Op-Amp Circuits: Part 6

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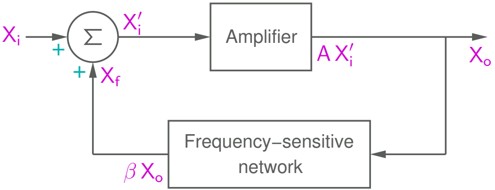
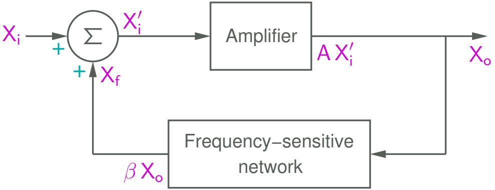


Consider an amplifier with feedback.



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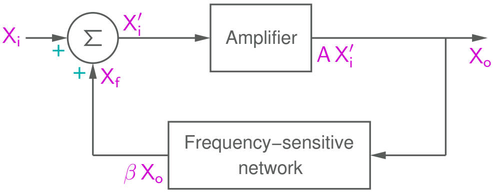

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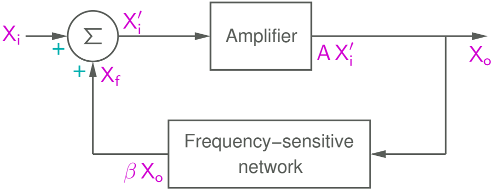

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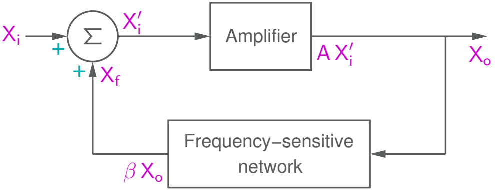
$$A_f(j\omega) = \frac{A\,(j\omega)}{1 - A\,(j\omega)\,\beta\,(j\omega)}.$$



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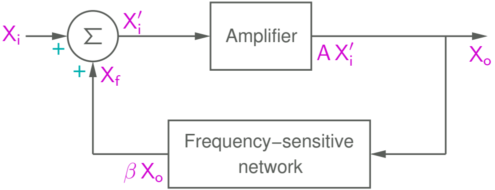
As $A\,(j\omega)\,\beta\,(j\omega) \rightarrow 1$, $A_f(j\omega) \rightarrow \infty$, and we get a finite $X_o\,(= A_f\,X_i)$ even if $X_i = 0$.



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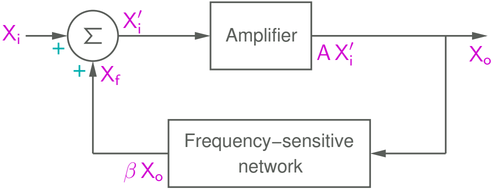
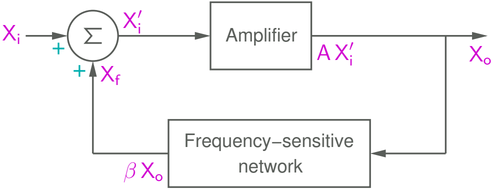
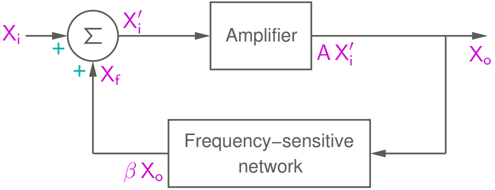
In other words, we can remove X_i and still get a non-zero X_o. This is the basic principle behind sinusoidal oscillators.



X_i
+
Σ
X_i'
Amplifier
$A\,X_i'$
X_o
+
X_f
Frequency−sensitive network
$\beta\,X_o$



* The condition, $A\,(j\omega)\,\beta\,(j\omega) = 1$, for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.



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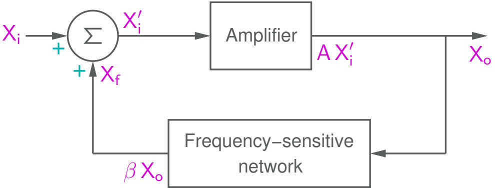
* For the circuit to oscillate at $\omega = \omega_0$, the β network is designed such that the Barkhausen criterion is satisfied only for ω_0, i.e., all components except ω_0 get attenuated to zero.



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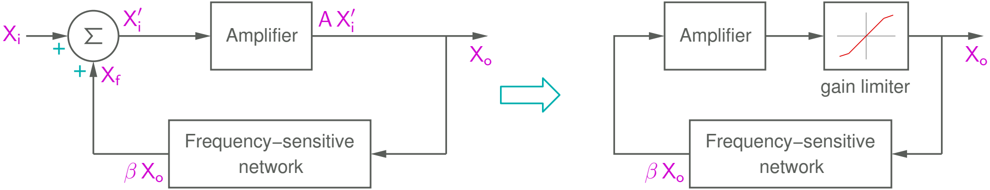
* For the circuit to oscillate at $\omega = \omega_0$, the β network is designed such that the Barkhausen criterion is satisfied only for ω_0, i.e., all components except ω_0 get attenuated to zero.
* The output X_o will therefore have a frequency ω_0 ($\omega_0/2\pi$ in Hz), but what about the amplitude?


X_i
+
Σ
X_i'
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Amplifier
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Frequency−sensitive network
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Amplifier
gain limiter
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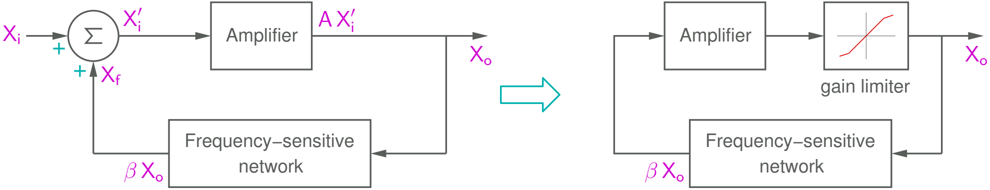
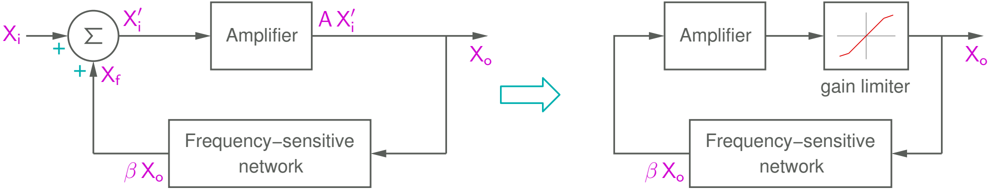


* A gain limiting mechanism is required to limit the amplitude of the oscillations.



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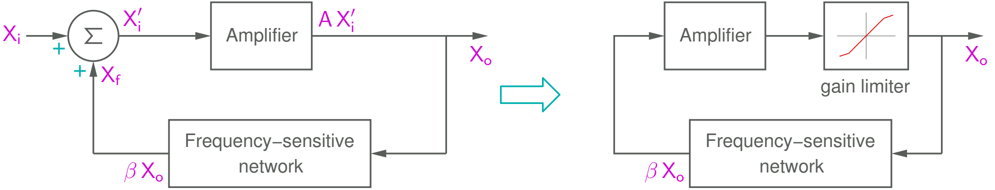
* Amplifier clipping can provide a gain limiter mechanism. For example, in an op-amp, the output voltage is limited to $\pm V_{\text{sat}}$, and this serves to limit the gain as the magnitude of the output voltage increases.



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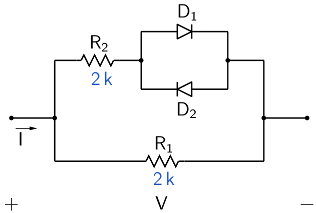
* For a more controlled output with low distortion, diode-resistor networks are used for gain limiting.

