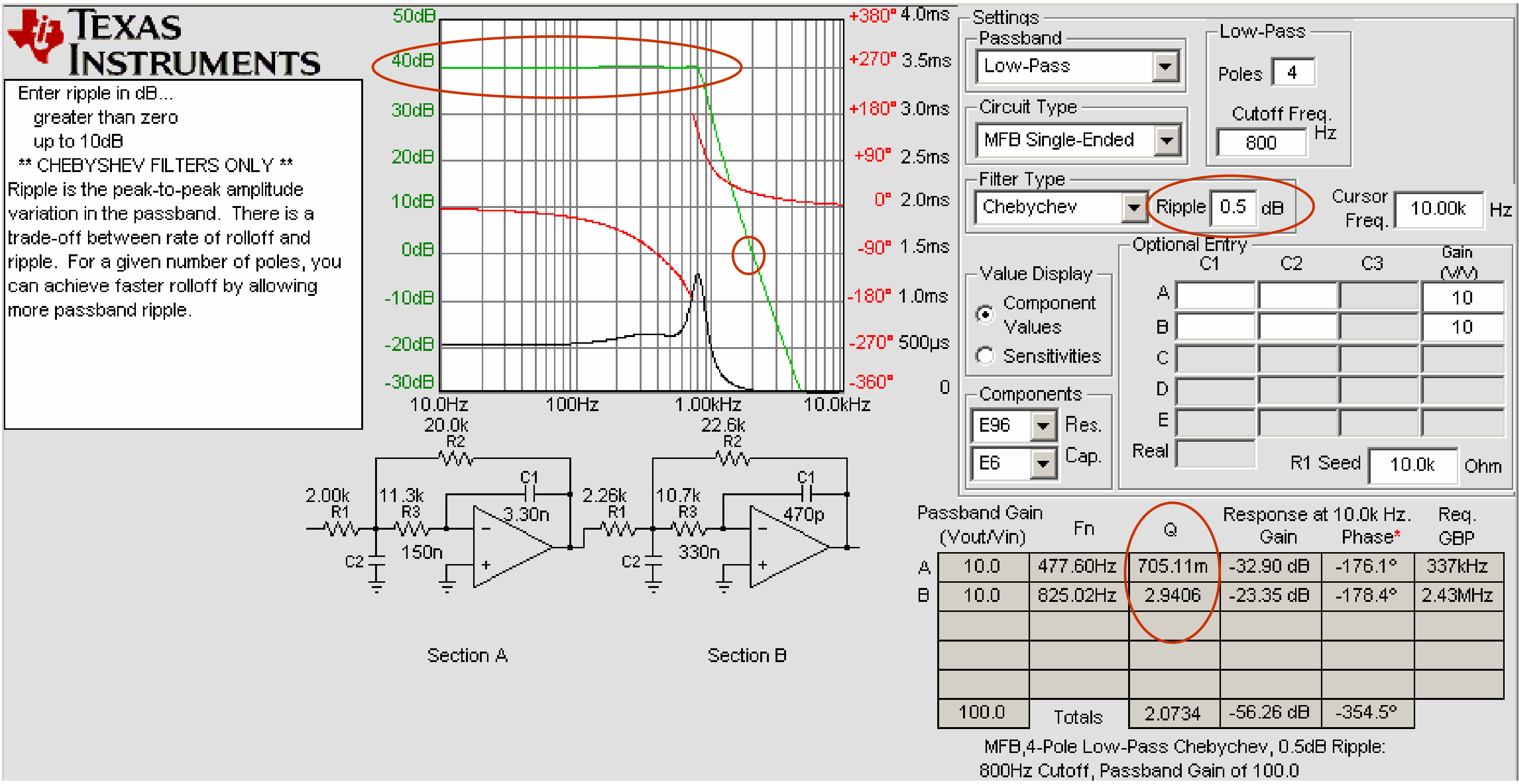
- If this were a headphone level filter, want gain = 1
- If this is the front end brick wall filter of a receiver:
  - Receiver needs 80 – 90 dB of total gain
  - A DC receiver might use half this gain in the filter (pre volume control), half in the audio amplifier after the volume control
  - ~40 to 45 dB of gain in this filter section
  - 40 - 45 dB = 100 to 180x voltage gain (dB=20*log(V gain))
- How much filter attenuation?
  - See how much we can get for two op-amps
  - Want filter Q = 3 or less

