IC Audio Power Amplifiers: Circuit Design For Audio Quality and EMC

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Audio Power Amplifier Applications
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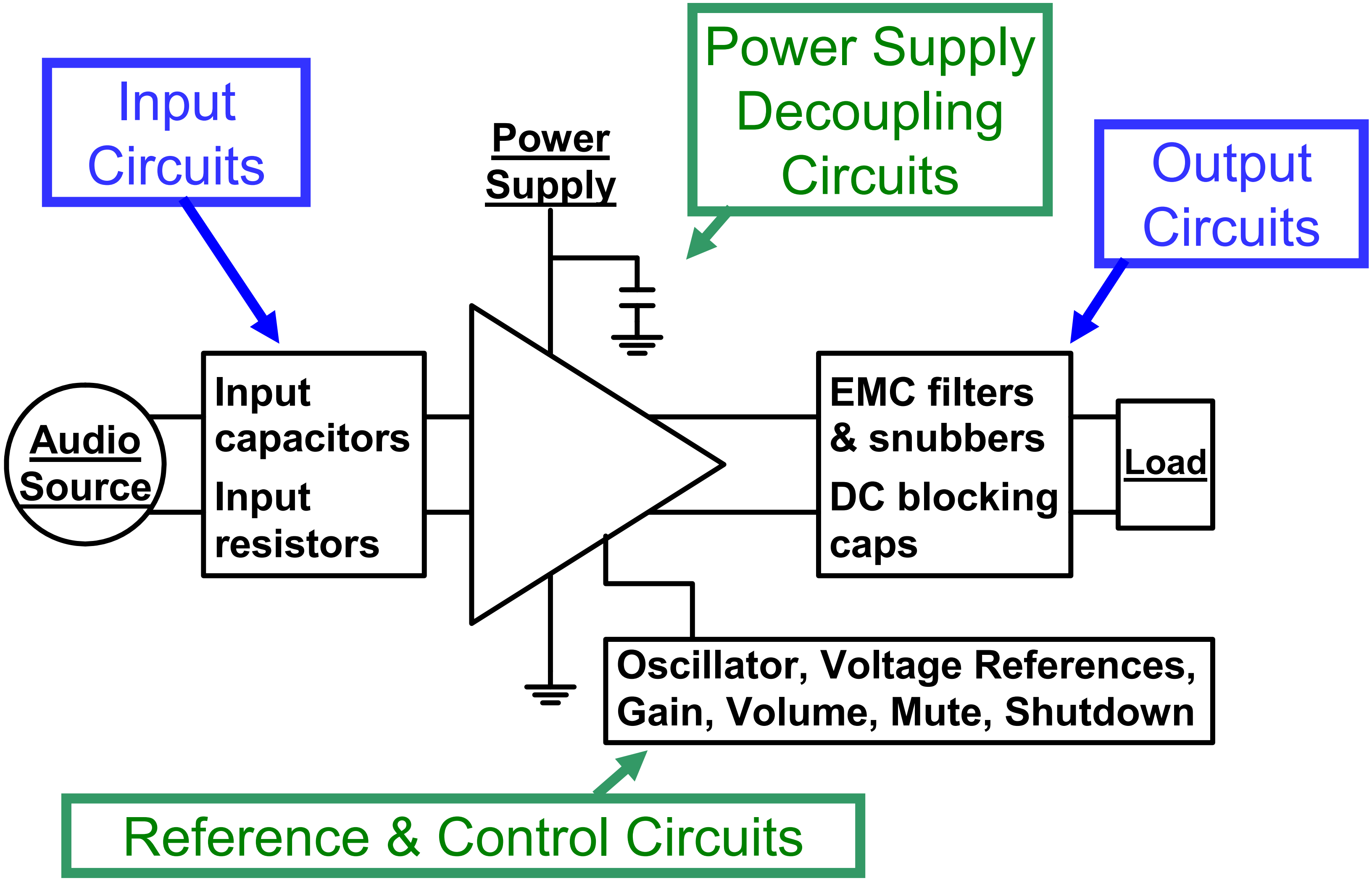
TEXAS INSTRUMENTS

Contents

IC Audio Power Amplifier Circuits

- IC audio power amplifier (APA) circuits include sub-circuits with different requirements.
- We will examine how to design these circuits for best performance.

IC Audio Power Amplifier Circuits

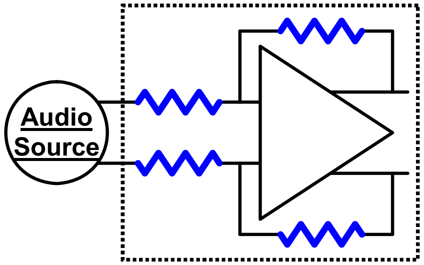


Audio Power Amplifier Input Circuits

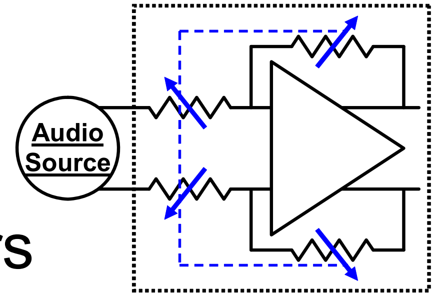
- Gain Setting and Input Impedance
- Input Source Configurations
- Input DC Blocking Capacitors
- Input Filters for Sigma-Delta DACs

Gain Setting

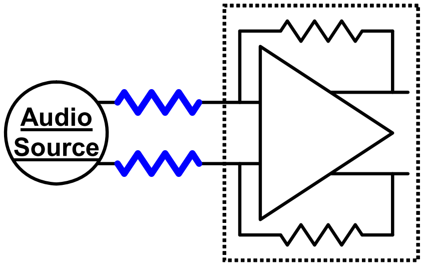
- Fixed Gain
  - Fixed by internal resistors



- Internal Gain Steps or Volume Control
  - Gain set by variable resistors

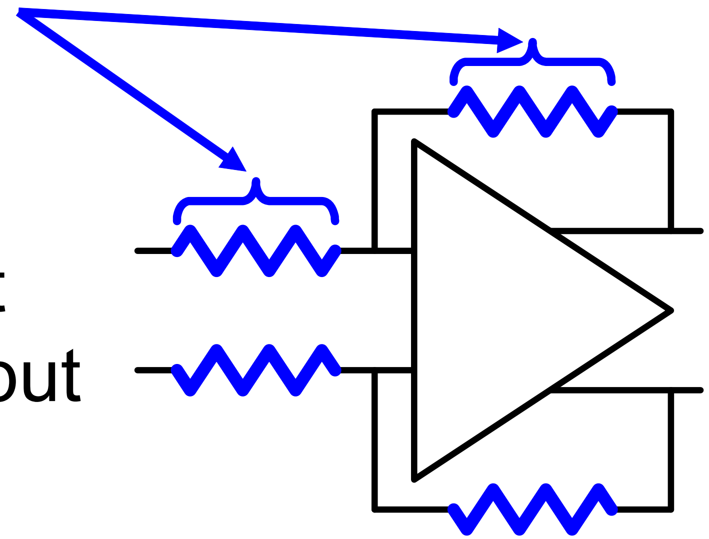


- External Input Resistors
  - Gain set by external resistors



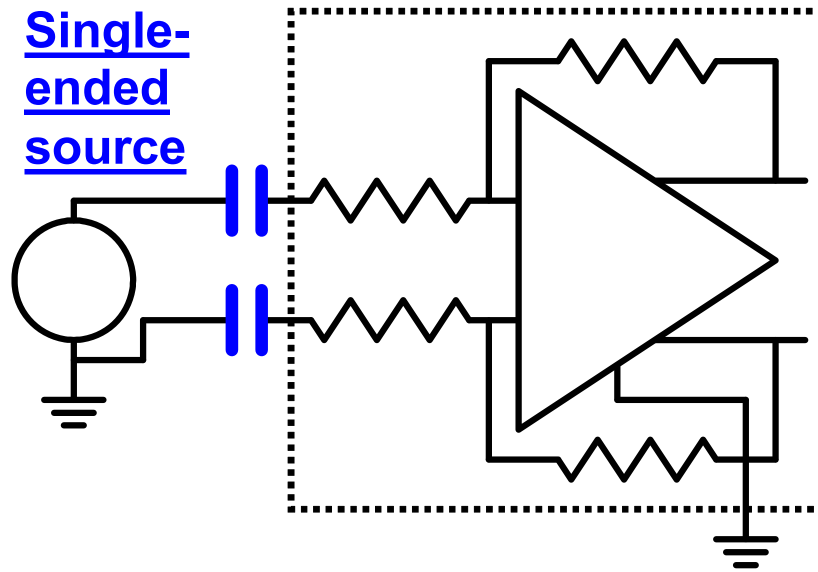
Gain and Input Impedance

- Input impedance depends on gain because resistors depend on gain.
- Input Z is usually lowest at highest gain. Gain and input Z are specified in IC APA data sheets.
- For external resistors Zin = external R.
- (For a differential input, input impedance is for <u>each side</u>.)



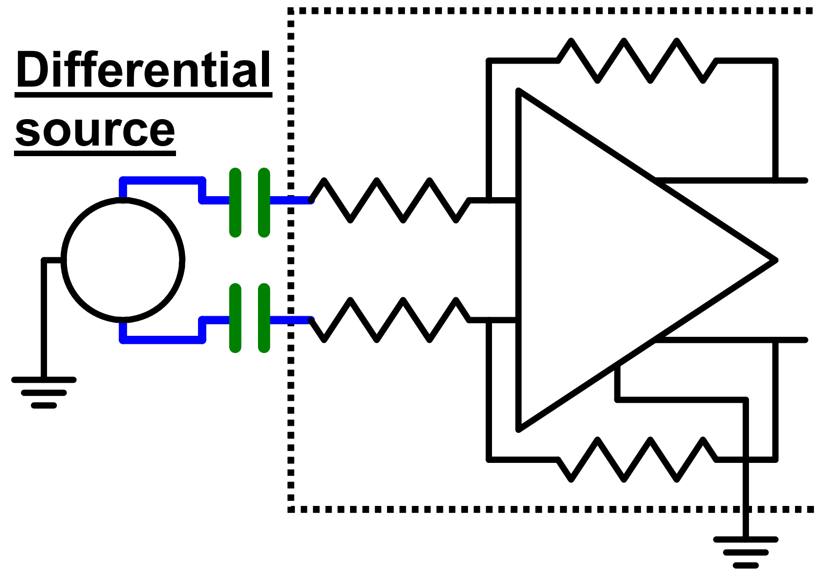
Input Source Configurations

- Single ended source:
  - DC blocking caps required.
  - Turn-on/off must be slow to avoid pop.
- Ground a differential APA input at the source, not the APA.
- This lets APA CMRR reject ground noise between APA and source.



Input Source Configurations Cont'd.

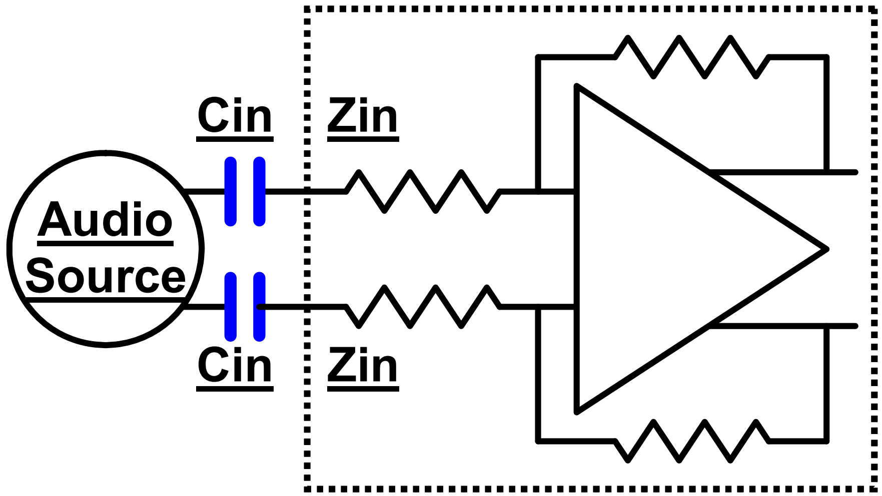
- Differential source:
  - DC blocking caps not required IF DC bias is within APA input common-mode range.
  - Pop does not require slow turn-on/off and is much less difficult.