Gain limiting network: example



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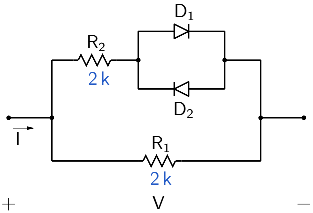

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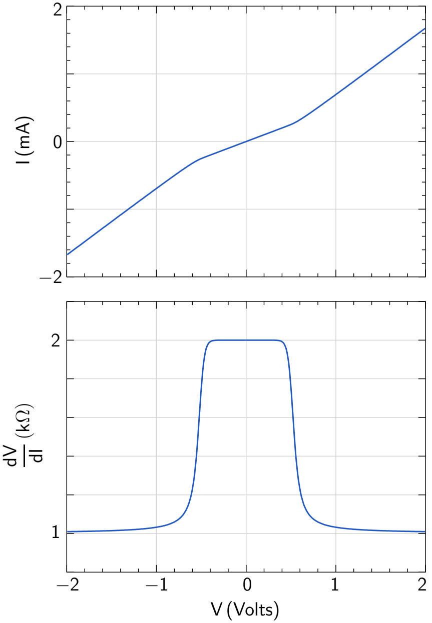

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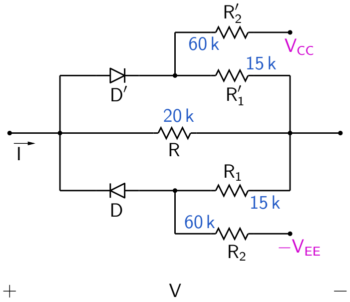
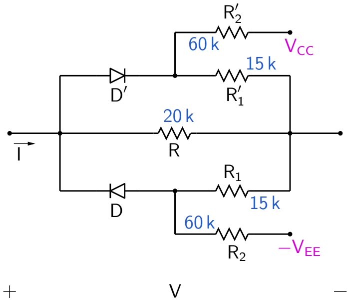


$(V_{CC} = 15\,\mathrm{V})$

Gain limiting network: example



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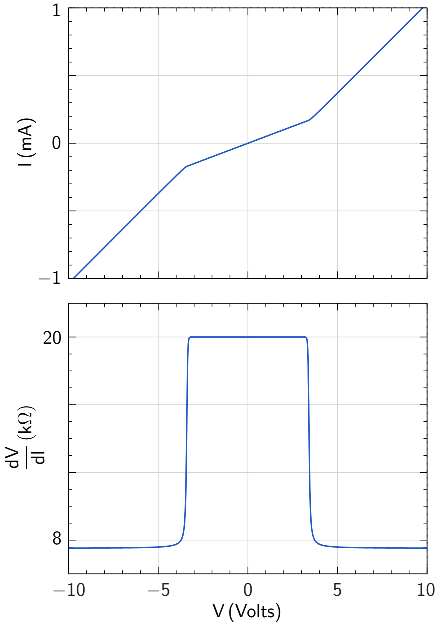
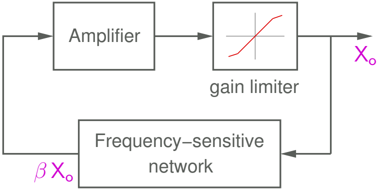
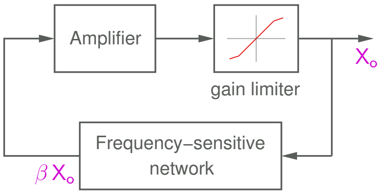
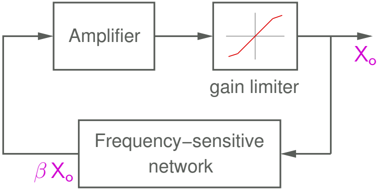



Amplifier
gain limiter
X_o
Frequency−sensitive network
βX_o



* Up to about 100 kHz, an op-amp based amplifier and a β network of resistors and capacitors can be used.

Sinusoidal oscillators



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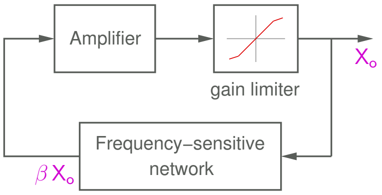
* At higher frequencies, an op-amp based amplifier is not suitable because of frequency response and slew rate limitations of op-amps.



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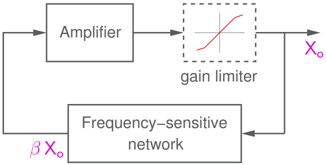
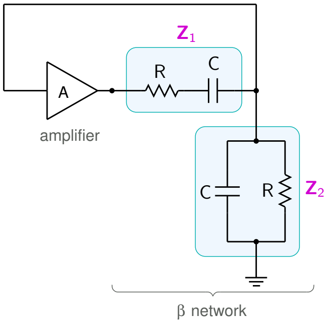
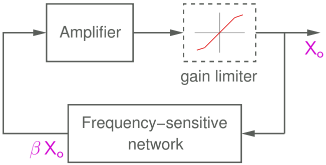
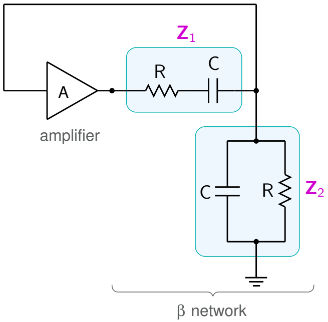
* For high frequencies, transistor amplifiers are used, and LC tuned circuits or piezoelectric crystals are used in the β network.

Wien bridge oscillator









Assuming $R_{\text{in}} \rightarrow \infty$ for the amplifier, we get

$$A(s)\,\beta(s) = A\,\frac{Z_2}{Z_1 + Z_2} = A\,\frac{R \parallel (1/sC)}{R + (1/sC) + R \parallel (1/sC)} = A\,\frac{sRC}{(sRC)^2 + 3sRC + 1}\,.$$

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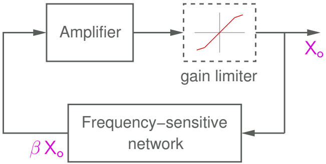

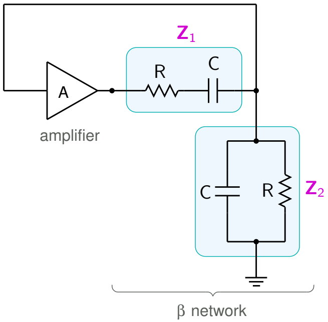

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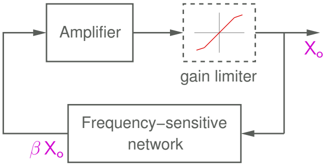
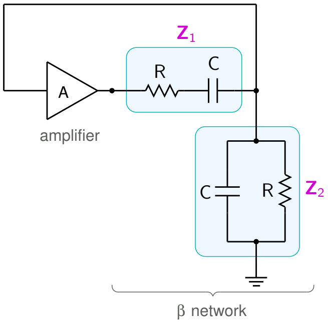
For $A\,\beta = 1$ (and with A equal to a real positive number),

$$\frac{j\omega RC}{-\omega^2 (RC)^2 + 3j\omega RC + 1}$$ must be real and equal to $1/A$.