Design of 800 Hz CW Low Pass Filter



- Set number of poles to 4 (two op-amps)
- Split the gain (100x) evenly between the two section (10x each)
  - This is voltage gain, dB = 20*log(voltage gain)
- Produces two sections, one with Q = 0.784 and one with Q = 3.559
  - Q of 3.559 is a bit high, so decrease “ripple” to adjust the Q to 3 dB or less

Design of 800 Hz CW Low Pass Filter



- Ripple selection of 0.5 dB produces a maximum section Q of 2.94
- Resulting filter has 40 dB of gain below 800 Hz and hits zero dB of gain near 2 KHz

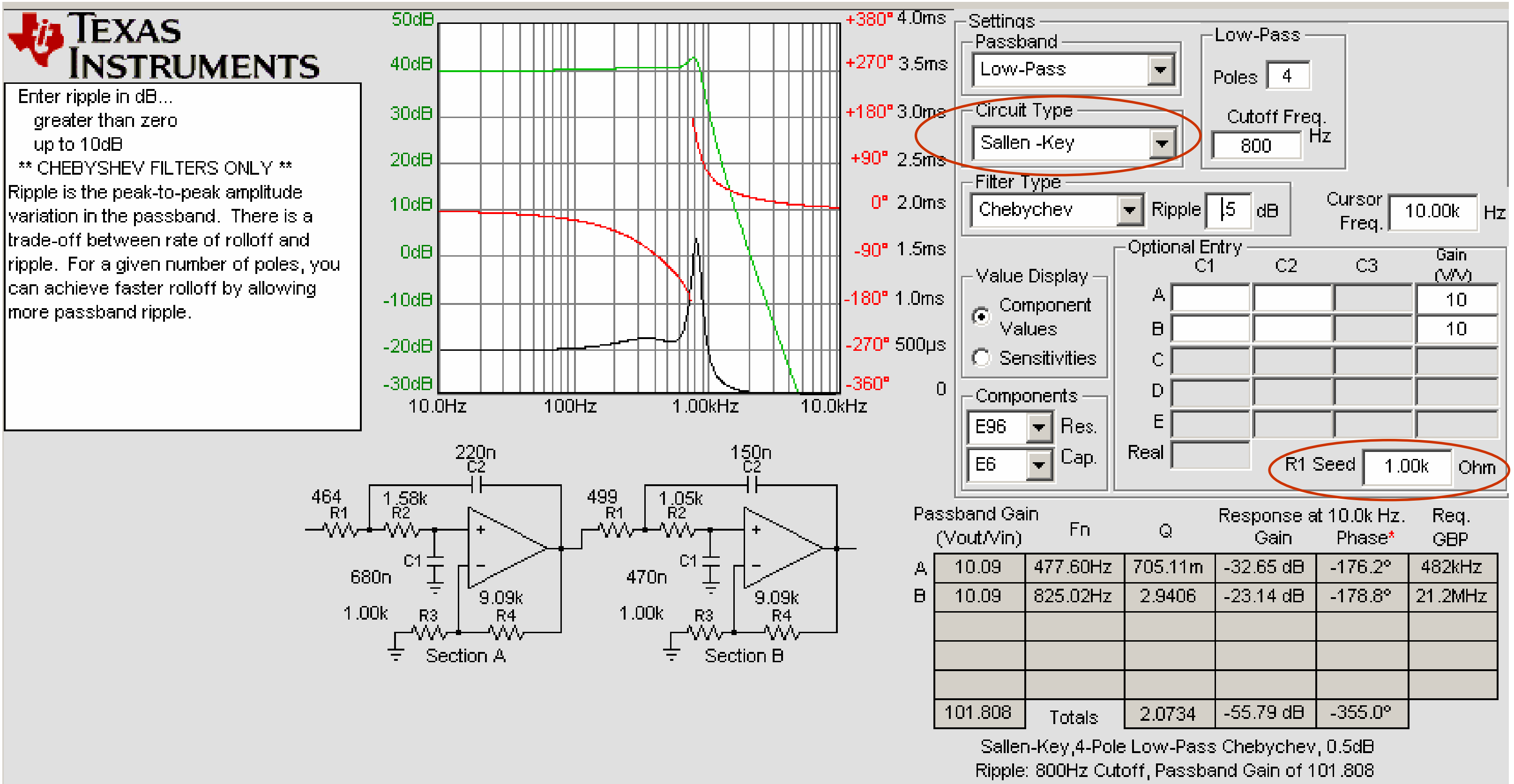
=> *0 dB crossover is important!* It shows where the filter reaches the point that the filter *cannot be overloaded* (because it is down to unity gain)