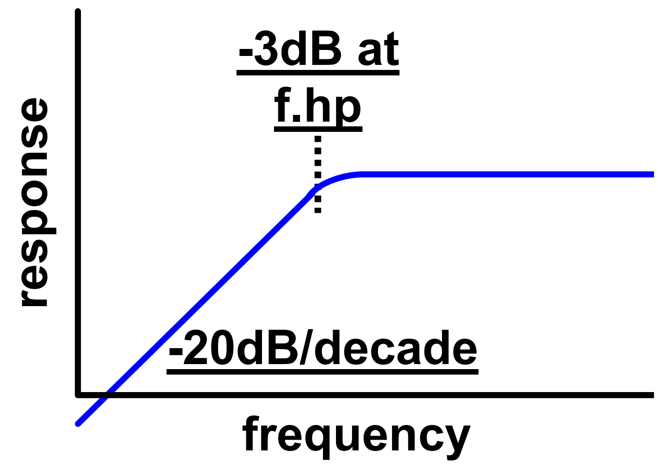


- Input capacitors may still be used to produce a high-pass response if this is desirable.

Input DC Blocking Capacitors

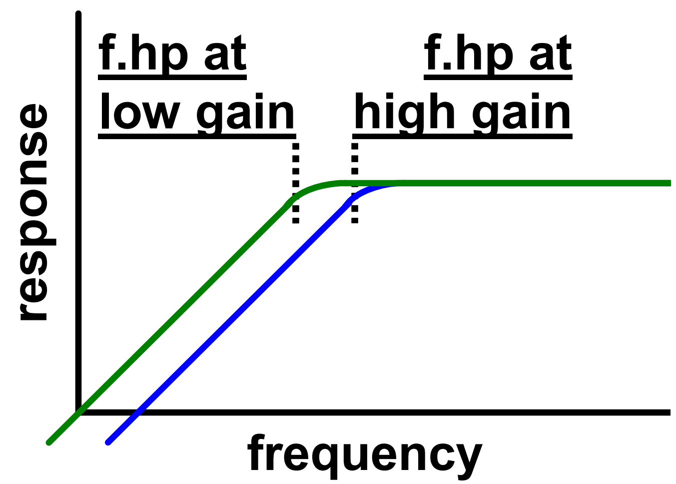
- When DC blocking capacitors are used, a cap is required at each side of a differential input.
- The cap, Cin, and APA input impedance, Zin, create a high-pass response.
- f.hp = 1 / (2pi * Cin * Zin)





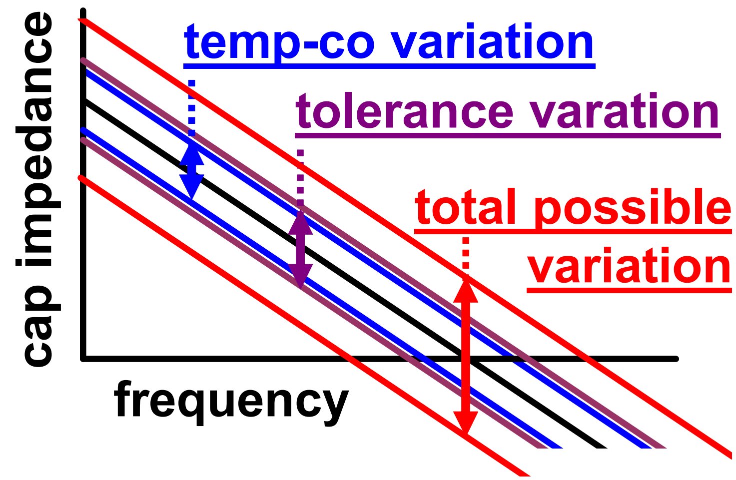
High-Pass Frequency vs. Gain

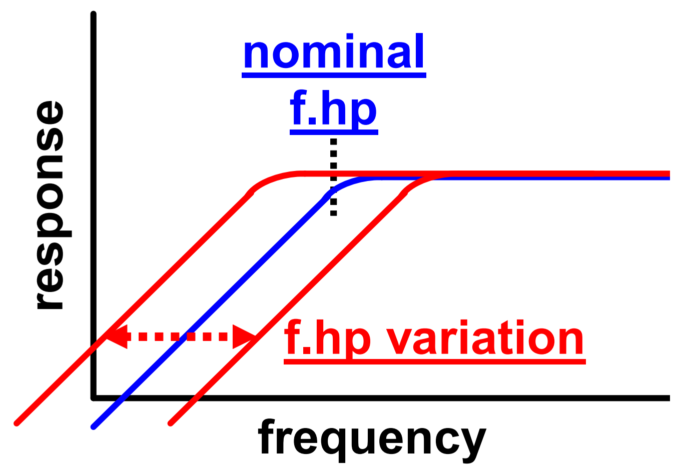
- When gain or volume is changed, high-pass frequency f.hp can change as well, because Zin changes.
- Choose Cin for target f.hp at the highest gain.
- f.hp will be lower at lower gain, and so frequency response will remain good.



Input Capacitor Material

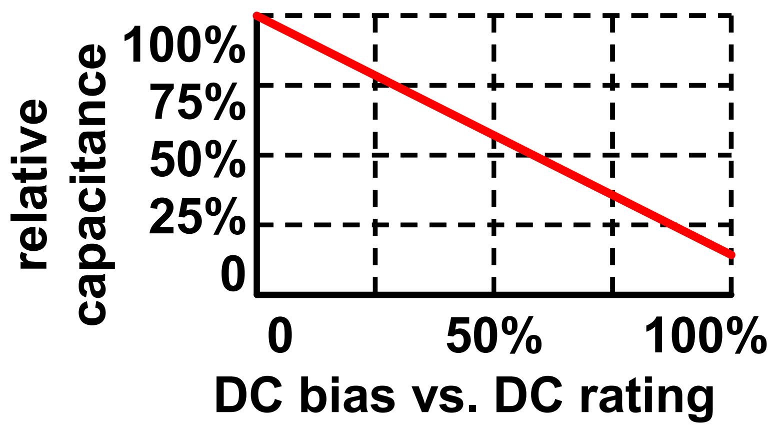
- High-K capacitors that have large temperature coefficients typically also have wide tolerances, so their variability is large.
- This includes material like Y5V or Z5U.
- These capacitors can cause large variations in high-pass f.hp.

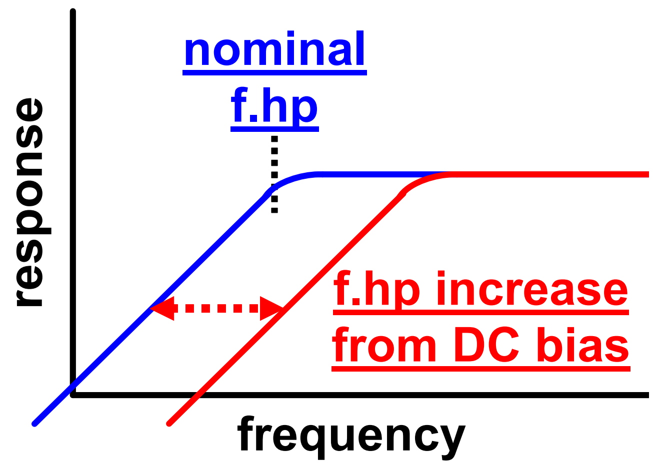




Input Capacitor Material Cont'd.

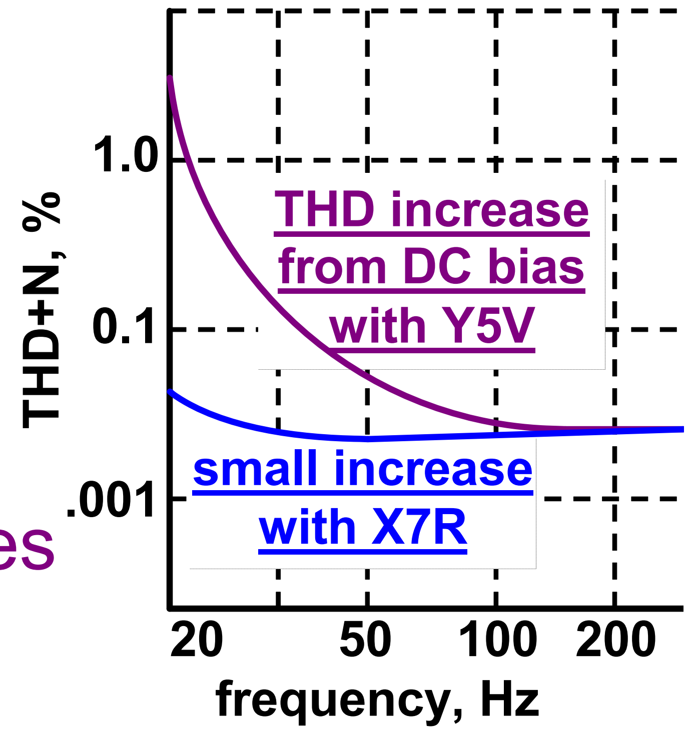
- High-K capacitors also have large coefficients of capacitance versus DC and AC voltage.
- Their capacitance falls with DC bias, by as much as 80% or more at rated DC voltage.
- This effect will increase f.hp dramatically.





Input Capacitor Material Cont'd.

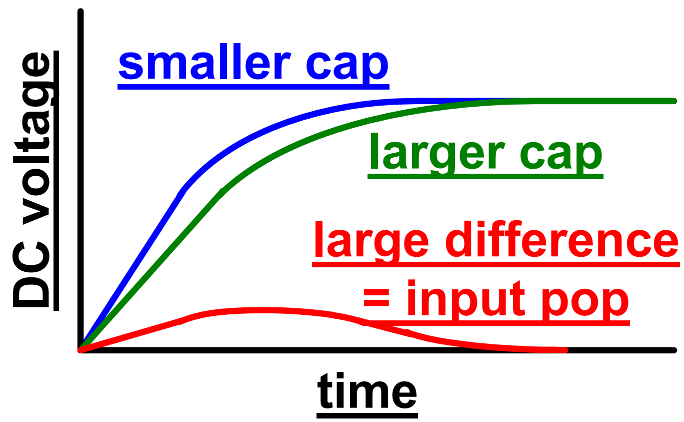
- A large coefficient of capacitance versus DC voltage is the worst effect in a high-K cap.
- Low-frequency AC across these caps will modulate capacitance, causing high distortion at low frequencies where cap voltage is high.

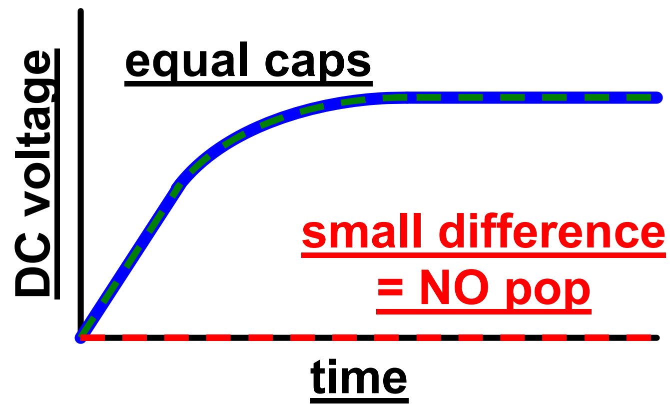


- This effect is much smaller for X5R and X7R material.

Input Capacitor Matching

- If input capacitors at a differential input are not well matched, they will charge at different rates.
- The difference creates a net input which produces a pop.
- This pop is avoided if the tolerance of the input capacitors is 5%.





Input Capacitor Selection

- These are all good reasons to avoid using capacitors made from materials like Y5V!
- We recommend using capacitors made from materials like X5R or better with 5% tolerance.
- Film capacitors may be required in the most demanding applications.
- Capacitor voltage rating should be at least twice the application voltage (power supply voltage).
  - For inputs, the application voltage is the input stage supply voltage.
  - For outputs it is the output stage supply voltage.

Input Capacitor Selection

- These rules apply generally to all capacitors used in audio circuits - better materials help maintain audio quality, including good frequency response and low THD.