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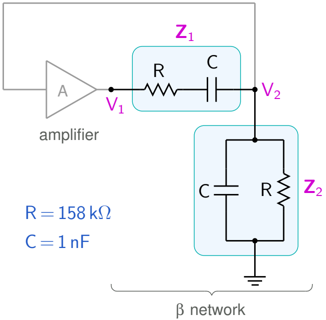
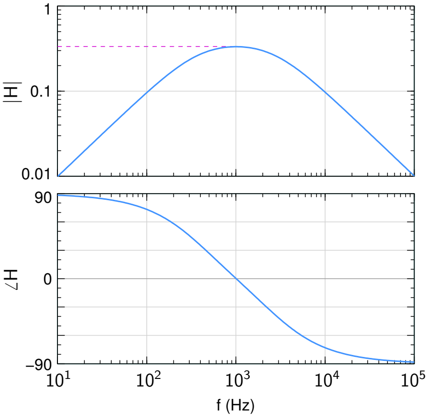
$$\rightarrow \boxed{\omega = \frac{1}{RC},\ A = 3}$$

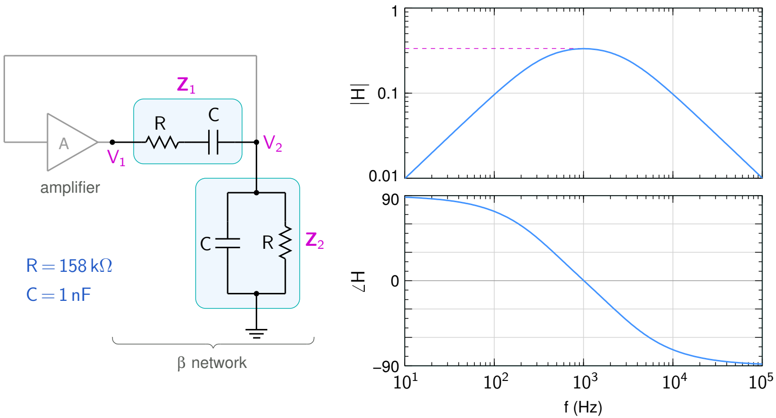


R = 158 kΩ

C = 1 nF



$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}.$$



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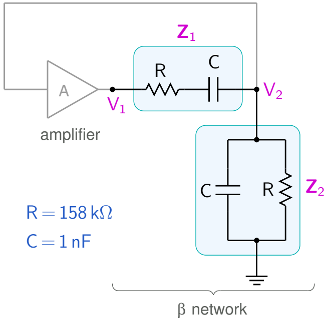
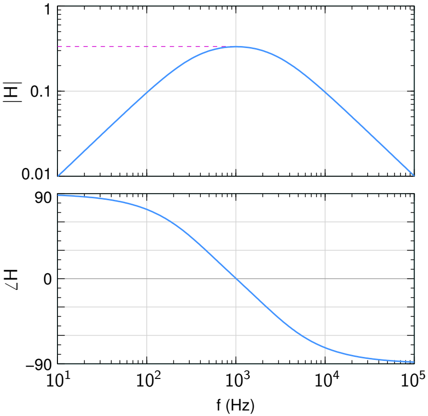
Note that the condition $\angle H = 0$ is satisfied only at one frequency, $\omega_0 = 1/RC$, i.e., $f_0 = 1\,\text{kHz}$.

At this frequency, $|H| = 0.33$, i.e., $\beta(j\omega) = 1/3$.





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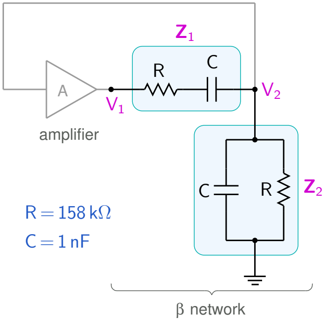
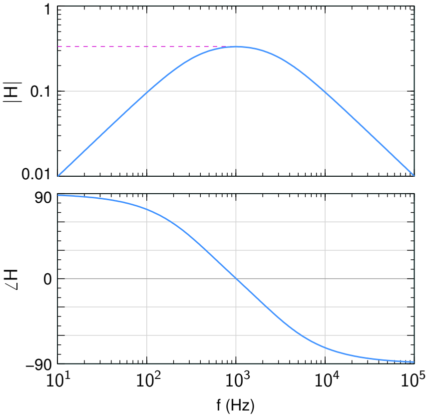
For $A\beta=1\rightarrow A=3$, as derived analytically.





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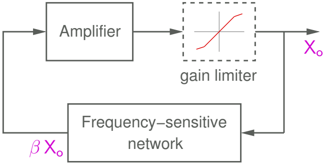
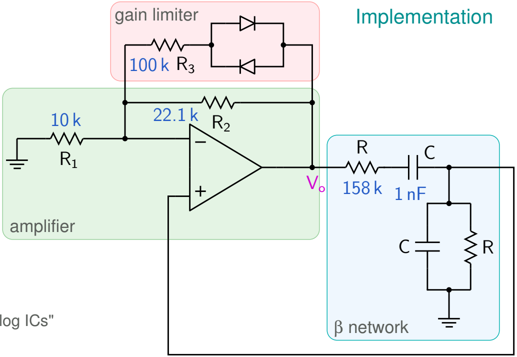
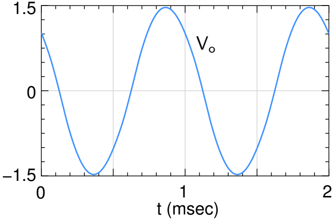
Block diagram



Implementation

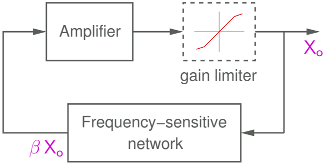


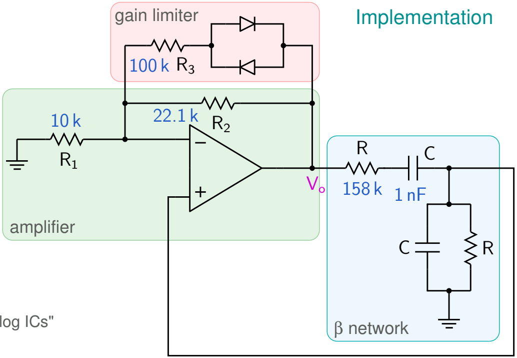
Output voltage

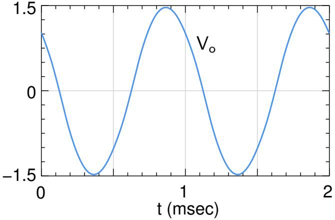


Ref.: S. Franco, "Design with Op Amps and analog ICs"

SEQUEL file: wien_osc_1.sqproj







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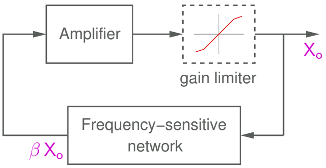
Wien bridge oscillator

Block diagram



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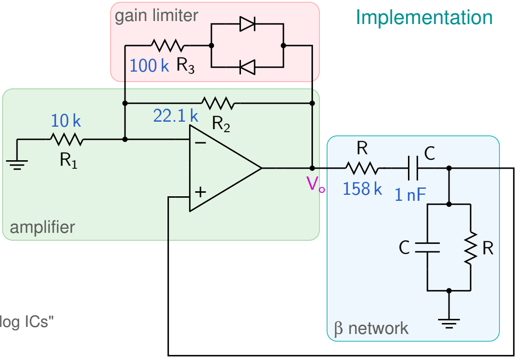

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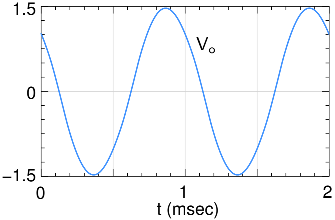

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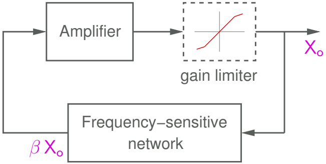
* Since the amplifier gain is required to be $A = 3$, we must have $1 + \dfrac{R_2}{R_1} = 3 \rightarrow R_2 = 2\,R_1$.