Active R/C Filter Noise Considerations

- For *headphone level*, resistor values (like 100K vs. 1K) are *not very important*
- For *very low level* receiver audio filtering, want to *keep resistor values low (50 to 1K)* for the first filter gain stage
  - 50 ohm is ~0.85 nV/SqrtHz of noise
  - Very best ultra low noise op-amps have 0.85 nV/SqrtHz of noise (LT1115 for example, $4)
  - Cheap LM5532 ($0.50) has 5 nV/SqrtHz
  - Noise voltage goes up with the square of the resistance
    - 5 nV noise is 5.9x larger than 0.85 nV, so equiv resistance is 5.9*5.9*50 or 1740 ohms
  - A stage with 10x gain may have 0.85 nV/SqrtHz input noise, but with the 10x gain has 8.5 nV/SqrtHz of noise on the output
    - Means the next stage can use higher resistances
    - 8.5 nV is 10x 0.85 nV, so equiv resistance noise is 10*10*50 or 5K ohms
    - Use resistors less than this equivalent resistance (25% if possible)

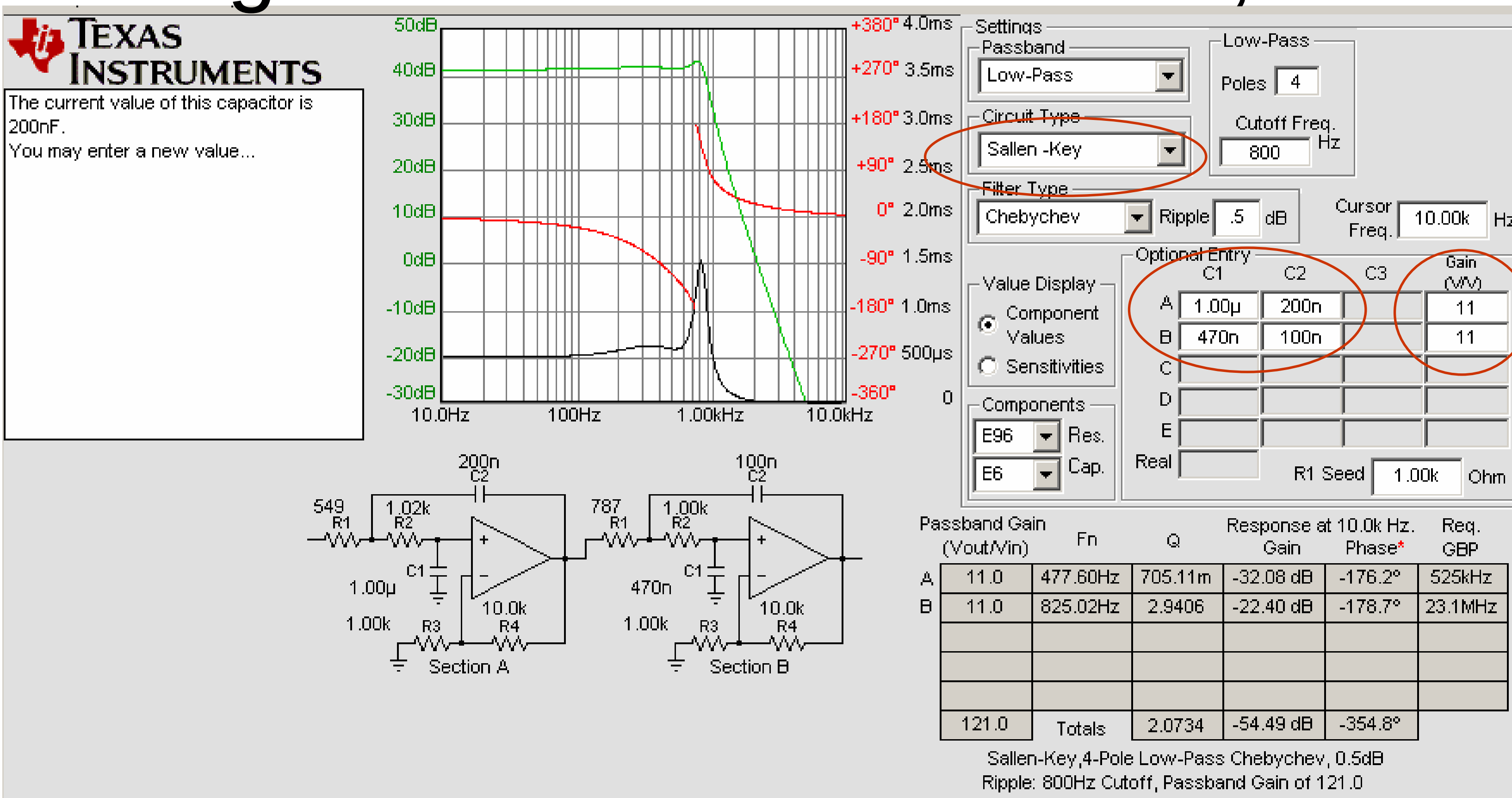
=> Resistor value range needs to match application