Input Capacitor Relationships

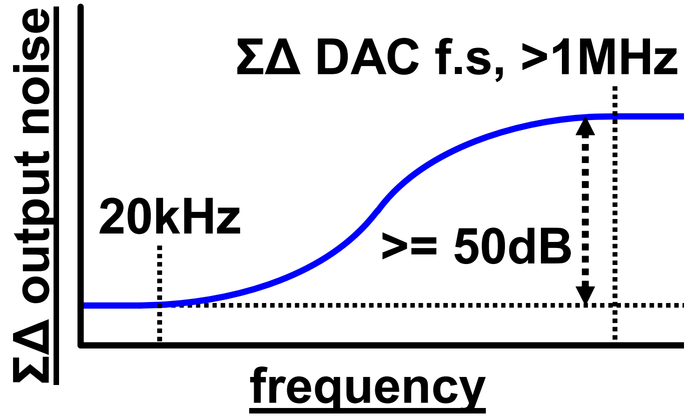
- Most IC APAs require bypass capacitors on critical analog reference voltages.
- The value of the input caps usually must be a specific multiple of the value of the bypass caps to prevent turn-on and turn-off pop.

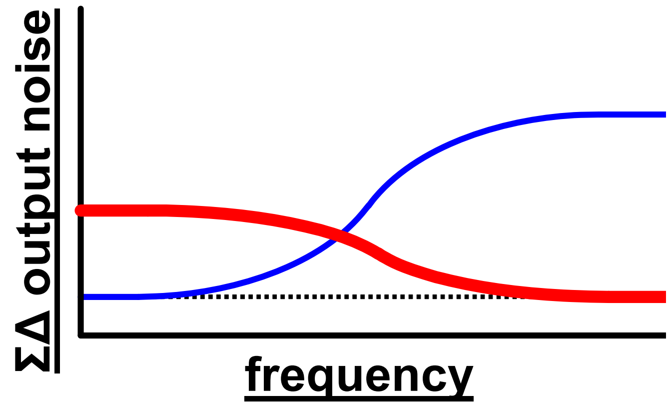
- These relationships are described in data sheets for individual IC APAs.

- **NOTE that rules about cap material for input caps also apply to bypass caps.**

Sigma-Delta DAC Noise

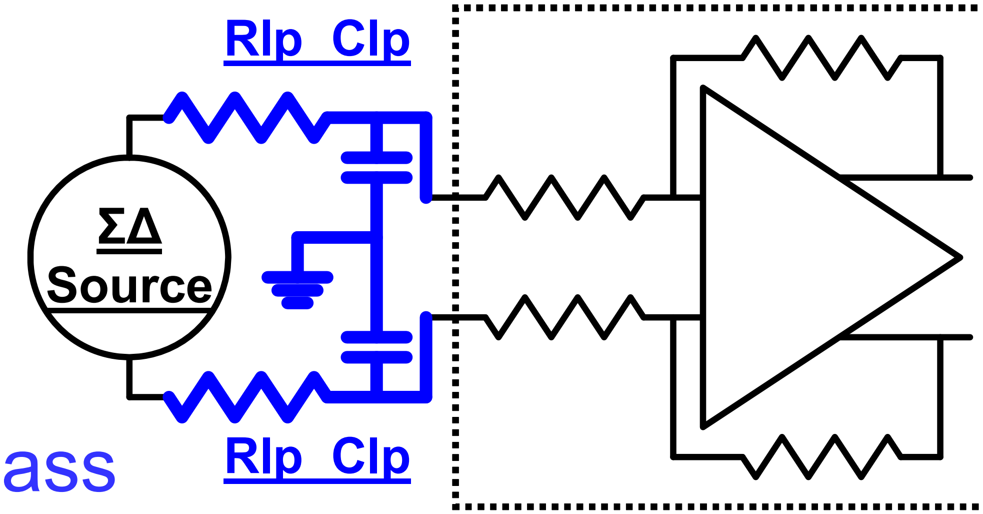
- All DACs produce noise that extends well above audio frequencies.
- This effect is strongest in sigma-delta DACs.
- Some of the out-of-band noise of a sigma-delta DAC can be modulated into the audio range where it will increase APA output noise.

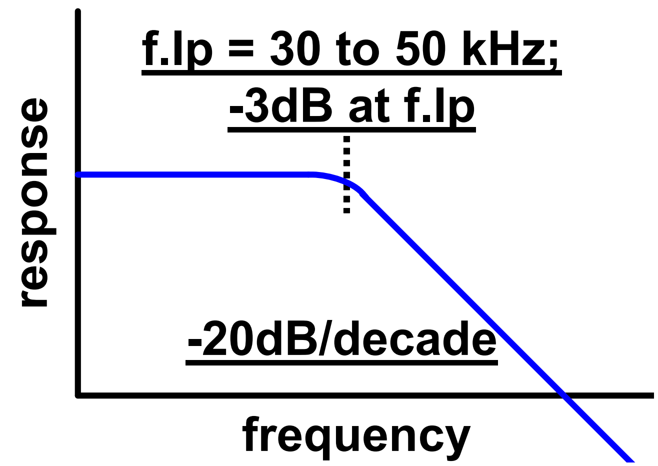




Filters for Sigma-Delta DAC Sources

- This problem can occur in Class-AB or Class-D APAs.
- Fortunately, it can be eliminated with a simple RC low-pass filter at the APA input.
- Make Rlp << Zin; then f.lp = 1 / (2pi * Rlp * Clp).
- Set f.lp between 30kHz and 50kHz.



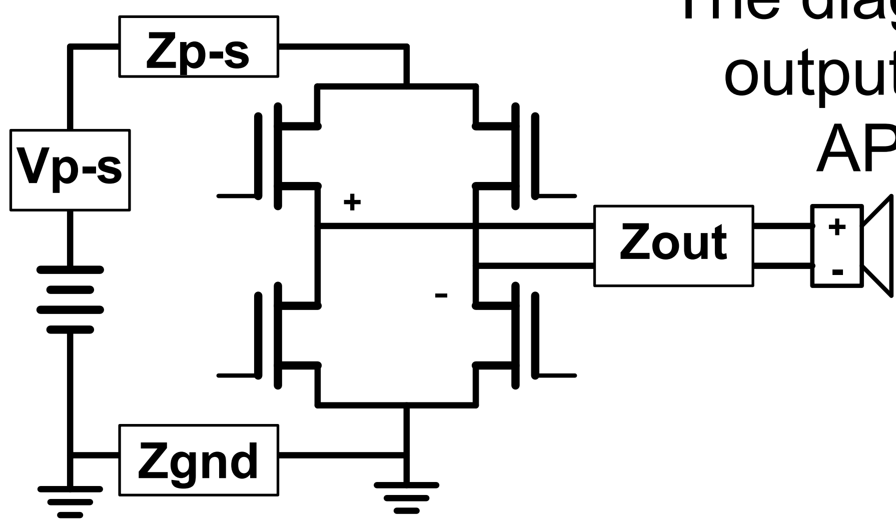


Audio Power Amplifier Power Supply Circuits

- APA Circuit Resistances
- Decoupling Capacitors

APA Circuit Impedances

- Audio power amplifier circuits include other impedances than load & APA output devices.

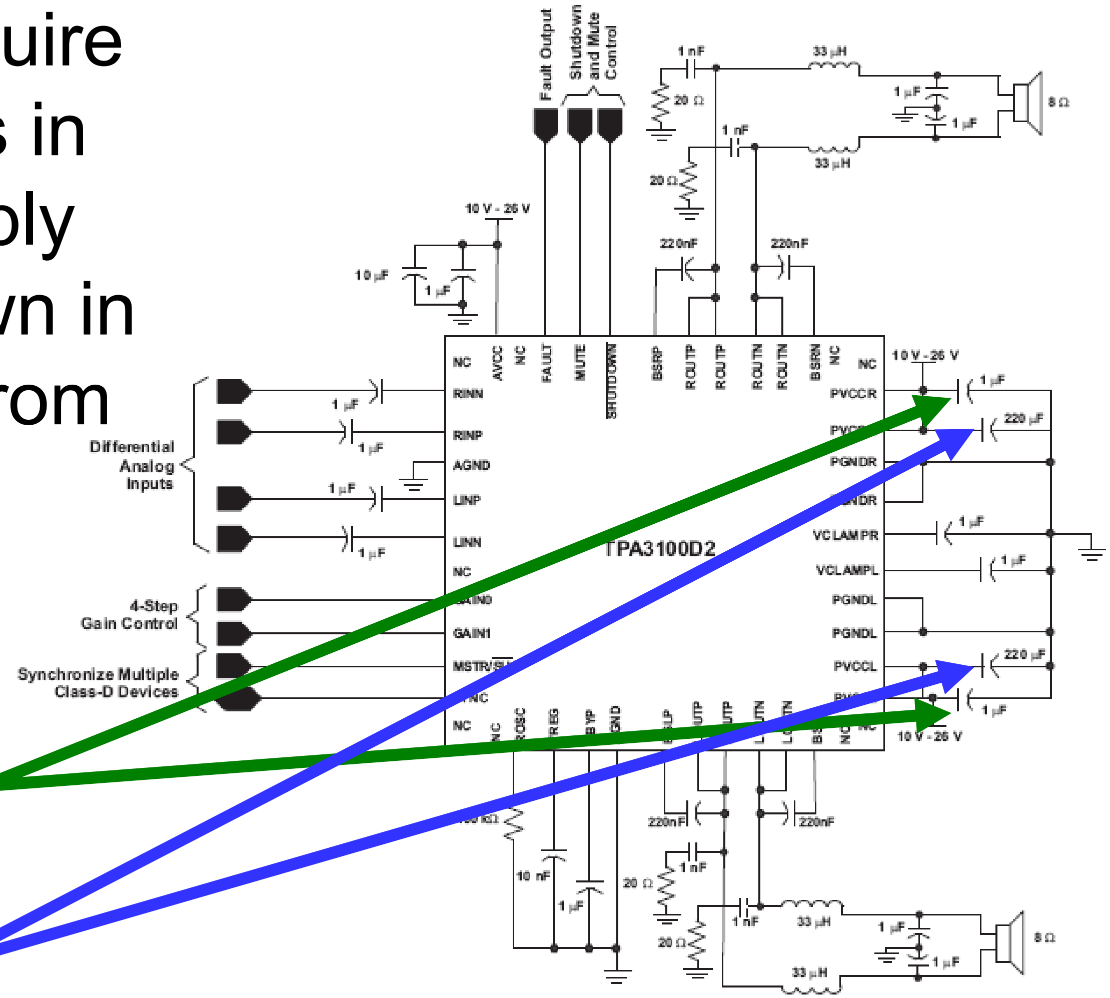


The diagram below shows the output H-bridge of a class-D APA with power supply & loudspeaker load.

- Power supply, ground and output impedances Zp-s, Zgnd and Zout must be small compared to load impedance to maintain efficiency.

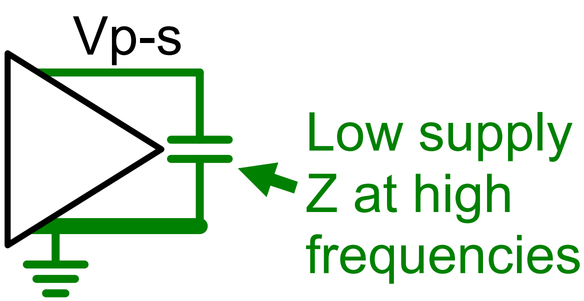
Decoupling Capacitors

- APA circuits require decoupling caps in their power supply circuits, as shown in this schematic from the TPA3100D2 data sheet.
- These include high-frequency caps (1µF here) and bulk caps (220µF here).



High-Frequency Decoupling Caps

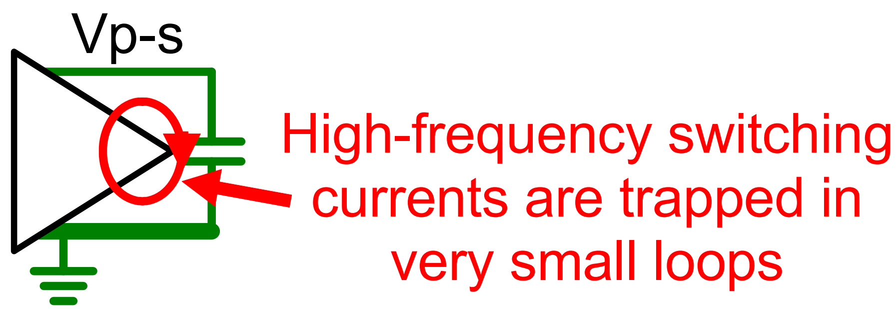
- High-frequency decoupling caps are required to provide very low power supply impedance at high frequencies.
- For this reason high-frequency caps should be placed no more than 1mm from APA power and ground pins.