Block diagram



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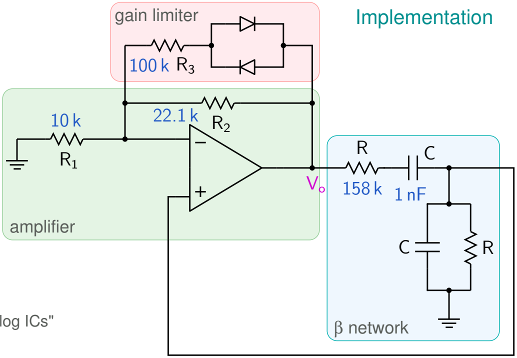
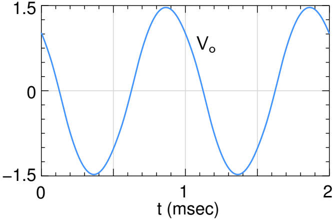
SEQUEL file: wien_osc_1.sqproj

Implementation



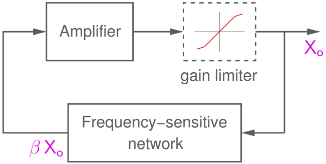
Output voltage



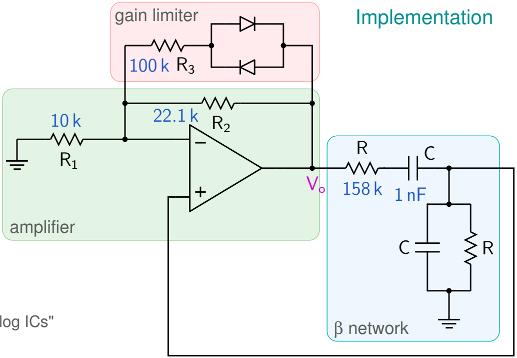
* $\omega_0 = \dfrac{1}{RC} = \dfrac{1}{(158\,\text{k}) \times (1\,\text{nF})} \rightarrow f_0 = 1\,\text{kHz}.$
* Since the amplifier gain is required to be $A = 3$, we must have $1 + \dfrac{R_2}{R_1} = 3 \rightarrow R_2 = 2\,R_1$.
* For gain limiting, diodes have been used. With one of the two diodes conducting, $R_2 \rightarrow R_2 \parallel R_3$, and the gain reduces.

Wien bridge oscillator

Block diagram



Implementation



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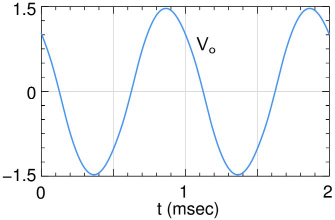

Ref.: S. Franco, "Design with Op Amps and analog ICs"

SEQUEL file: wien_osc_1.sqproj

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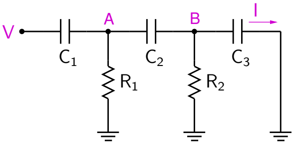
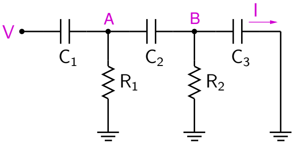
* For gain limiting, diodes have been used. With one of the two diodes conducting, $R_2 \rightarrow R_2 \parallel R_3$, and the gain reduces.
* Note that there was no need to consider loading of the β network by the amplifier because of the large input resistance of the op-amp. That is why β could be computed independently.

Phase-shift oscillator

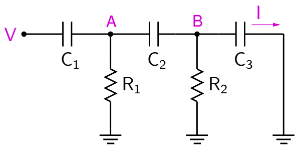


SEQUEL file: ee101_osc_4.sqproj



SEQUEL file: ee101_osc_4.sqproj

Let $R_1 = R_2 = R = 10\,\mathrm{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\mathrm{n}F$.



SEQUEL file: ee101_osc_4.sqproj

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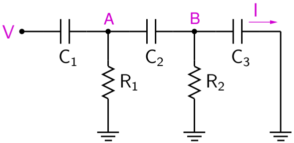
Using nodal analysis,

$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$



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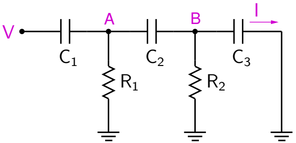
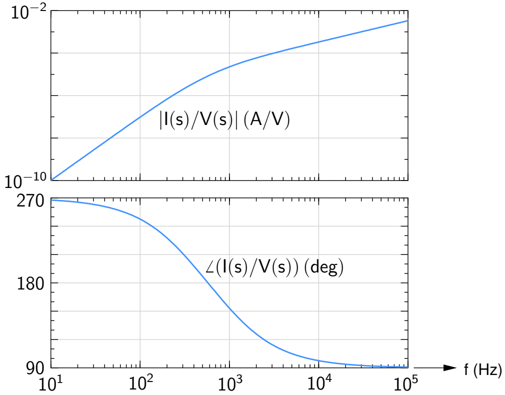
Solving (1) and (2), we get $I = \dfrac{1}{R}\,\dfrac{(sRC)^3}{3\,(sRC)^2 + 4\,sRC + 1}\,V$.



SEQUEL file: ee101_osc_4.sqproj



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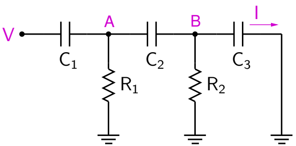

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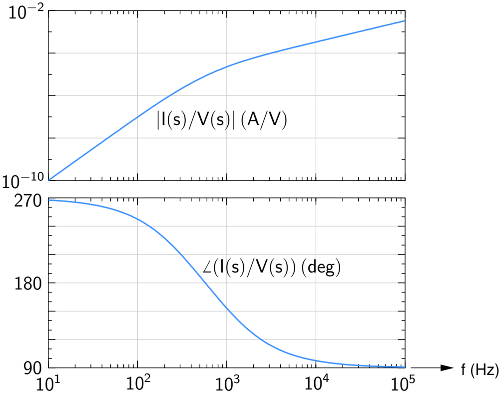

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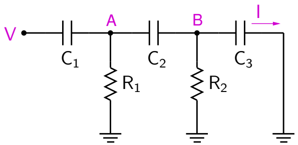
Phase-shift oscillator



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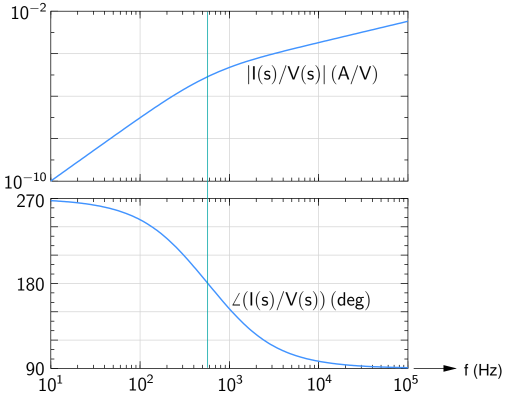

$(R_1 = R_2 = R = 10\,\mathrm{k}$, and $C_1 = C_2 = C_3 = C = 16\,\mathrm{n}F.)$

$$\beta(j\omega) = \frac{I(j\omega)}{V(j\omega)} = \frac{1}{R}\,\frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\,j\omega RC + 1}\,.$$

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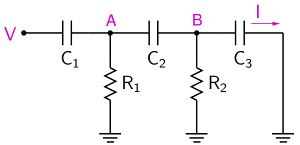