Design of CW Low Pass Filter, cont



- Assume low signal level, so set “seed” value to 1K as a starting point
- Circuit shown is a MFB (Multiple Feed Back) type
- Can also use Sallen-Key type circuit
- In order to get the best component match, end design may use Sallen-Key for one stage, MFB for another

Design of CW Low Pass Filter, cont



- Can play with gain, C1, C2 for each stage to try to get more common values
  - 200n = 2 x 0.1uF, a very cheap cap value
  - 1uF is much more commonly available value than 680n!

=> A lot of time is wisely spent playing with these values to create designs using Rs and Cs that are common and already used elsewhere in the design

Receiver Audio Hearing Protection

- This is headphone issue
  - A typical superhet QRP receiver audio output is a LM386 or a LM380 running 8 to 13.8v.
  - If the output stage generates a *12v pk-pk* maximum signal into a set headphones, that is a *1.1w* signal into 16 ohm headphones

=> 1.1w peaks into a pair of headphones does not seem like a good idea!

=> How much is too much for headphones?

=> What can we do about it?

How Much Audio is too Much?

This week: Oct 11, 2008

BRUSSELS, Belgium (AP) - The European Union told music lovers Monday to turn down the volume of MP3 players, saying they risk permanent hearing loss from listening too long at maximum levels.

EU scientists reported that between 2.5 million and 10 million Europeans could suffer hearing loss from listening to MP3 players at unsafe volumes - over 89 decibels - for more an hour daily for at least five years.

EU spokeswoman Helen Kearns said the EU executive was asking people, especially children and young people, "to turn it down" now because they may be damaging their hearing without noticing it.

"It's damage that may come back and haunt you later in life," she said at a news conference.

She said regulators would look next year at lowering the EU legal limit of 100 decibels for MP3 players.

Apple was forced to pull its iPod player from store shelves in France and upgrade software on the device to limit sound to 100 decibels.

The Cupertino, California-based company ships a warning with each iPod that cautions "permanent hearing loss may occur if earphones or headphones are used at high volume."

EU noise rules are meant to limit noise levels in the workplace, construction sites, factories and even orchestras.