* Cap placed 1mm from the IC, with strong power & ground connections

High-Frequency Decoupling Cont'd.

- Proper use and placement of high-frequency decoupling caps is especially important with class-D APAs.
- By providing low impedance at high frequency, good high-frequency decoupling traps switching currents in tight loops immediately at the APA.

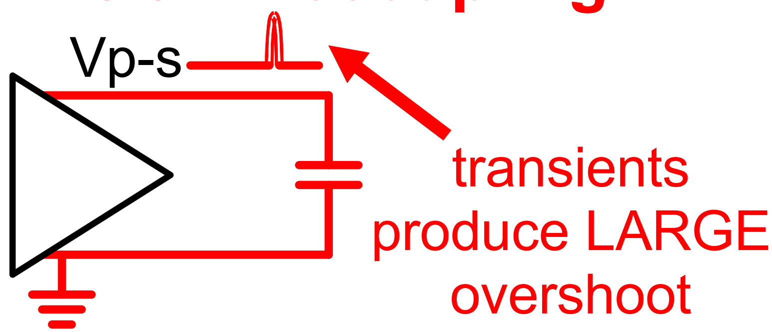


- This prevents these currents from flowing into other parts of the circuit.

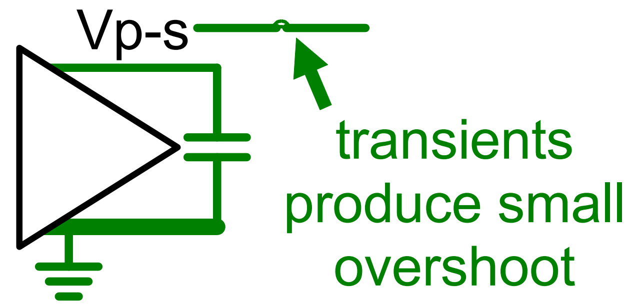
High-Frequency Decoupling Cont'd.

- Good high-frequency decoupling caps also minimizes overshoot and ringing on the power supply line caused by current transients in power supply parasitic inductance.

POOR Decoupling:



Good Decoupling:



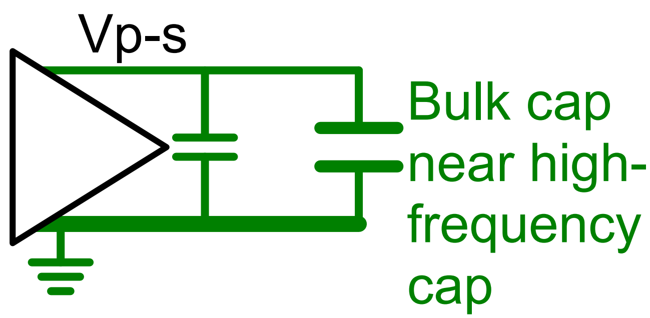
- All of this is important for audio performance, reliability and EMC.

High-Frequency Decoupling Cont'd.

- High-frequency caps also store a small amount of energy to stabilize power supply voltage.
- However, this is enough to help ONLY at very high frequencies: 1A from a 1μF cap for even 1uS reduces its voltage $\Delta V = I * \Delta t / C = 1V$.
- So an APA also requires low-frequency bulk decoupling capacitance, much larger than the high-frequency capacitance.
- **A low-impedance power supply connection is still vital – decoupling does not replace it.**

Bulk (Low-Frequency) Decoupling

- Bulk decoupling caps are required to stabilize power supply voltage at the IC APA when large low-frequency load currents are generated.
- For this reason bulk decoupling caps should be placed as close as possible to APA power and ground pins.



* Cap placed so its leads are within 10mm of the IC, with strong power & ground connections

- This is important for stabilizing supply voltage.

Decoupling Cap Characteristics

- High-frequency decoupling caps should be high quality ceramic SMD components.
- Just as capacitors made of materials like Y5V should not be used in audio circuits, they should not be used in decoupling circuits, because their capacitance is undependable.

- To be sure of achieving the needed capacitance, use capacitors made of X5R or better material with tolerances of 10%.

Decoupling Caps Cont'd.

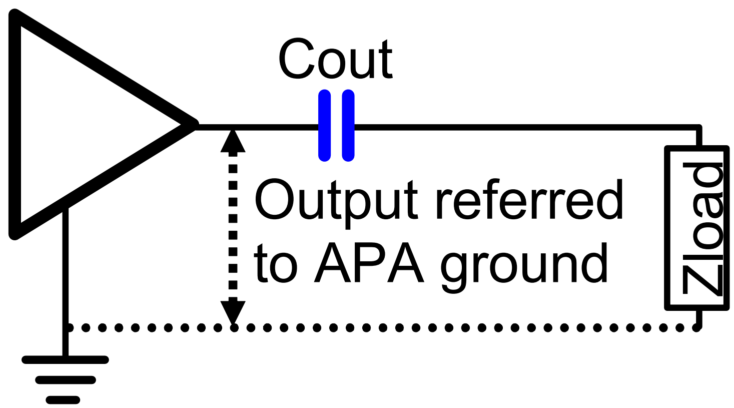
- Bulk decoupling caps in low-power circuits can also be good quality ceramic SMD components, in X5R or better material.
- Use high-quality electrolytics as bulk decoupling caps in high-power circuits to give the needed capacitance in reasonably small volume.
- These should be radial-lead parts, because self-inductance is lower than in axial parts.
- They should be low-ESR caps with ripple current ratings greater than peak load currents, to avoid issues with ripple currents flowing in them.

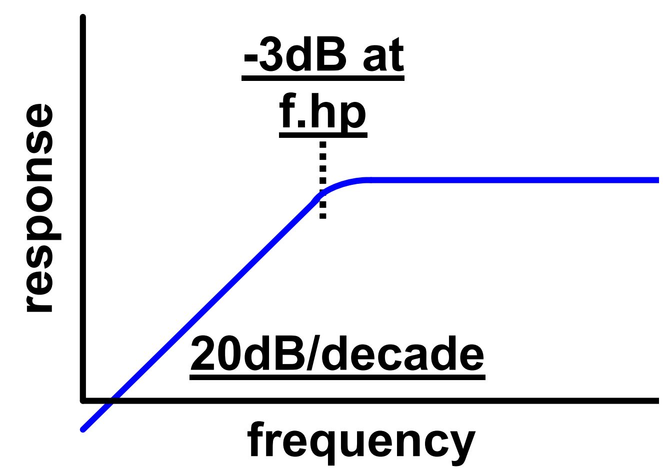
Audio Power Amplifier Output Circuits

- Output DC Blocking Capacitors
- EMC Filters (LC and Ferrite Bead)
- Output and EMC Snubbers

Output DC Blocking Capacitors

- Single-ended APAs with single power supplies require DC blocking caps at their outputs.
- The cap, Cout, and load impedance, Zload, create a high-pass response.
- f.hp = 1 / (2pi * Cout * Zload)





DC Blocking Cap Characteristics

- As with low-frequency bulk decoupling caps, use high-quality electrolytics as DC blocking caps feeding loudspeaker loads to give the needed capacitance in reasonably small volume.
- These should be radial-lead parts, because self-inductance is lower than in axial parts.
- They should be low-ESR caps with ripple current ratings greater than peak load currents, to avoid issues with load currents flowing in them.

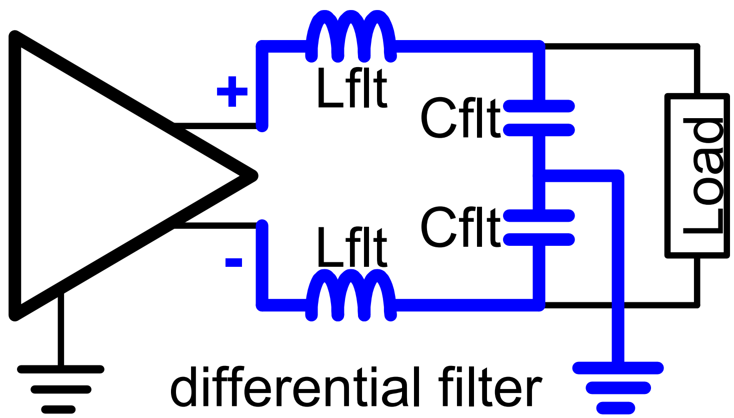
Class-D APA Output Filters for EMC

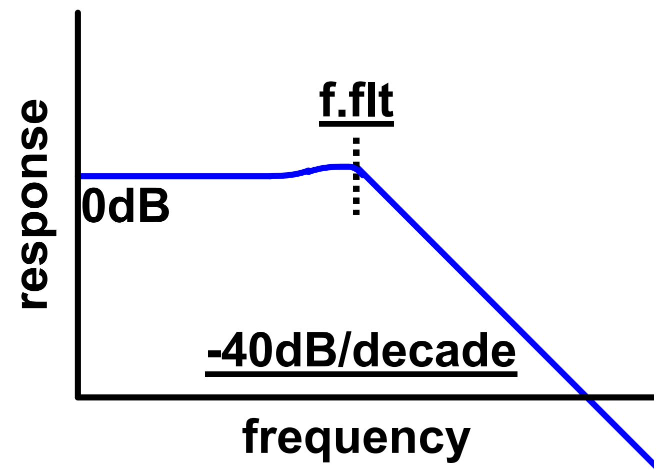
- Switching outputs of Class-D APAs can produce harmonics that extend to several hundred MHz, so they may require output filters for EMC.
  – LC filters are usually needed for switching voltages above 12V or output cables more than ~22 inches, ~56 cm, long.
  – Ferrite-bead + capacitor filters may work for lower switching voltages or shorter output cables.

- TI APAs that use BD modulation often do not require filters for EMC when used with output cables less than ~3 inches, ~7.6 cm, long.

Inductor+Capacitor Output Filters

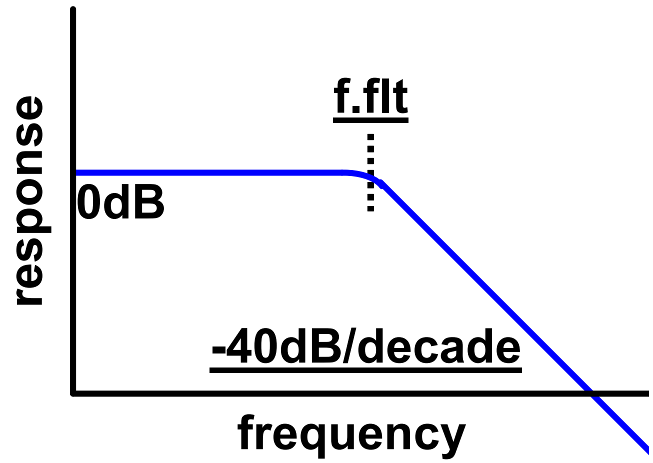
- LC filters like the differential output filter shown here are intended to attenuate the full band of RF harmonics.
- Characteristic frequency of this LC filter is f.flt = 1 / (2pi * sqrt(Cflt*Lflt)).
- Q of the differential output to the load = Rload / (2*sqrt(Lflt/Cflt)).

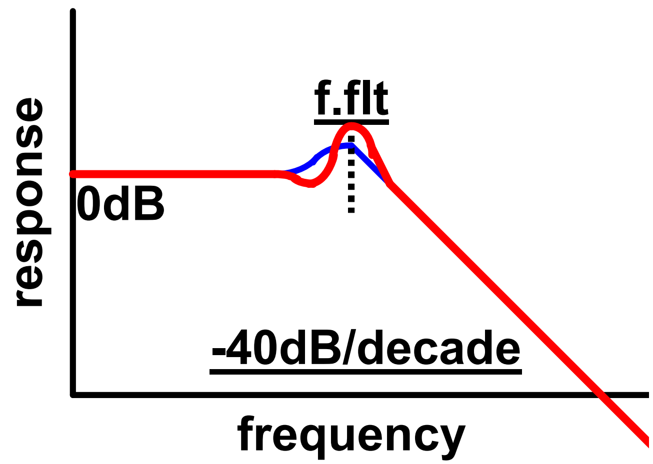




LC Filter Audio Response

- If filter differential Q = 0.707, response is -3dB at f.flt, with no peaking.
- Higher Q produces a response peak, but this will not be a problem if f.flt is well above 20kHz.
- All loudspeakers include inductance, and load inductance can cause ripples in response!