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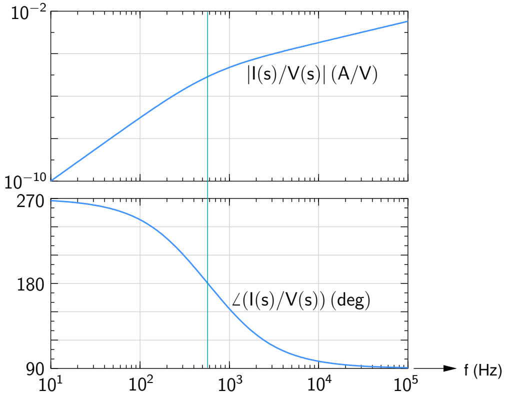

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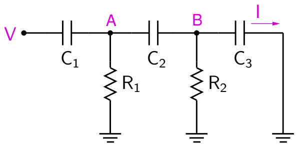
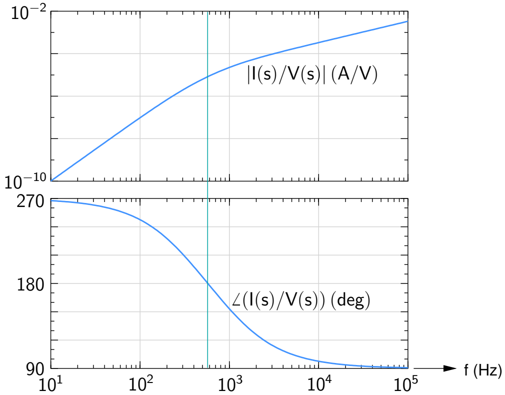
For $\beta(j\omega)$ to be a real number, the denominator must be purely imaginary.

$$\rightarrow -3(\omega RC)^2 + 1 = 0, \text{ i.e., } 3(\omega RC)^2 = 1 \rightarrow \omega \equiv \omega_0 = \frac{1}{\sqrt{3}}\,\frac{1}{RC} \rightarrow f_0 = 574\,\text{Hz}\,.$$

Phase-shift oscillator



SEQUEL file: ee101_osc_4.sqproj



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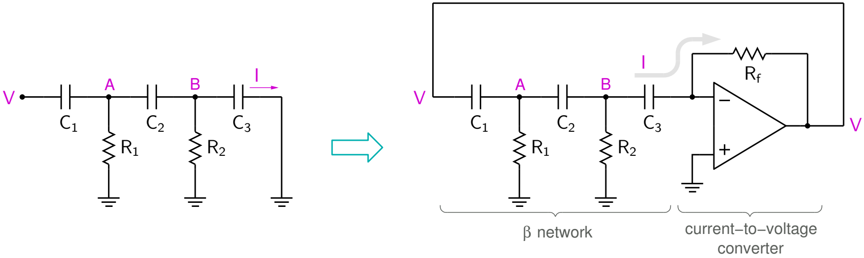
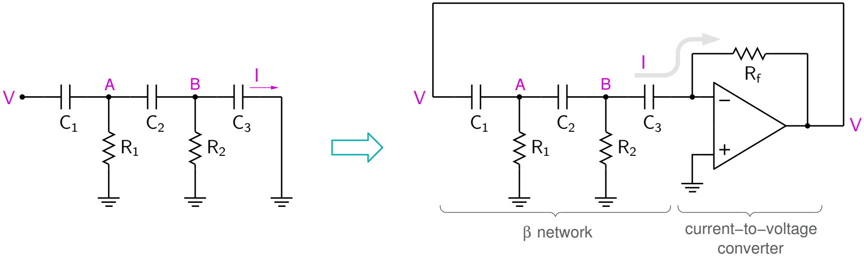
Note that, at $\omega = \omega_0$, $\beta(j\omega_0) = \dfrac{1}{R}\,\dfrac{(j/\sqrt{3})^3}{4\,j/\sqrt{3}} = -\dfrac{1}{12\,R} = -8.33 \times 10^{-6}$.

Phase-shift oscillator



Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the op-amp.

Phase-shift oscillator



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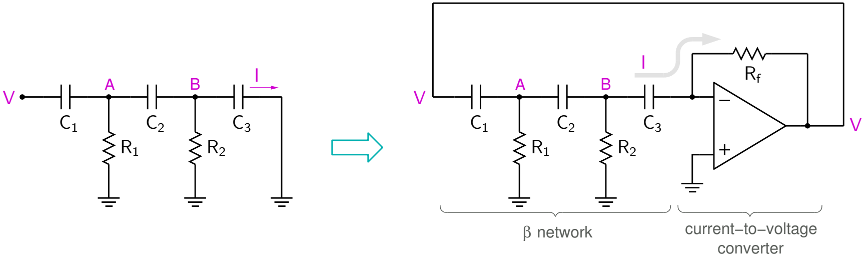
The amplifier gain is $A(j\omega) \equiv \dfrac{V(j\omega)}{I(j\omega)} = \dfrac{0 - R_f I(j\omega)}{I(j\omega)} = -R_f$.

Phase-shift oscillator



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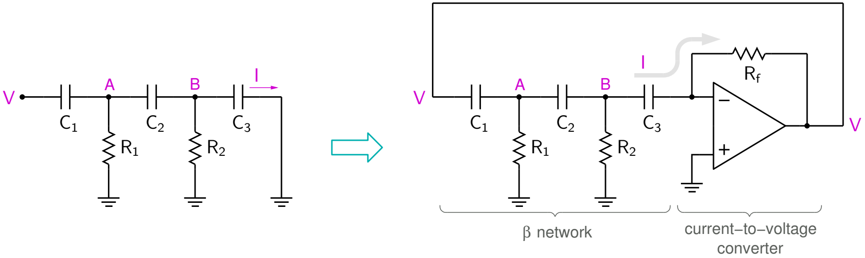

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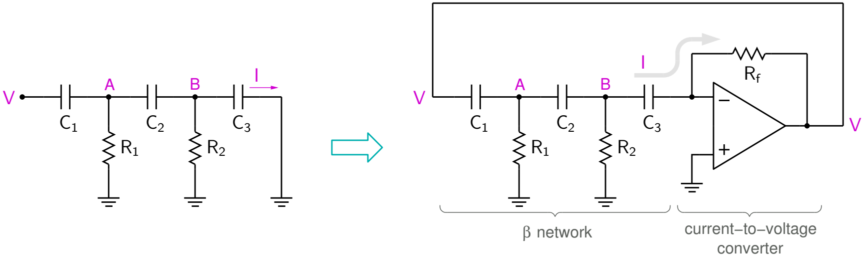
As seen before, at $\rightarrow \omega = \omega_0 = \dfrac{1}{\sqrt{3}}\,\dfrac{1}{RC}$, we have $\dfrac{I(j\omega)}{V(j\omega)} = -\dfrac{1}{12\,R}.$



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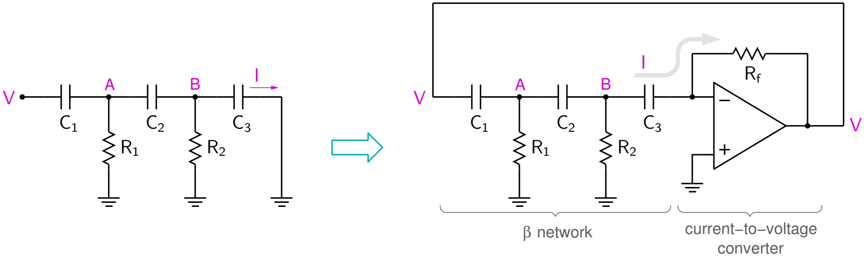
For the circuit to oscillate, we need $A\beta = 1 \rightarrow -R_f\left(-\dfrac{1}{12\,R}\right) = 1$, i.e., $\boxed{R_f = 12\,R}$



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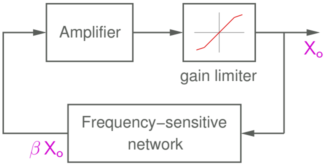
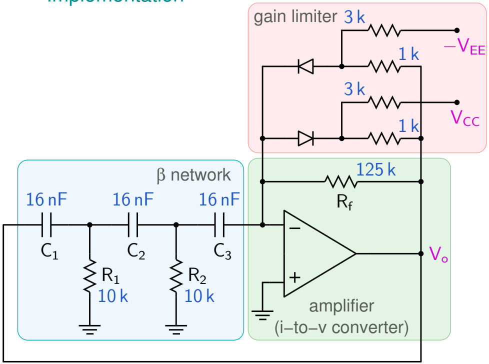
In addition, we employ a gain limiter circuit to complete the oscillator design.