- Headphones are rated at dB SPL (sound pressure level) per mW
  - For sine waves, P=V*V/(8*R) where V is pk-pk

=> For common 106 dB SPL "in ear" headphone types, 100 db = *0.25 mW* = *180 mV pk-pk* at 16 ohms

- For 106 dB types, 89 dB SPL ("unsafe level") is *50 mV pk-pk* (16 ohms)
- *50 mV pk-pk is a long way from 12v pk-pk! (40+ dB!)*

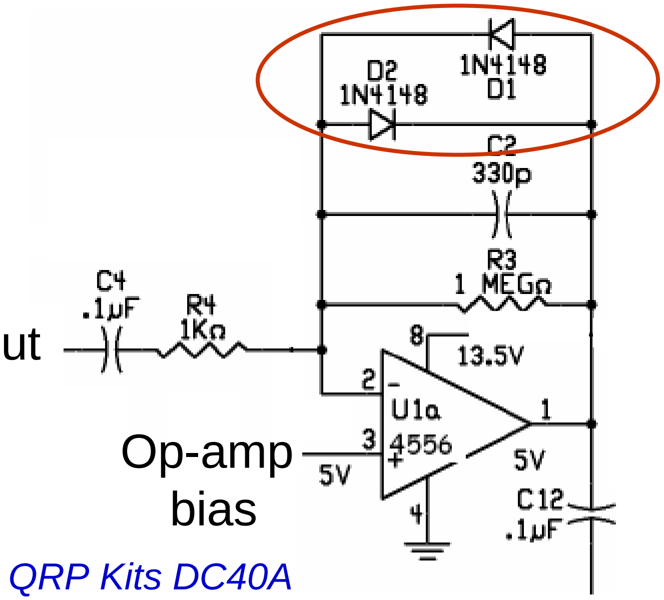
Loudness Listening Test

- Sensitive headphones (-106/-112 dB SPL) produce comfortably loud audio using *10 to 20 mV pk-pk* output
- Try it yourself with your favorite headphones!
  - Connect to favorite rig, turn up for comfortable listening
  - Measure comfortable pk-pk voltage output with scope
  - Extra credit: Also measure uncomfortably loud signals

=> Bottom line: Audio limiting is strongly recommended when using headphones

- ~0.3v pk-pk max for sensitive headphones
- ~0.7 to 1v pk-pk max for less sensitive headphones