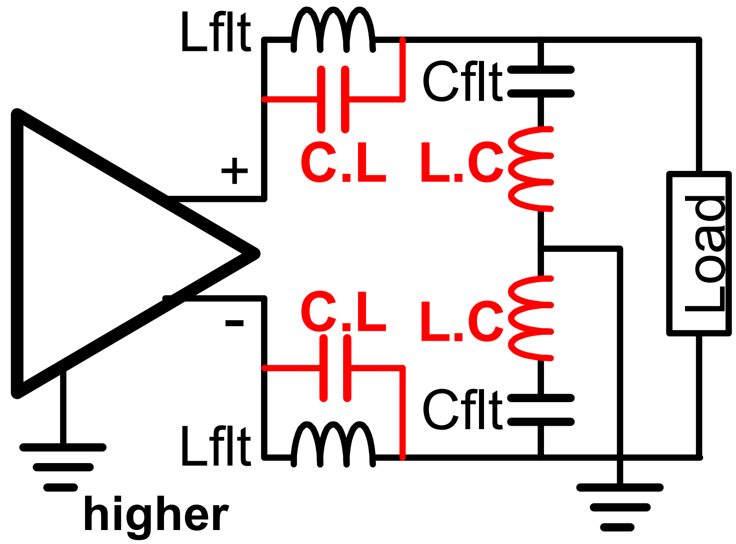
Increasing LC Filter Frequency

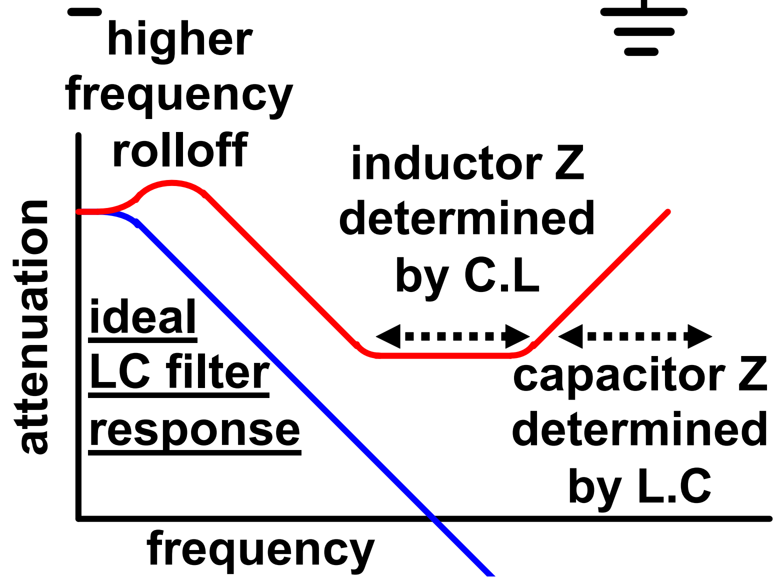
- So it is tempting to increase LC filter frequency.
  - Higher frequency filters use lower-value inductors, and these are smaller and cheaper.
  - Higher frequency filters force filter response peaks farther above 20kHz, so peaks matter less.

- HOWEVER, there are good reasons to minimize LC filter frequency, too – we will look at these.
  - Higher frequency filters have less attenuation at RF frequencies and so are less likely to provide EMC.
  - Higher frequency filters may conduct common-mode currents at the switching frequency.

LC Filter RF Response

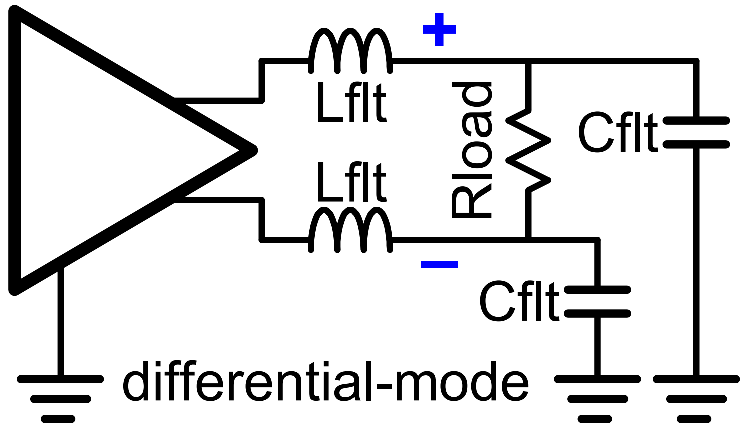
- Higher filter frequencies roll off later, reducing filter RF attenuation.
- In addition, real LC filter components include parasitic elements like **C.L** and **L.C** in the schematic at right.
- These limit attenuation even more, as shown in the graph at right.



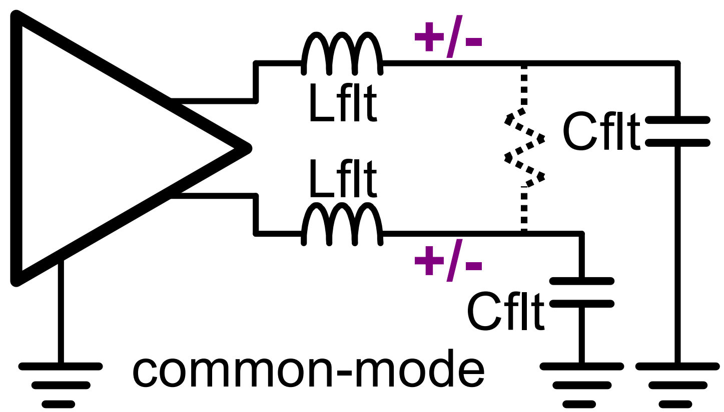


Differential versus Common-Mode

- We usually think of an APA driving a filter with differential signals.
- The load resistance provides damping and keeps filter Q low.



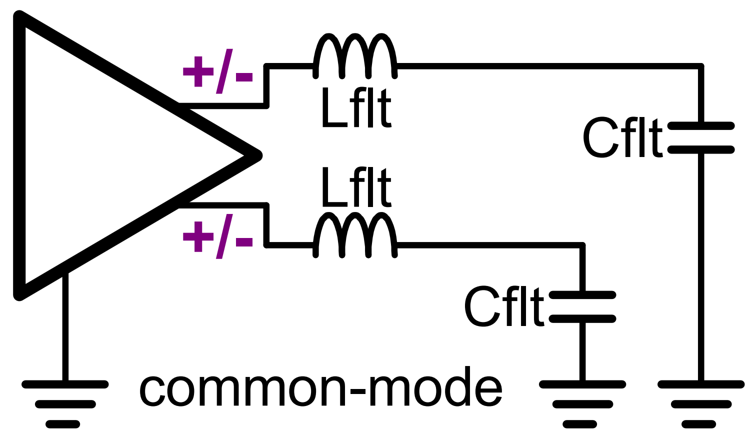
- However, there is some common-mode signal as well as differential signal in all APA outputs.

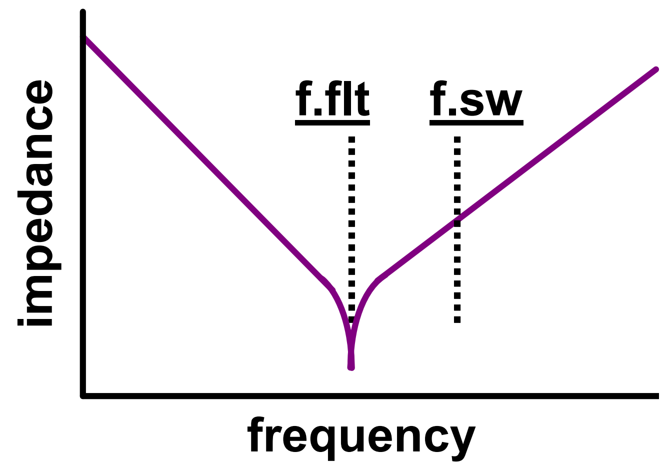


LC Filter Common-Mode Response

- With equal voltages at each terminal the load cannot provide damping.
- So common-mode filter impedance has a notch at f.flt as shown at right.

- If this notch is close to the switching frequency f.sw, the filter will resonate and draw excessive current.





Choosing LC Filter Frequency

- So it is important to choose LC filter frequency in the range of about 30kHz to about 70kHz.
  - This places filter frequency above the audio range, to minimize errors in frequency response.
  - This also places filter frequency well below typical Class-D APA switching frequencies, 200 to 400 kHz, to avoid drawing extra current, increasing quiescent current by burning extra power.
  - This also keeps filter frequency to a fairly low value, so filter RF attenuation will be strong.
  - This permits using inductors with values between 33μH and 10μH.

LC Filter Component Characteristics

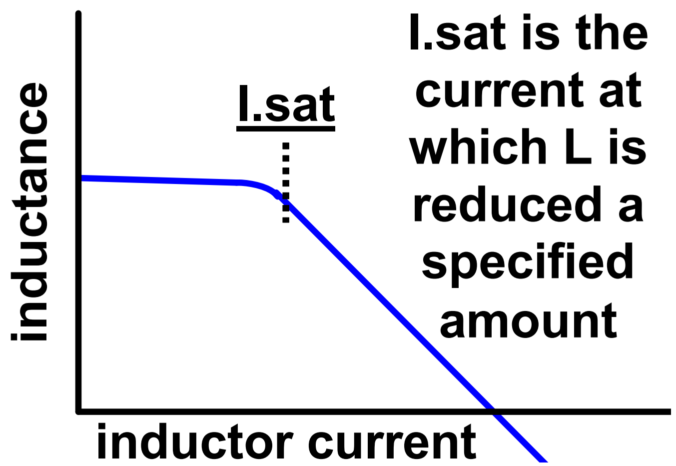
- To optimize LC filter performance and cost, we must understand component characteristics.
- We have already talked about SMD capacitors:

  the rules that apply for input capacitors also apply for output filter capacitors.

- Inductors also have limitations.
  - As noted above, parasitic capacitance in inductors reduces their usefulness above self-resonance.
  - Saturation causes loss of inductance at high currents.
  - DC resistance and core losses cause output losses.

Inductor Core Saturation

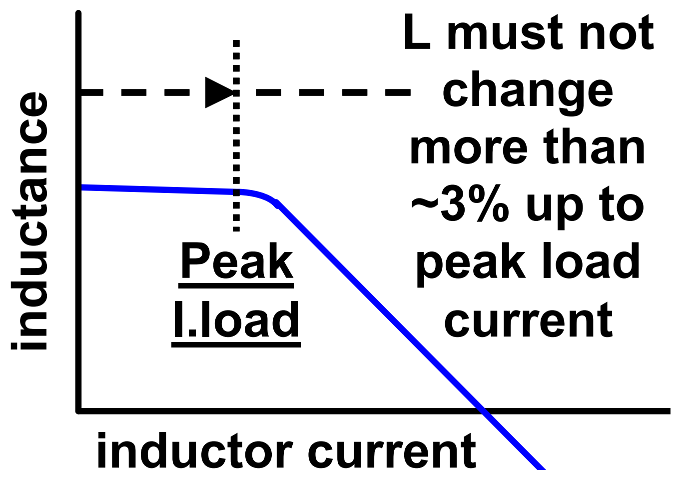
- At higher currents an inductor's core saturates, its permeability falls, and so inductance falls.
- Inductor saturation can reduce effectiveness of an LC filter.



- Inductor manufacturers specify I.sat at different percentages of inductance loss, so review their data sheets for this information.

Inductor Saturation Cont'd.

- Also, if inductance is not nearly constant at lower currents, the inductor can cause distortion.
- A loss of inductance of more than about 3% at peak load current can increase THD.



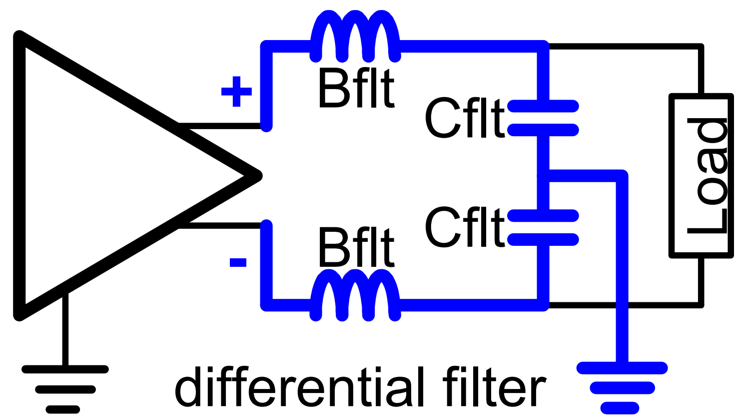
- For higher power H-bridges with overcurrent resistors, inductance must remain at least 5µH up to twice the OC setting for effective OCP.