Phase-shift oscillator

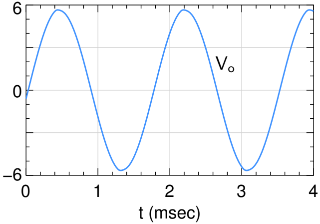
Block diagram



Implementation



Output voltage

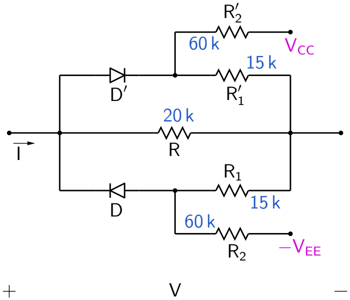


Ref.: Sedra and Smith, "Microelectronic circuits"

SEQUEL file: `ee101_osc_3.sqproj`

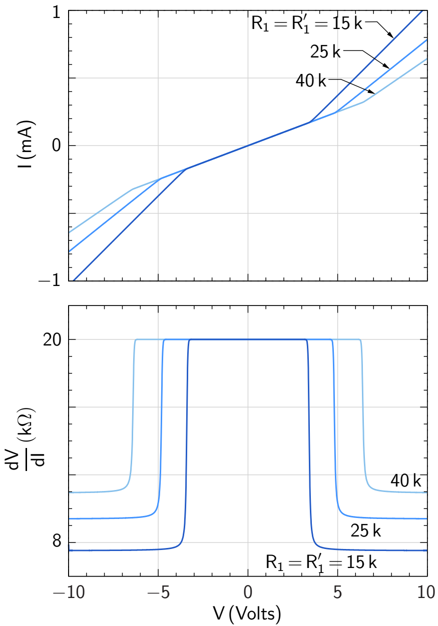
$$\omega_0 = \frac{1}{\sqrt{3}} \frac{1}{RC} \rightarrow f_0 = 574\,\text{Hz}, \quad T = 1.74\,\text{ms}\,.$$

Amplitude control using gain limiting network

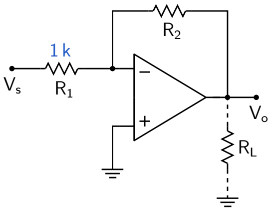


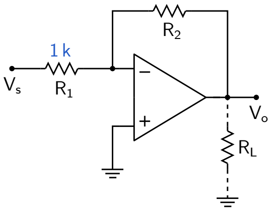
$(V_{CC} = 15\,V)$

SEQUEL file: ee101_diode_circuit_15.sqproj

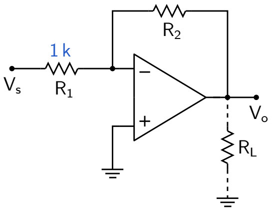


Inverting amplifier, revisited





* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.



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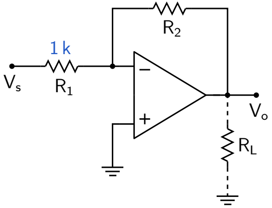
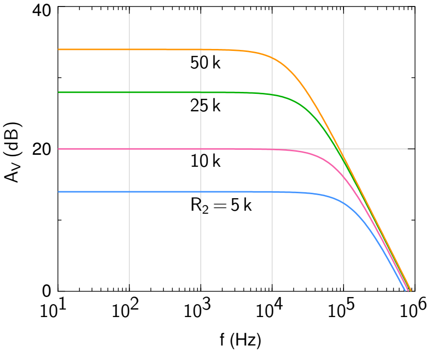
* However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.

Inverting amplifier, revisited



SEQUEL file: `ee101_inv_amp_3.sqproj`



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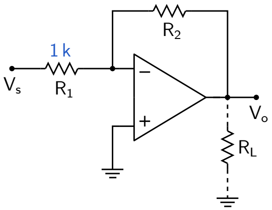
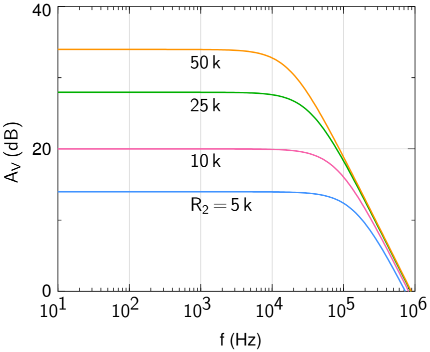


SEQUEL file: `ee101_inv_amp_3.sqproj`



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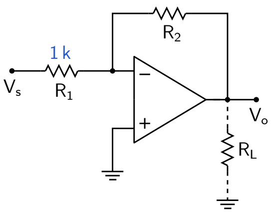
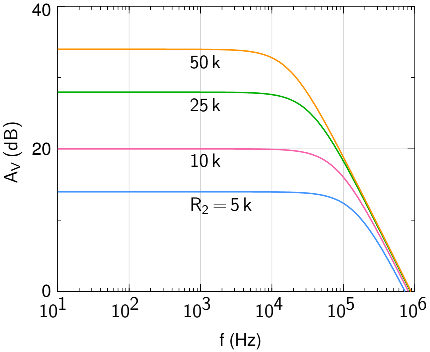


SEQUEL file: `ee101_inv_amp_3.sqproj`



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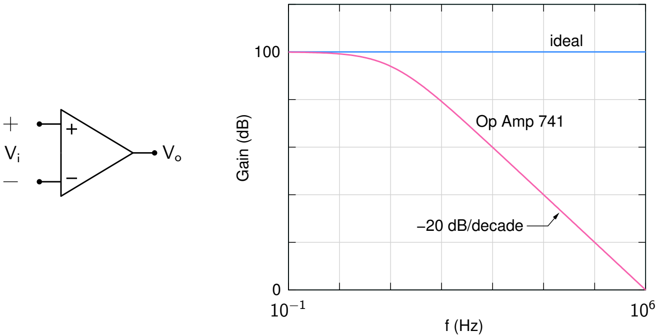
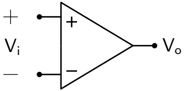
* However, a measurement with a real op-amp will show that $|A_V|$ starts reducing at higher frequencies.
* If $|A_V|$ is increased, the gain "roll-off" starts at lower frequencies.
* This behaviour has to do with the frequency response of the op-amp which we have not considered so far.

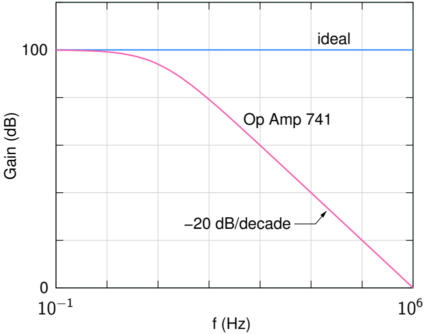
Frequency response of Op-Amp 741



The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

Frequency response of Op-Amp 741





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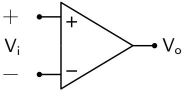
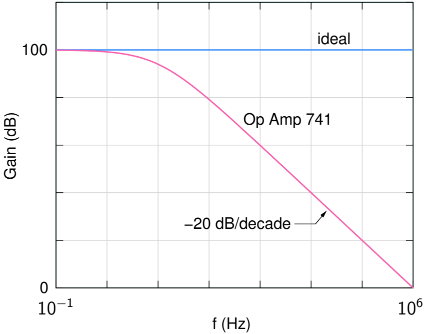
The 741 op-amp (and many others) are *designed* with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).