Simple Audio Diode Limiter Circuit



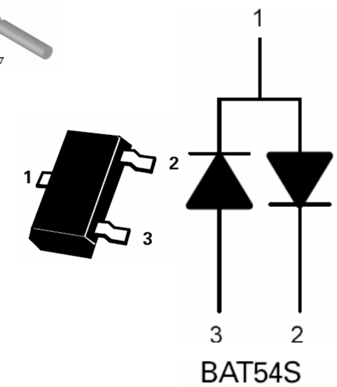
signal input

Op-amp bias

Circuit from QRP Kits DC40A

signal output

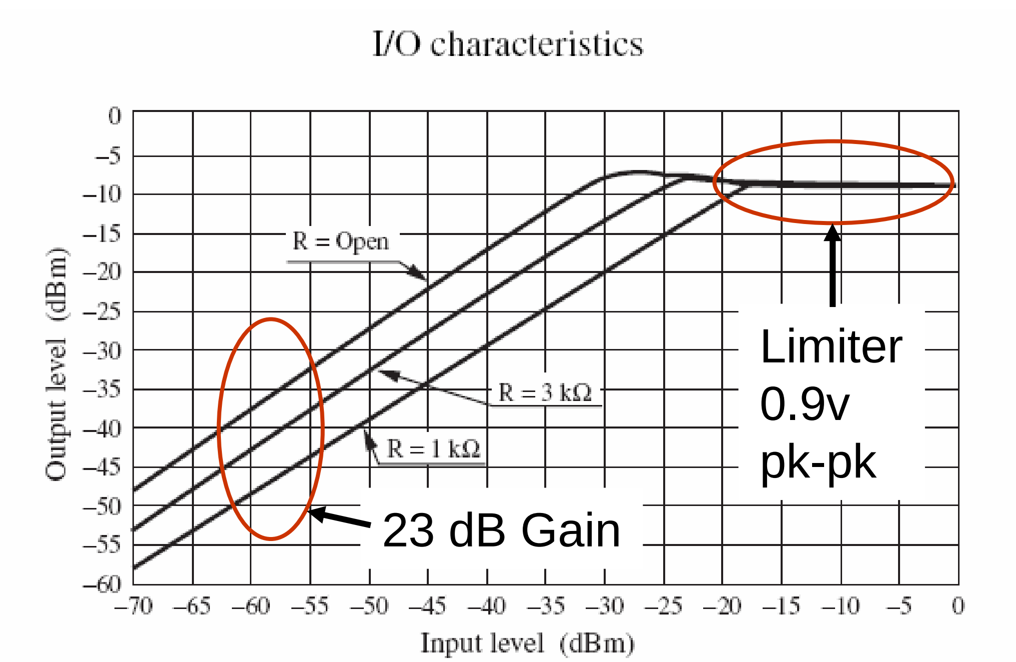
- R3/R4 ratio sets stage gain
- 1 Meg/1K = 1000x (60 dB) gain
- 1N4148 *silicon diodes* limit output signal to *~0.7v pk-pk*

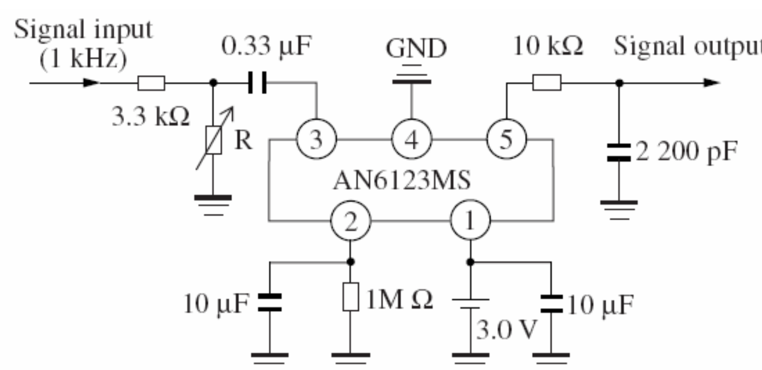


- Simple back to back diodes limit gain in final audio stage
  - Large signals tend get gain reduced (rounded, not clipped)
  - Diodes conduct on large signals making R3 “look” smaller
  - Conducting diodes reduce gain
- *Schottky diodes* can be used to lower the max output to *~0.3v pk-pk*
  - Use a pair of single diodes such as SD101B ($0.08) or dual BAT54S ($0.06)
  - BAT54S used in NC2030 audio limiter

Hearing Protection Circuits

- AGC (Automatic Gain Control)
- Simple audio AGC IC: AN6123MS ($1.06 Digikey)
  - AN6123MS used in ATS3 audio chain
  - ~23 dB of gain plus limiter in one package





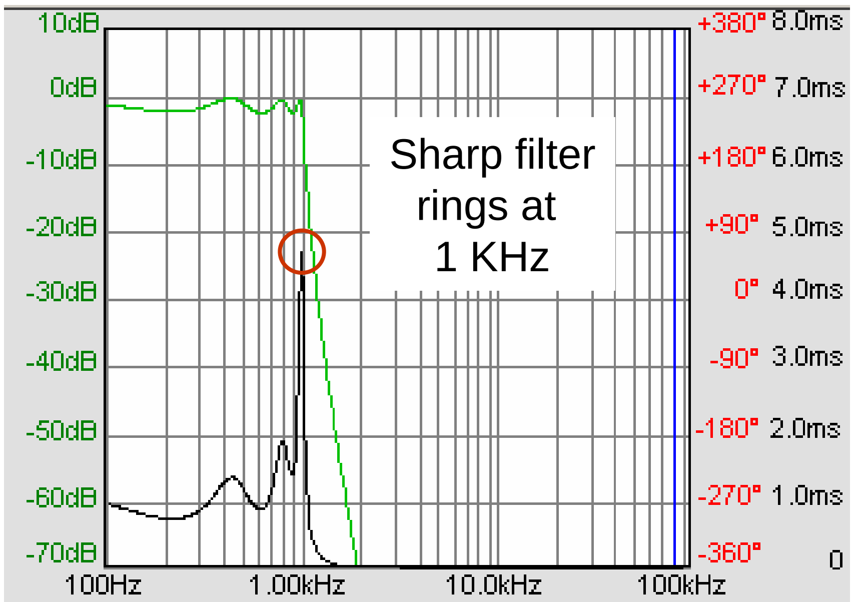
AN6123 typically used as an AGC stage in a cordless telephone