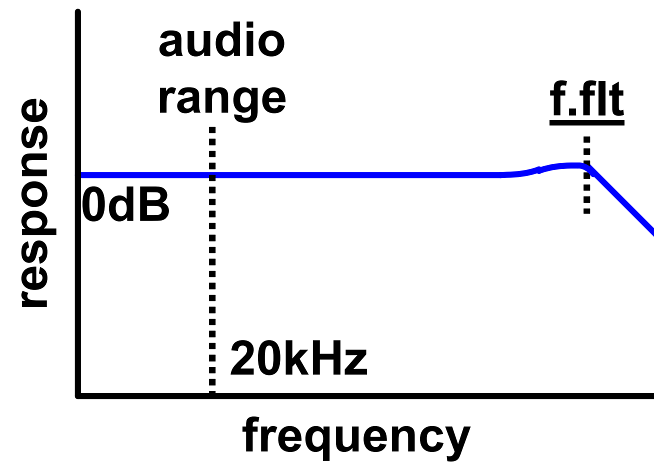
Inductor Loss Elements

- Inductors also have DC resistance and core losses, which can cause significant losses in output power if they are not kept small.
- Core losses are negligible at audio frequencies, but in some inductors they are significant at switching frequencies.
- To avoid significant reduction of audio output power, total DC losses resistance plus inductor core losses should be limited to a small percentage of load power.

Ferrite-Bead+Capacitor Filters

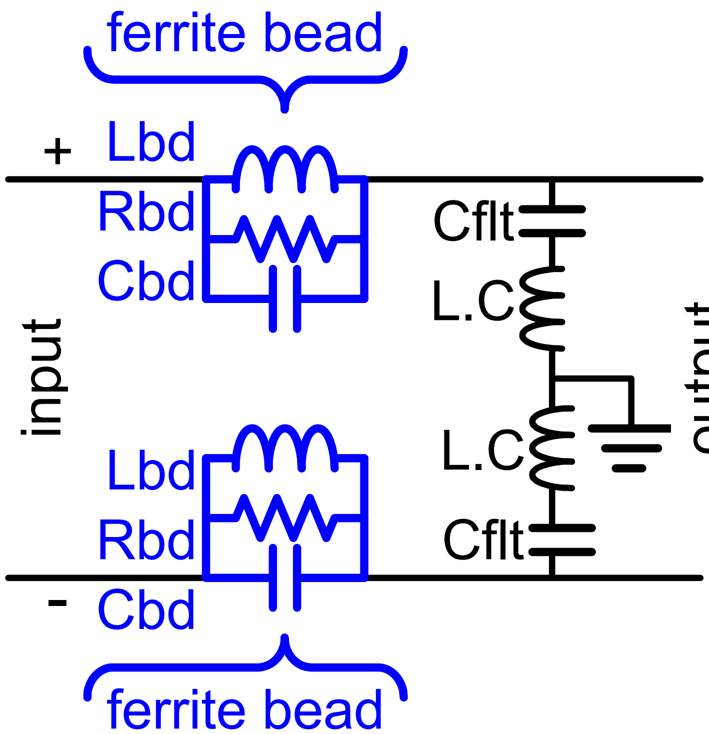
- Filters with ferrite beads like the differential output filter at right attenuate higher RF harmonics.
- Characteristic frequency of the ferrite-bead filter is far above 20kHz, so it does not affect audio frequency response.





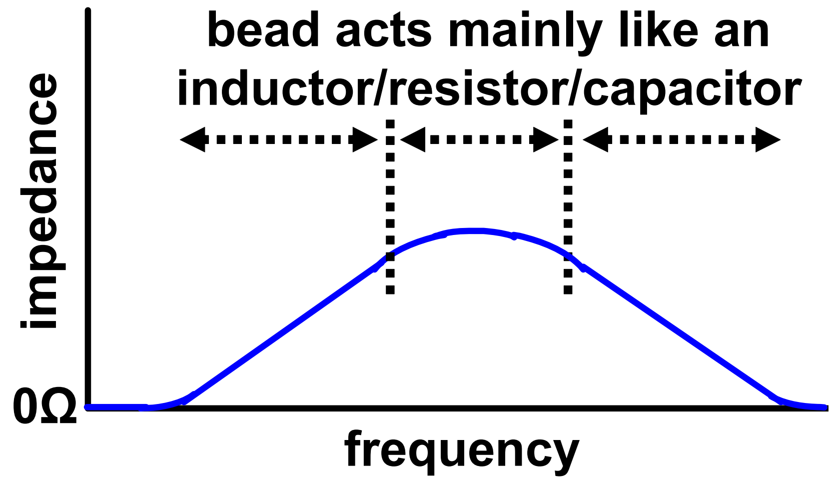
Simple Ferrite-Bead Model

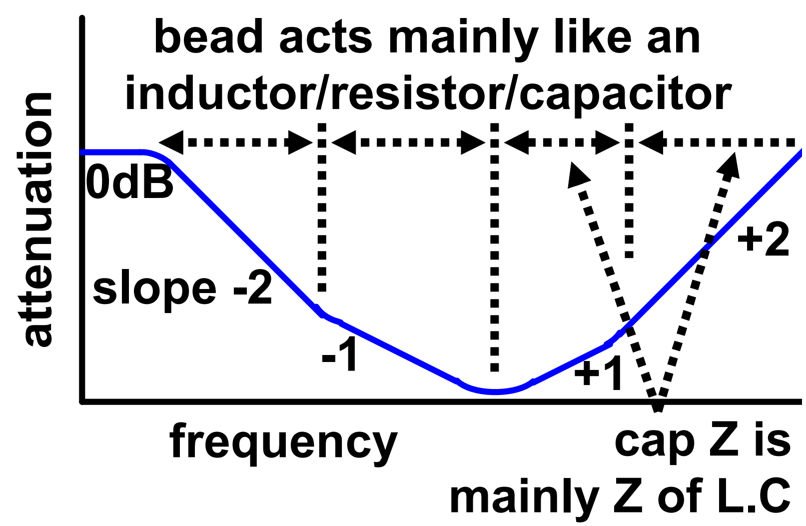
- A simple model for a ferrite bead is a parallel L, R and C.
- An equivalent circuit for a differential ferrite-bead filter, including filter cap with parasitic inductance, is shown at right.
- Lbd, Rbd and Cbd are bead L, R and C.



Ferrite-Bead Filter RF Response

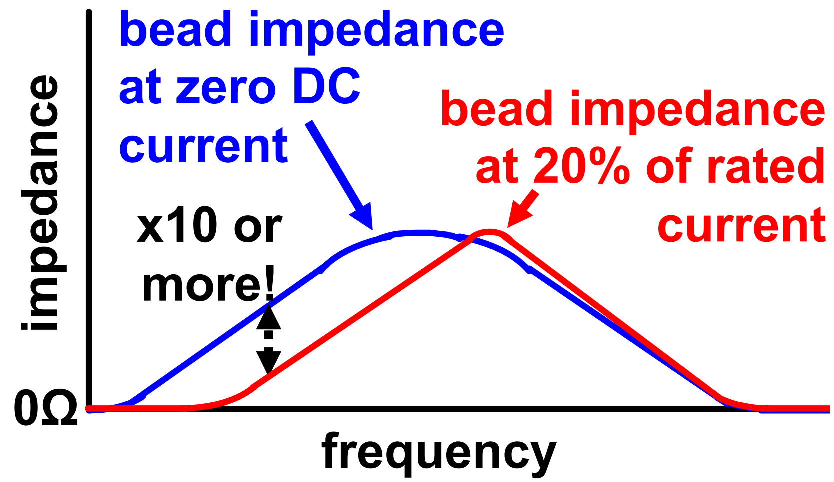
- Bead impedance is shown in at right.
- Nominal RF response of a filter using this bead is shown in the bottom graph.
- Attenuation increases where the bead is inductive or resistive but falls where the cap is inductive.





Ferrite-Bead Saturation

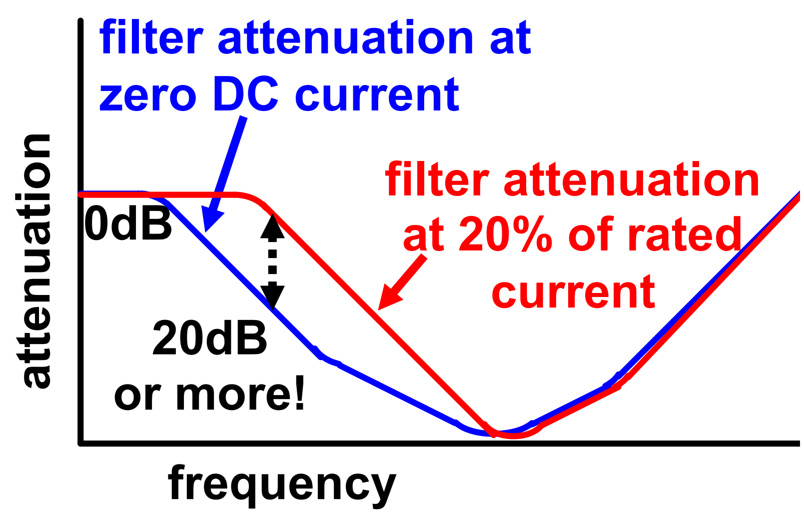
- However, ferrite beads typically saturate more easily than inductors – in many beads, low-frequency impedance falls by a factor of 10 or more at a fraction of rated current!



- Ferrite bead current ratings are thermal and are not related to impedance!

Ferrite-Bead Saturation Cont'd.

- Audio currents are low enough in frequency to saturate ferrite beads like DC currents during their current peaks.
- Switching currents in ferrite beads can also cause saturation.
- Saturation can reduce low and mid frequency attenuation 20dB and more from levels we calculate with zero current impedance.

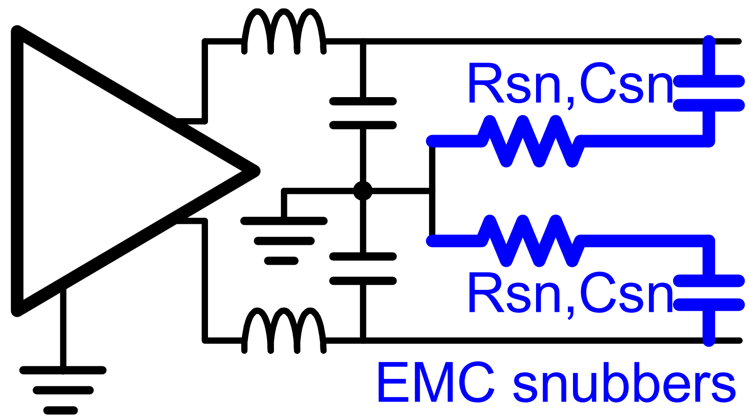


Ferrite-Bead Saturation Cont'd.

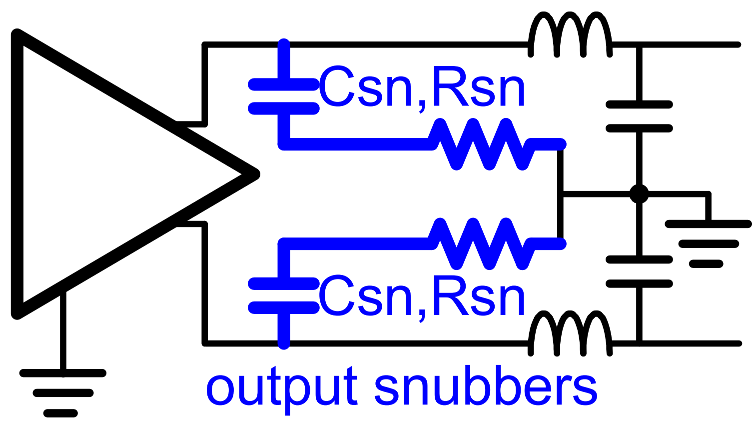
- Before using a bead, make sure its impedance remains high enough to provide adequate filtering at the peak currents it will carry!
- Not all bead vendors publish this information – insist on getting it from the vendor before designing in a bead!
- The appendix includes some examples of vendor data about saturation.