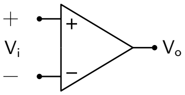


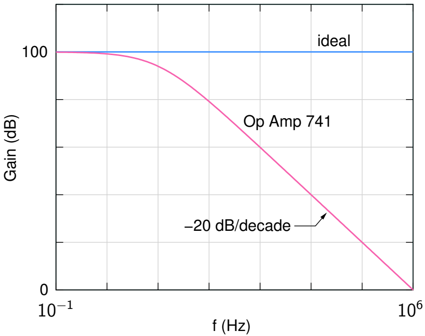
The gain of the 741 op-amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

The 741 op-amp (and many others) are *designed* with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).

In other words, the op-amp has been *internally compensated* for stability.

Frequency response of Op-Amp 741





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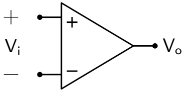
In other words, the op-amp has been *internally compensated* for stability.

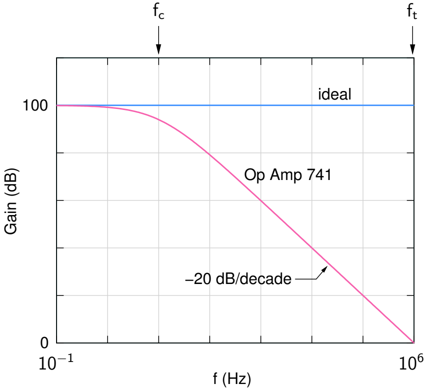
The gain of the 741 op-amp can be represented by,

$$A(s) = \frac{A_0}{1 + s/\omega_c},$$

with $A_0 \approx 10^5$ (i.e., 100 dB), $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

Frequency response of Op-Amp 741

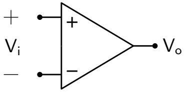


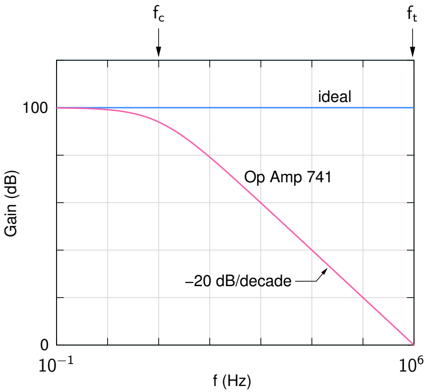


$A(j\omega) = \dfrac{A_0}{1 + j\omega/\omega_c}$, $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

For $\omega \gg \omega_c$, we have $A(j\omega) \approx \dfrac{A_0}{j\omega/\omega_c}$.

Frequency response of Op-Amp 741





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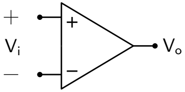
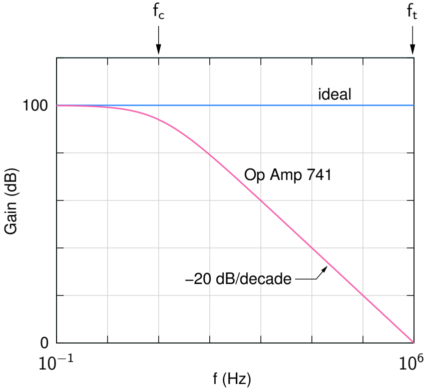
$|A(j\omega)|$ becomes 1 when $A_0 = \omega/\omega_c$, i.e., $\omega = A_0\omega_c$.





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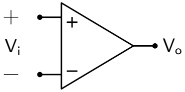
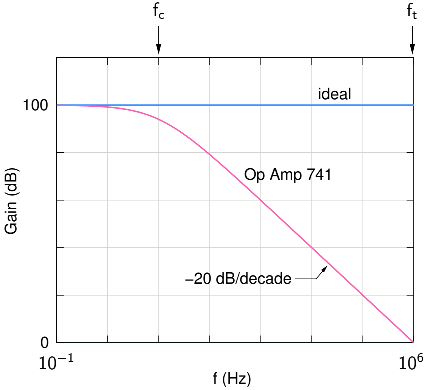
This frequency, $\omega_t = A_0\omega_c$, is called the unity-gain frequency.

For the 741 op-amp, $f_t = A_0 f_c \approx 10^5 \times 10 = 10^6$ Hz.





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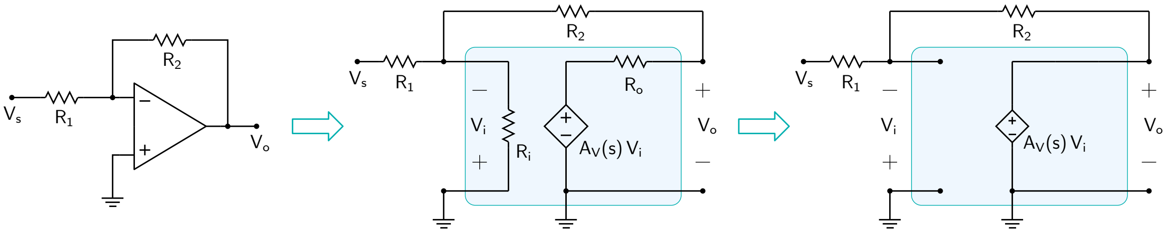
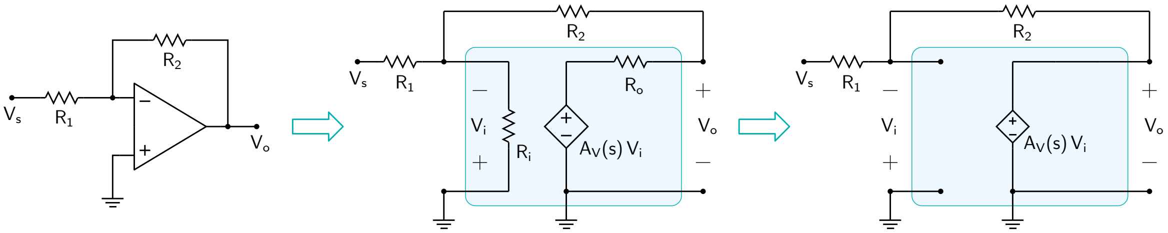
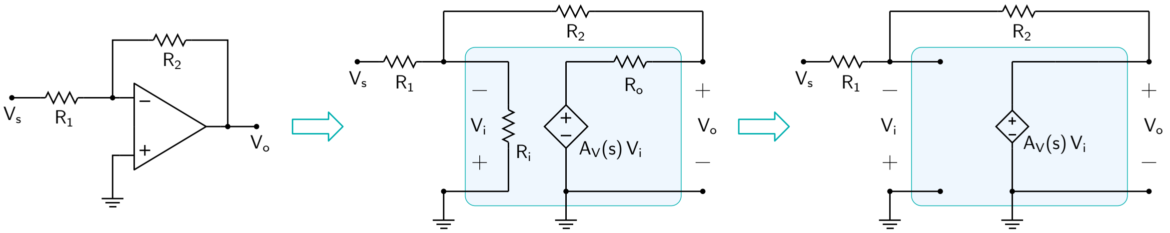
Let us see how the frequency response of the 741 op-amp affects the gain of an inverting amplifier.