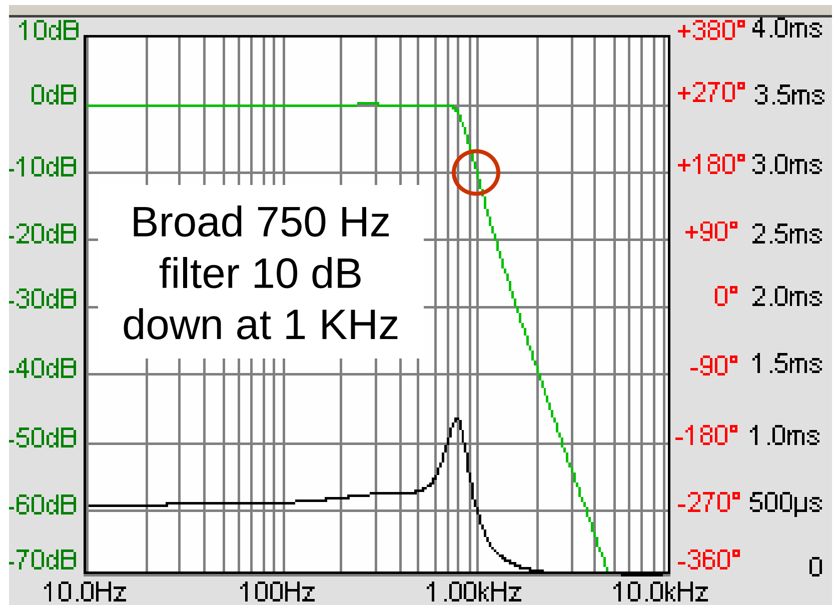
Stage has ~ 24 dB of gain up to limit point (300 Hz to 3 KHz audio)

Advanced Design: Tandem Filters

- Sharp filters have high delay “ears” at the edge of the filter that cause ringing, but have steep cut off curves
- Suppose we could “cut off” the high delay frequency ears with another more gradual filter?

=> End result: Sharp cut off *and* low ring!



