Combination Notch and Bandpass Filter

- Clever filter design for graphic equalizer can perform both notch and bandpass functions
- Gain or attenuation is controlled by a potentiometer for specific frequency bands
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[Diagram of the circuit with labeled components: 4.7kΩ, 1kΩ, 9kΩ, 1H, 4.7kΩ, 0.1μF, and a graph showing frequency response.]
Combination Notch and Bandpass Filter

![Diagram of a combination notch and bandpass filter with resistors, capacitors, and inductors labeled with values 4.7k, 9k, 1k, 1H, and 0.1uF.](Image)

*Graph showing frequency response with peaks at specific frequencies.*
Integrator via Negative Impedance Converter

- Presents a **negative resistance** at the input terminals
- Best analyzed by applying a test voltage and measuring the input current

If it is behaving like a linear circuit, we can calculate the Thevenin equivalent
If it’s **passive**, we can simply calculate its impedance (resistance in this case)
Thevenin/Norton Equivalents

- By definition, a **linear** circuit has a straight-line i-v characteristic.

\[ v = Ri + V_{oc} \]

Which can be represented by

\[ i = \frac{v}{R} + I_{sc} \]
Thevenin/Norton Equivalents

- If the line passes through the origin, then it is a **passive** linear circuit --- a single impedance
- Only one \((v_x,i_x)\) point is needed to determine the slope

\[
\text{slope} = \frac{v_x}{i_x} = R
\]

- A negative resistance is recognized by a negative slope *(with directions shown)*
Thevenin/Norton Equivalents

- Note that the same Thevenin/Norton conversion steps --- applying test voltages and measuring test currents --- works for complex impedances too

\[
Z_C = \frac{1}{sC} \quad Z_L = sL
\]

- We just can’t draw them as two dimensional i-v characteristics
Negative Impedance Converter

- Calculate $v_{in}/i_{in}$
Negative Impedance Converter

\[ V_o \]

\[ R_1 \]

\[ R_2 \]

\[ R \]

\[ i_{in} \]

\[ v_{in} \]
Voltage-to-Current Converter

- The negative impedance converter can be used to create a voltage-to-current converter where the output load current is independent of the load impedance.
Voltage-to-Current Converter

- We could also write out all of the current equations and get the same result
Integrator

- Use the voltage-to-current converter to design an integrator
Integrator

- Need a low output impedance for this circuit -- why?

- If the output impedance is not low enough, what is another design option?
More Nonidealities

- Along with the frequency dependence of the gain, and the finite output/input impedances of the devices, there are other nonidealities associated with opamps that can cause distortion
- **Saturation**: the output is really limited to a voltage that is 1 to 3 volts less than VCC
- **Slew Rate**: limited gain of transconductance input amplifier can cause severe distortion in the output
- **CMRR**: the signal component that is common to both differential inputs is amplified somewhat, and the CMRR specifies the quality with which this phenomenon is rejected
- **dc Offset Voltage**: the input differential voltage required to set the output to zero when no other signals are applied
- **Finite Input/Output Impedances**: the input resistance/impedance of the inputs and the limited current sourcing capability of the output
- **dc Input Bias Current**: small currents required to bias the transistors at the input stage of the opamp
Slew Rate Limitations

- We know that an opamp behaves like a low pass filter due to the frequency dependence of the gain.
- A unity gain amplifier has a bandwidth of $\omega_t$.

741 Open Loop Characteristics

$$A(s) = \frac{A_o}{1 + \frac{s}{\omega b}}$$
Slew Rate Limitations

• So we can write an expression for the closed-loop gain as:

\[
\frac{V_o}{V_i} = \frac{1}{1 + \frac{s}{\omega_t}}
\]

• Which is like a STC with a time constant of \( \frac{1}{\omega_t} \)
• In the time domain we’d expect a step response of the form:

\[
v_o(t) = V \left( 1 - e^{-\frac{t}{\tau}} \right)
\]

• Which has a maximum possible change in output voltage of

\[
\frac{dv_o(t)}{dt} = \frac{V}{\tau}
\]
Slew Rate Limitations

- If the output wants to change faster than this, it will not be able to do so
- This is especially difficult for large signals; e.g. when $V$ is large
- The maximum switching speed is limited by $\omega_t$, which is due to the compensation capacitor in this case, but all capacitors in the circuit in general
- The open loop roll-off with frequency is due to the limited current sourcing capability of the amplifier and these capacitors

$$\frac{\Delta V}{\Delta t} \Rightarrow \frac{I_{max}}{C}$$

- So the maximum current sourcing capability and the compensation capacitor, for example, may determine the slew rate

$$SR = \frac{dV_o}{dt} \bigg|_{max} \text{ (volts/\mu s)}$$

- A smaller change in voltage can go to higher frequencies before encountering the SR limitation
Opamp Macromodels

- We can look at this limited current sourcing capability of the opamp in terms of the opamp macromodel

- When change in \( v_{id} \) is sudden, \( G_m \) can only supply a limited amount of current, \( I_{max} \) for a real input transconductance amplifier
Slew Rate Limited Response

- At the slew rate limit the output can only ramp up with a slope of $\frac{I_{\text{max}}}{C(1+\mu)}$

For a sudden change in the input voltage, $v_{\text{id}}$
741 Example

• Slew Rate for a 741 is 0.63V/µs
• For a sinusoidal signal, the maximum change occurs near the zero crossing, so this is where we will notice the first signs of slewing

\[ \frac{dV_o}{dt} \bigg|_{max} = \omega V \]

• What’s the maximum allowable frequency for a peak sinusoidal input voltage of 5.0 volts?
741 Example

- Input and output voltage for a 5 volt peak, 10kHz frequency
741 Example

- Input and output voltage for a 5 volt peak, 20kHz frequency
741 Example

- Input and output voltage for a 5 volt peak, 40kHz frequency
741 Example

- Note that the frequency response of the opamp does not affect the input signal at 20kHz
- It is a slew rate limitation that depends on the magnitude of the input voltage (has $I_{\text{max}}$ of the input transconductance amplifier been reached?)