V_s
R_1
R_2
V_o
R_i
R_o
V_i
$A_V(s)\,V_i$



Assuming R_i to be large and R_o to be small, we get

$$-V_i(s) = V_s(s)\,\frac{R_2}{R_1+R_2} + V_o(s)\,\frac{R_1}{R_1+R_2}\,.$$



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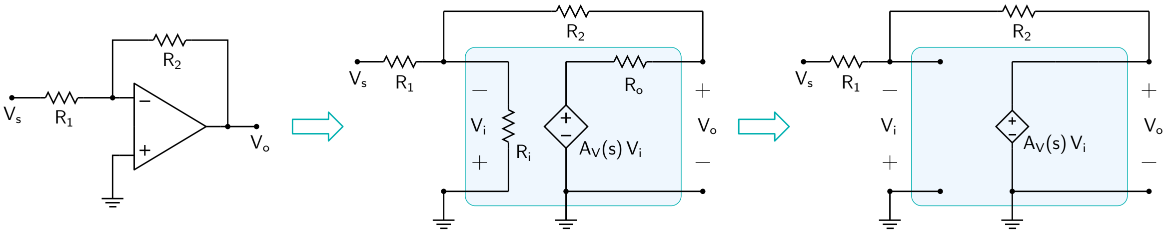
Using $V_o(s) = A_V(s)\,V_i(s)$ and $A_V(s) = \dfrac{A_0}{1+s/\omega_c}$, we get

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{\left[1+\left(\dfrac{R_1+R_2}{R_1}\right)\dfrac{1}{A_0}\right]+\left(\dfrac{R_1+R_2}{R_1 A_0}\right)\dfrac{s}{\omega_c}}$$

Inverting amplifier, revisited



Assuming R_i to be large and R_o to be small, we get

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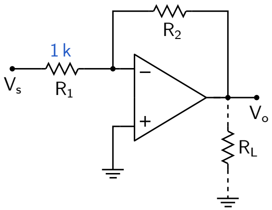
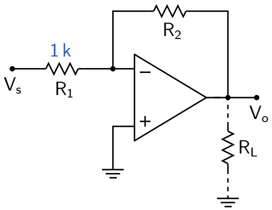
$$\approx -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'}, \quad \text{with } \omega_c' = \frac{\omega_c A_0}{1+R_2/R_1} = \frac{\omega_t}{1+R_2/R_1}.$$

Inverting amplifier, revisited



SEQUEL file: `ee101_inv_amp_3.sqproj`



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$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

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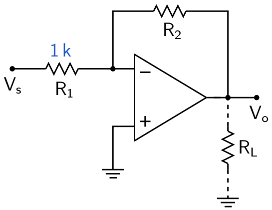

R_2	gain (dB)	f_c' (kHz)
5 k	14	167

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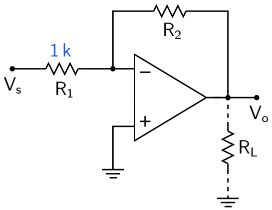

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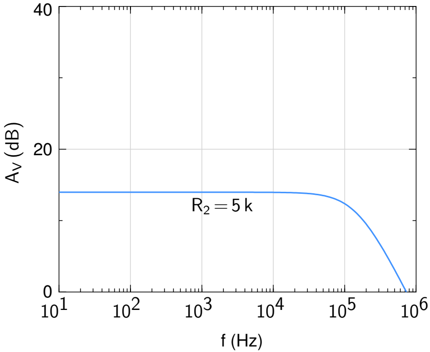

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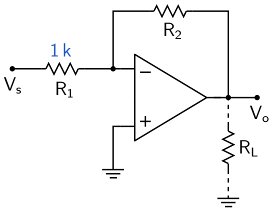

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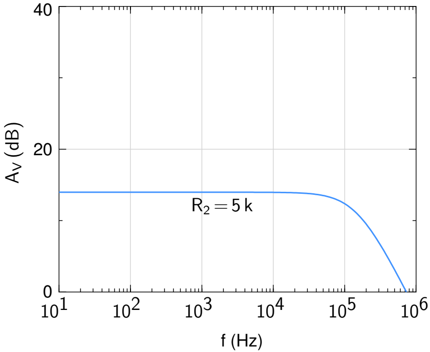
R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91



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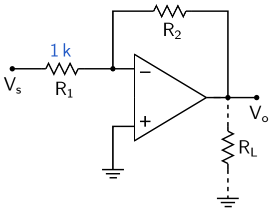

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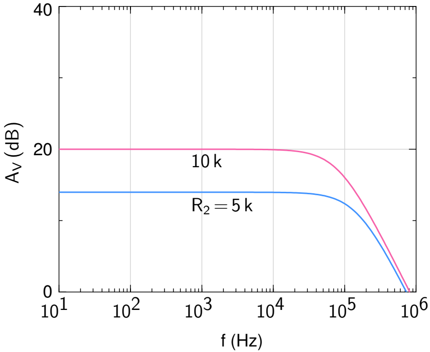

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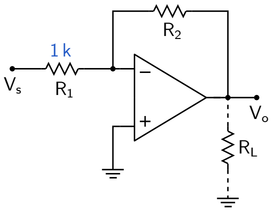
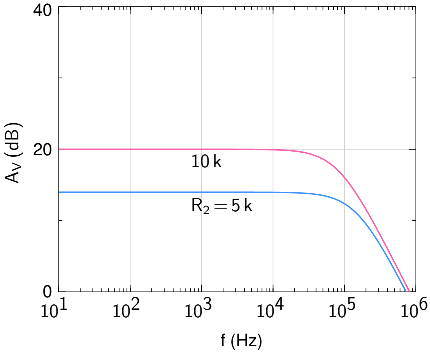


R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38



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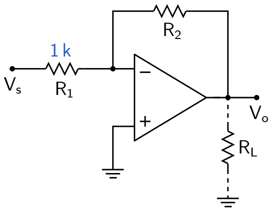

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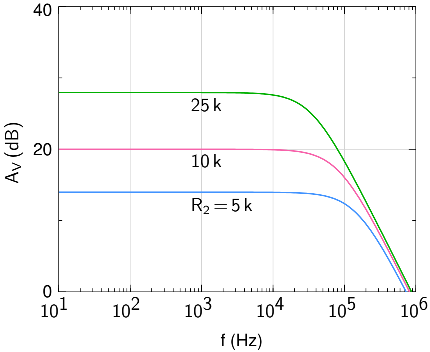

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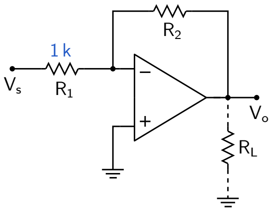

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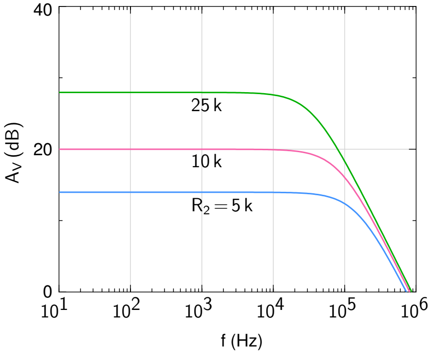
50 k	34	19.6



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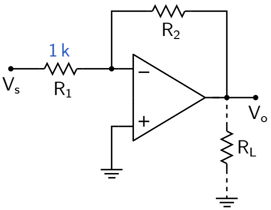

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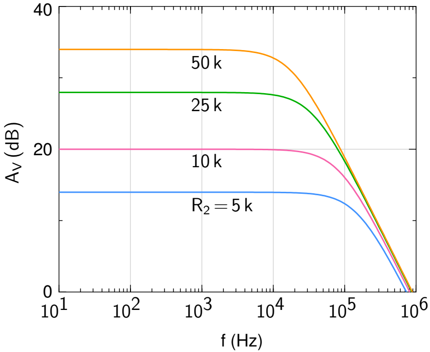

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