EMC and Output Snubbers

- RC snubbers are used on the outputs of some ICs and output filters to improve EMC and THD.
- Component values for these snubbers are specified in data sheets and user guides.
- To achieve optimal performance follow these recommendations.



EMC snubbers



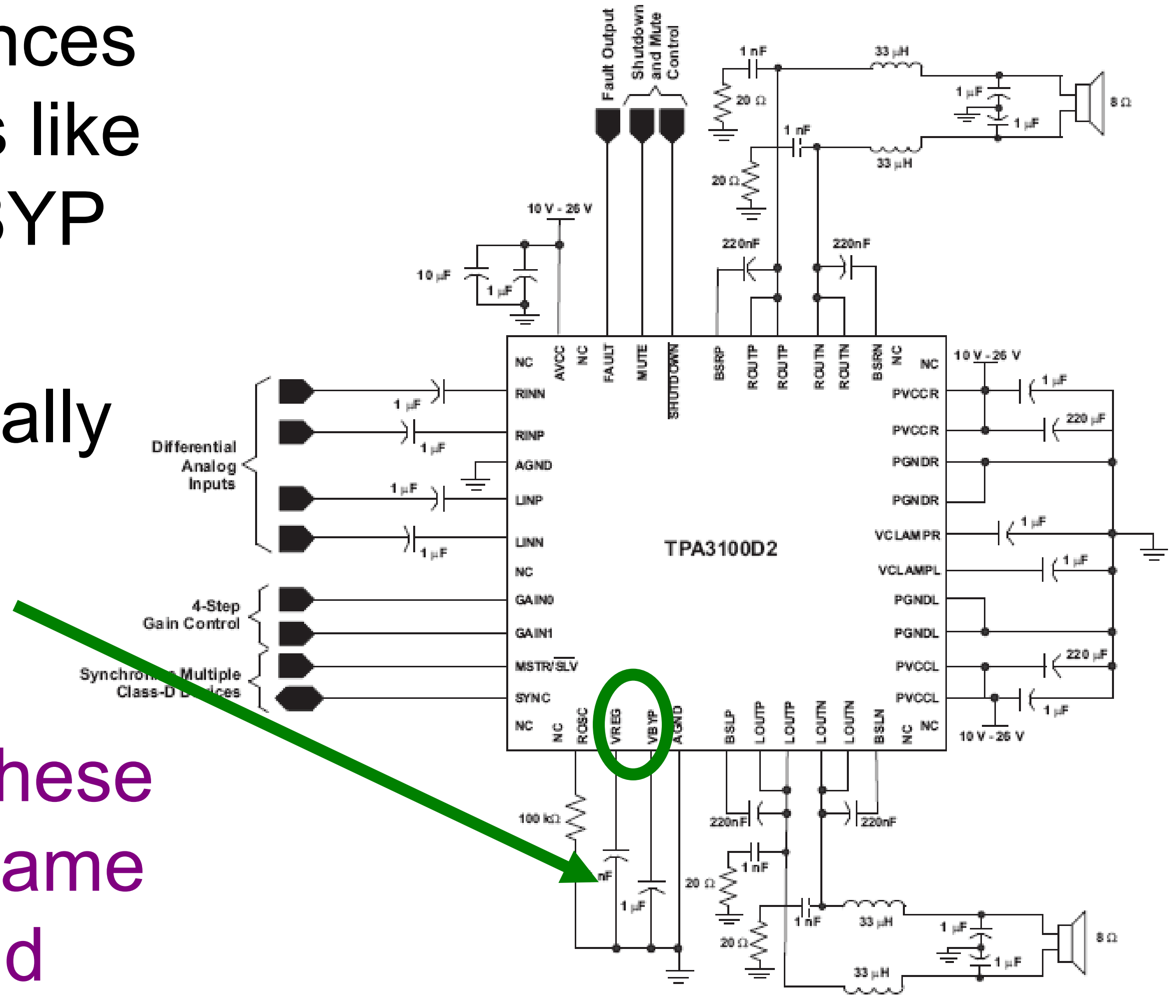
output snubbers

Audio Power Amplifier References and Control Circuits

- Analog Reference Voltages
- Class-D Triangle-Wave Oscillators
- Reference and Oscillator Grounding
- Control Circuits

Analog Reference Voltages

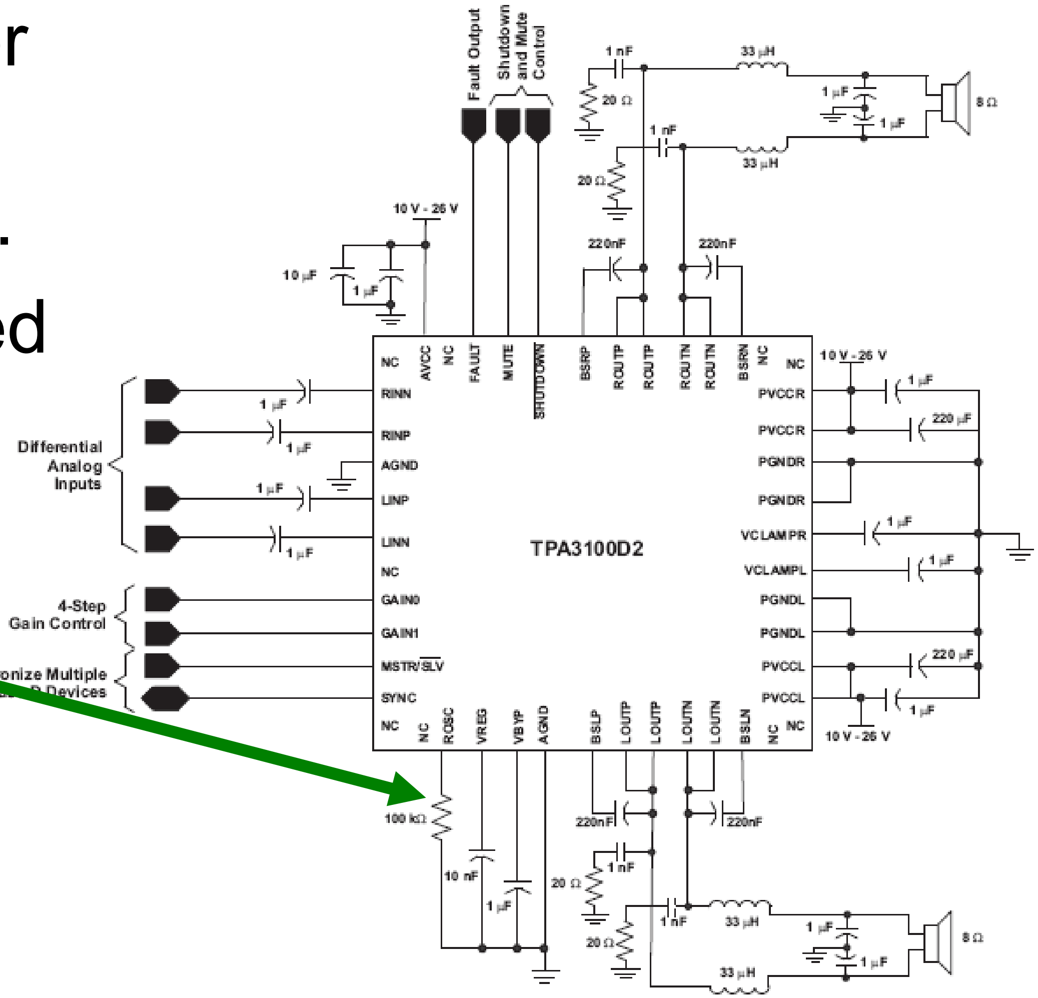
- Analog references and regulators like VREG and VBYP are critical.
- They are typically bypassed with ceramic caps.



- The rules for these caps are the same as for input and decoupling caps.

Class-D Triangle-Wave Oscillators

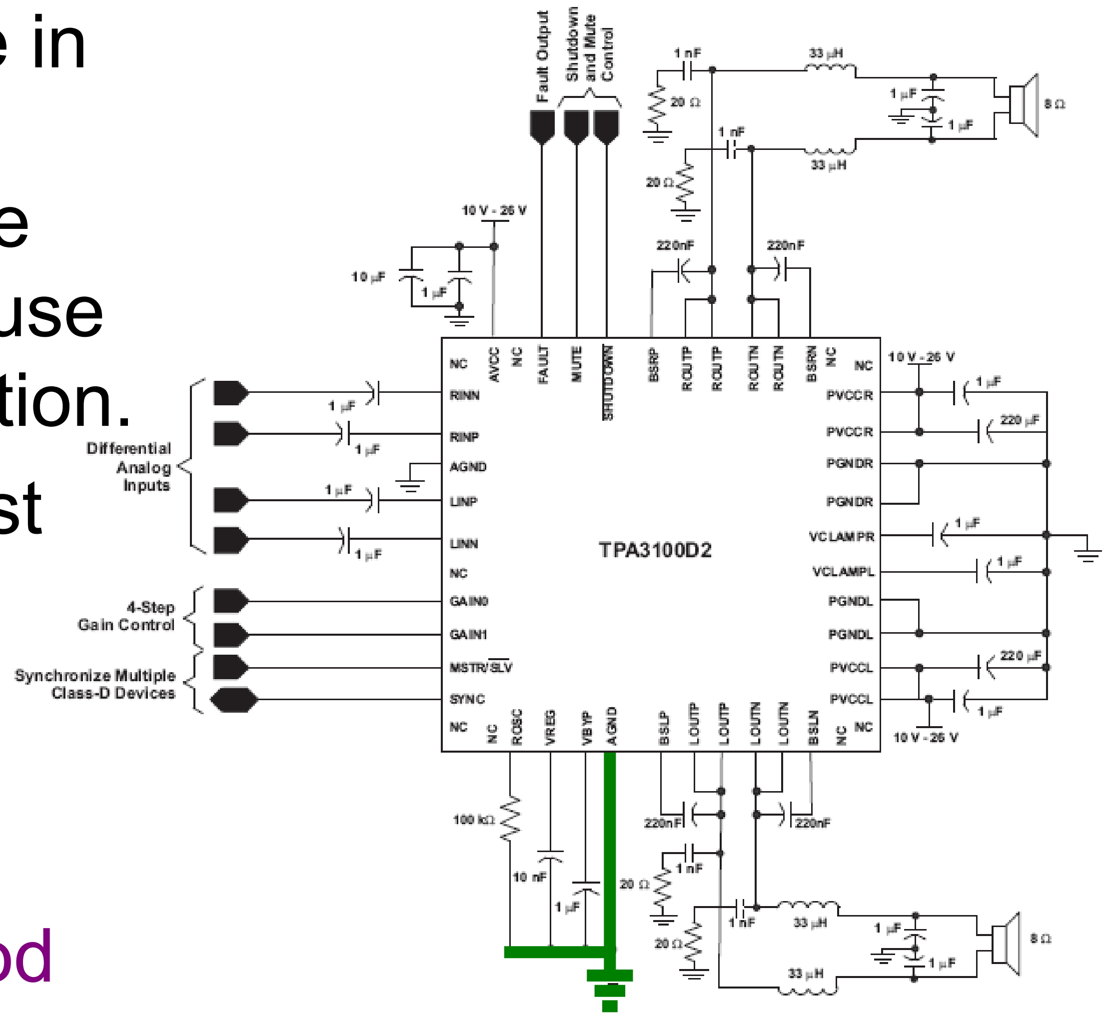
- A triangle oscillator controls Class-D APA switch timing.
- It may be controlled by a resistor and capacitor or just a resistor.



- The triangle wave must be very pure to avoid adding noise and distortion.

Reference and Oscillator Grounding

- Any interference in components for references or the oscillator will cause noise and distortion.
- Ground them first to APA AGND, then to APA central ground.
- This vital for good performance.



Texas Instruments

Logic and DC Input Control Circuits

- Logic inputs control shutdown, mute and other APA parameters, as well as gain in some APAs.
- When these are grounded they may be returned to central ground for the APA.
- Volume of some APAs is controlled by DC voltages from potentiometers or other circuits.
- Potentiometers should be grounded to AGND of the APA, not PGND, to prevent interference from power and output currents.
- Refer to instructions in data sheets about how to connect potentiometers to avoid problems.

QUESTIONS?