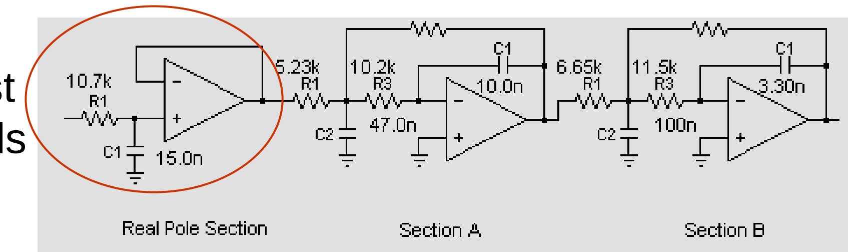


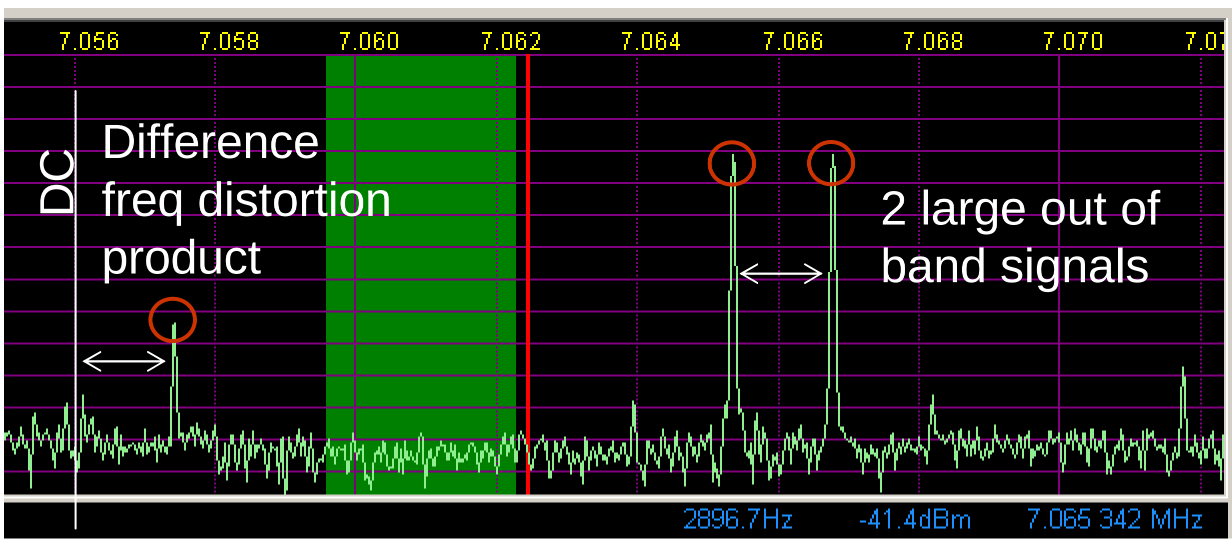
Broad 750 Hz “post filter” used to clean up high Q “ringing” at 1 KHz
Filter pair totals 110 dB down at 2 KHz – Very high performance indeed!
Trick used in NC2030 – Main R/C filter + very sharp SCAF headphone “clean up” filter

Advanced Design: Op-amp Distortion

- The very first filter stage sees the largest out-of-band signals
  - These very large signals will not make it through the filter
- These very large signals produce “difference” distortion products that can fall within the filter pass band

First stage sees highest out-of-band signal levels





Real life example of op-amp with *moderate distortion specs* operating *at low voltage* and using *too much gain*

Unused gain reduces distortion

Op-amp Distortion Comparison

- Check op-loop gain at the frequency of interest
  - TLV2462: 78 dB at 1 KHz, Distortion 0.006% at 1 KHz (84 dB down)
  - NE5532A: 80 dB at 1 KHz,
  - LT1115: 100 dB at 1 KHz, Distortion 0.0002% at 1 KHz (114 dB)
  - AD797: 100 dB at 1 KHz, Distortion 0.0001% (120 dB) at *20 KHz*
  - OPA2228: 90 dB at 1 KHz, Distortion 0.00005% at 1 KHz (126 dB)
  - LM4562: 96 db at 1 KHz, Distortion 0.00003% at 1 KHz (130 dB)
  - OPA827: 90 db at 1 KHz, Distortion 0.00002% at 1 KHz (134 dB)
- Common characteristic of highest performing devices
  - Using largest possible op-amp supply voltage *(+/- 15v typical*)
  - "Sweet spot" of ~3v RMS output (8.5v pk-pk)
    - Sweet spot output is ~25% of the op-amp supply voltage
  - Extremely high DC open loop gain (130 to 140+ dB)
  - Best distortion at unity gain, *distortion increases with gain*
    - *Use low gain* for the first stage, 5 to 10x
  - Best distortion when used in "inverting" gain configuration

=> For least distortion: high voltage, low gain and best devices

Summary

- SCAF filters make excellent headphone level filters – *cheap, simple, effective*
- High Q filters cause ringing and delay variation
  - For active R/C filters *keep Q < 3*
- *Designing* active R/C filters *is easy* with freely available tools
- Headphone audio output *should be limited*
  - Less than *0.3v pk-pk* for sensitive headphones
- Tandem filter pairs can be used to *reduce ring* and apparent *delay variation problems*
- For very high performance R/C filters, the *distortion* and *gain* of the first stage is important