APPENDIX:
Component Data

Capacitors

- Capacitor manufacturers generally provide graphs of impedance vs. frequency.
- The graph below is by Kemet. The added red line approximates Z of 1nF.

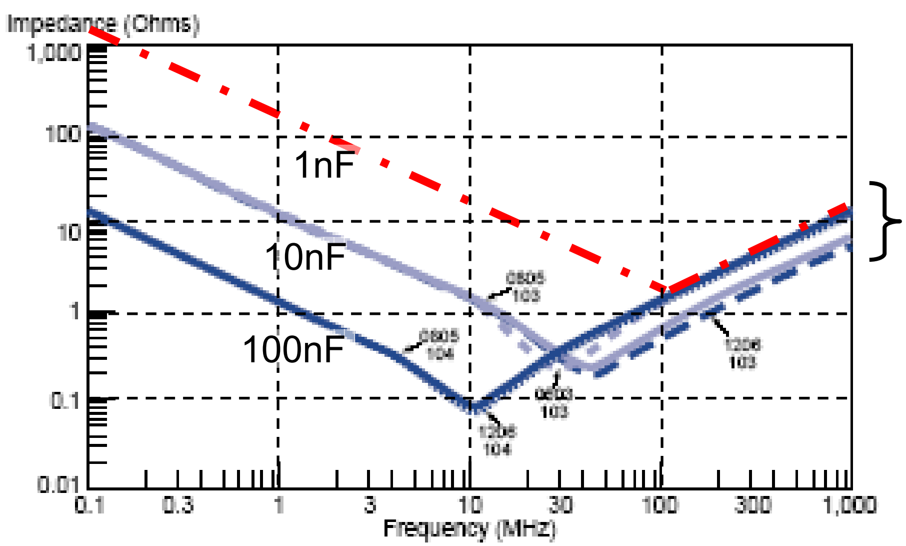


FIGURE 5 Impedance versus Frequency X7R Dielectric

ESL (equivalent series inductance) is ~ 2 to 4 nH.

High-K Ceramic Capacitors

- It may seem desirable to use high-K (high dielectric coefficient) ceramic capacitors in audio circuits for their small size and low cost.
- HOWEVER: be aware that <u>in application</u> the actual working capacitance of these parts is typically much less than their nominal values!!!

High-K Capacitor Sensitivity

- Capacitance of high-K ceramic capacitors is sensitive to a number of factors.
  - Temperature.
  - Applied DC voltage.
  - Applied AC voltage.
  - Applied frequency.
- The worst of these are temperature and DC voltage.

Sensitivity to Temperature

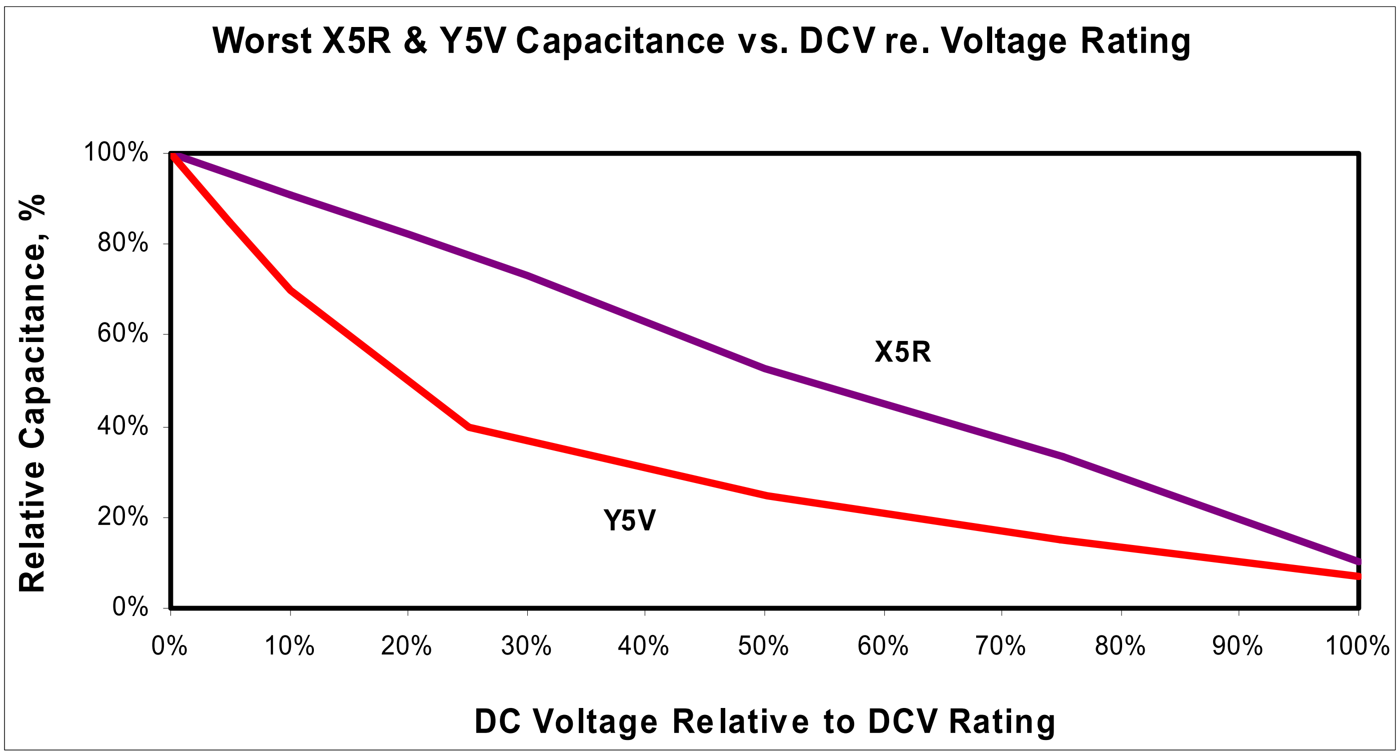
- Capacitors made with high-K material can vary dramatically over temperature.

Typical tolerance and temperature coefficient of capacitance by material				
Material:	COG/NP0	X7R	X5R	Y5V
Typ.tolerance:	+/-5%	+/-10%	+/-10%	+80/-20%
TempCo:	+/-30ppm	+/-15%	+/-15%	+22/-82%
Range,C:	-55/+125C	-55/+125C	-55/+85C	-30/+85C

- A capacitor made with X5R material can lose 15% of its capacitance at a temperature in its working range!
- Y5V is much worse!

Sensitivity to DC Voltage

- The graph below illustrates the WORST loss of capacitance versus DC bias that we have observed for X5R and Y5V capacitors.

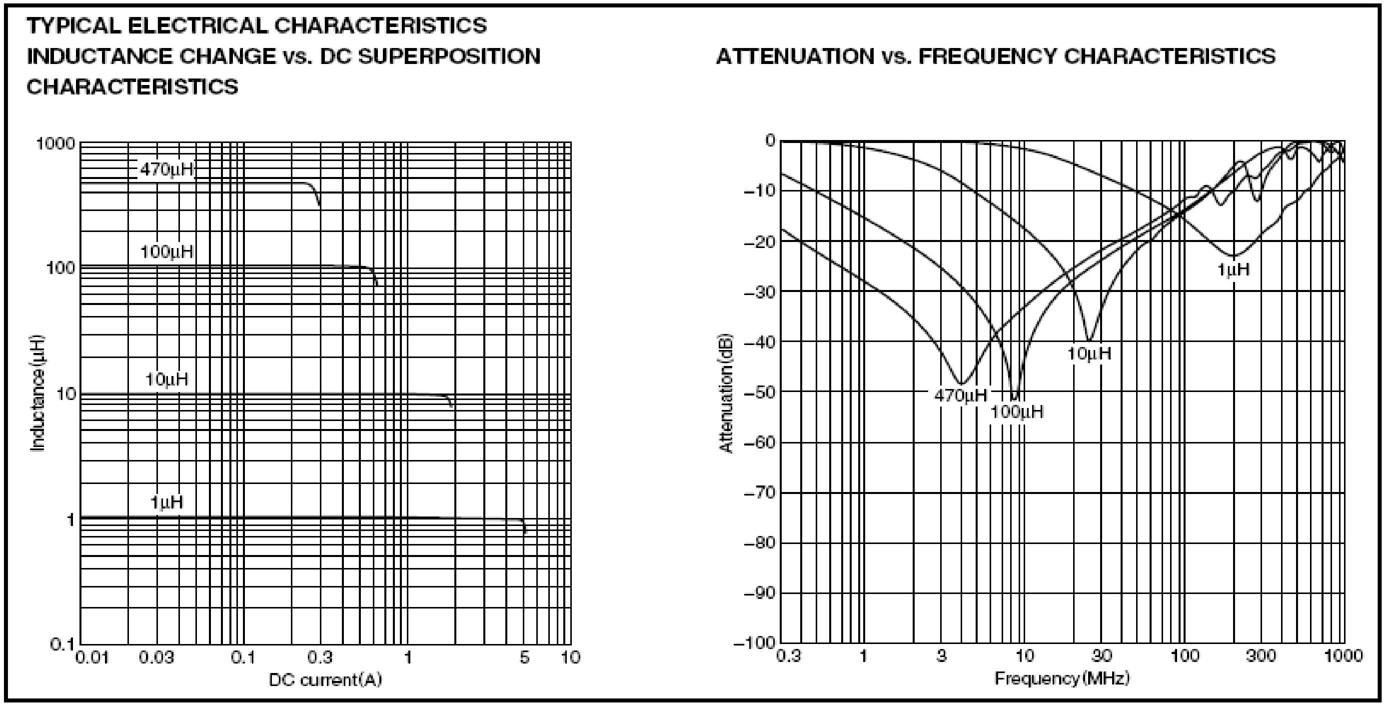


Effect of These Sensitivities

- Capacitance of high-K parts can be reduced to less than half of nominal at 50% of their rated DC voltage !!
- Combined effects of temperature and DC voltage can easily reduce capacitance to well under 50% of nominal !!
- There are also sensitivities to AC voltage and frequency. These are far less severe but they still make things a little worse!

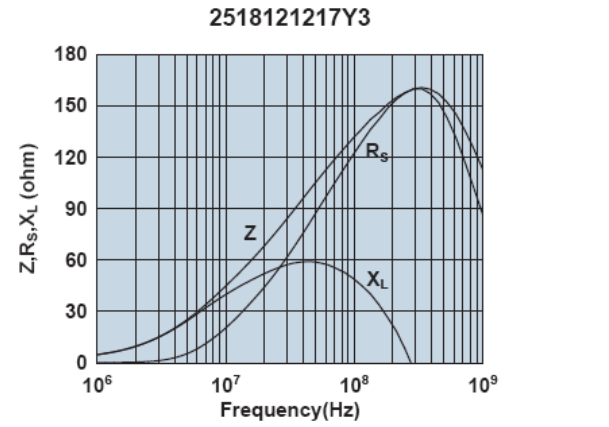
Inductors

- Inductor manufacturers generally provide some information on saturation & resonant frequency.
- Here is an example. Resonance in Attenuation vs. Frequency reflects parasitic capacitance.

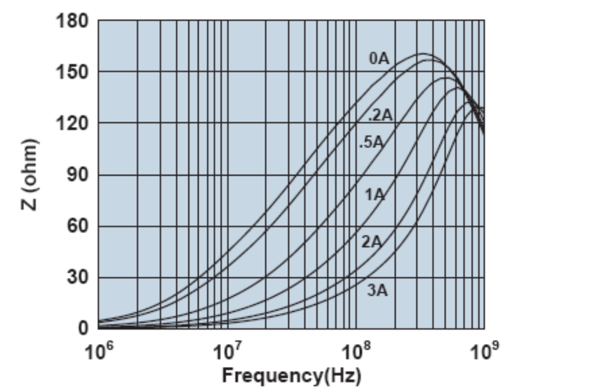


Ferrite Bead Saturation

- The graphs at right are from Fair-Rite, who provide relatively complete information on their beads.
- This is 2518121217Y3, the 120-ohm, 3A, 1812 bead used in our TPA3008D2 EVM.



Impedance, reactance, and resistance vs. frequency.



Impedance vs. frequency with dc bias.

More on Ferrite Bead Saturation

- TDK has provided this graph of impedance vs. DC current for their lower-current MMZ bead series.
- This can be used to predict saturation in higher-current beads like MPZ2012S221A, a 220-ohm 3A 0805.