Introduction to Frequency Selective Circuits

- We wish to analyze the effect of changing frequency on circuit voltages and currents

  → which leads to the frequency response of a circuit.

Note that ;

- Varying the frequency of a sinusoidal source

  → alters the impedance of capacitors and inductors because their impedances are functions of frequency.

Therefore ;

- Choosing appropriate values for the circuit elements and their connections to other elements

  → allows us to construct circuits that pass to the output only those input signals that reside in a desired range of frequencies.

- Such circuits are called "frequency selective circuits"

  → often used by phones, radios, televisions and satellites.

- Also referred to as filters

  → due to their ability to filter out certain input signals on the basis of frequency.

- No practical filter can filter out selected frequencies

  → they can only attenuate any input signals with frequencies outside a particular frequency band.

Some preliminaries

- The transfer function of a circuit provides an easy way

  → to compute the steady-state response to a sinusoidal input.

- To study the frequency response of a circuit,

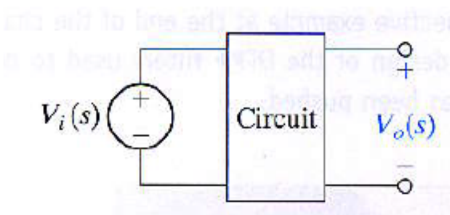
  → we replace a fixed-frequency sinusoidal source with a varying-frequency sinusoidal source.

- The transfer function is still useful

  ↳ because the magnitude and phase of the output signal depend only on the magnitude and phase of the transfer function $H(j\omega)$

- Consider the following circuit in which

  ↳ both the input and output signals are sinusoidal voltages.



$$\Rightarrow \quad H(s) = \frac{V_0(s)}{V_i(s)} \quad \text{"transfer function"}$$

Some terminology

Passband ⇒ a band of frequencies such that the signals passed from the input to the output fall within.

Stopband ⇒ the frequencies which are NOT in a circuit's passband.

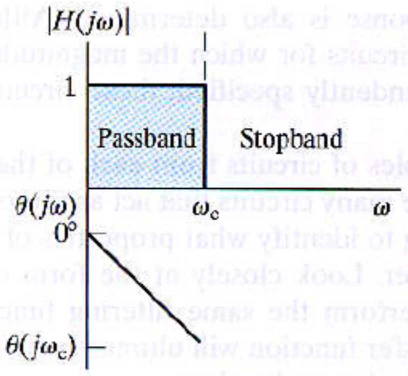
Frequency response plot ⇒ shows how a circuit's transfer function changes wrt source frequency.

Magnitude plot, $|H(j\omega)|$ | phase angle plot, $\theta(j\omega)$

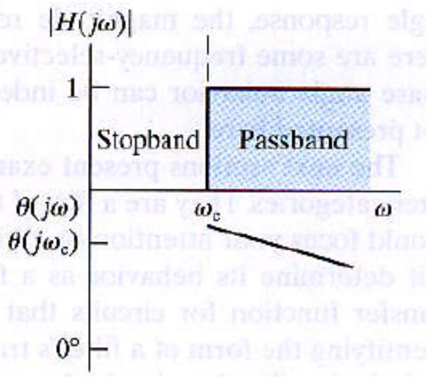
Major categories of filters

1. Low pass
2. High pass
3. Band pass
4. Band reject

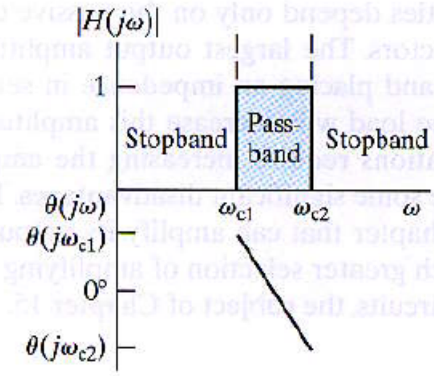
- The ideal plots of these filters are shown as :



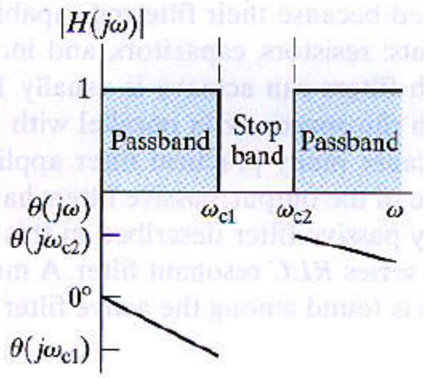
Low pass filter



High pass filter



Band pass filter



Band reject filter

cutoff frequency

- The frequency that seperates the passband and stopband.
- All of these filters we will consider are passive filters

  → their filtering capabilities depend on the passive elements.

- The largest output amplitude such filters can achieve is usually 1

  → which is a significant disadvantage of the passive filters.

Because ;

- Many practical filter applications require increasing the amplitude of the output

  → leading to the use of active filters.

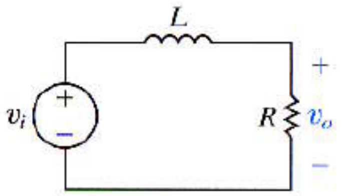
Low pass filters

- We investigate two filters that behave as low-pass filters

  → series RL and series RC circuit.

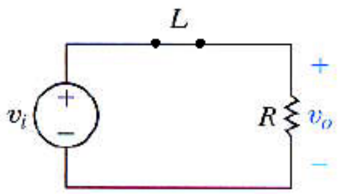
Series RL circuit-qualitative analysis

- We consider



- At low frequencies, the inductor's impedance is very small compared with the resistor's impedance

  i.e. the inductor effectively functions as a short-circuit.

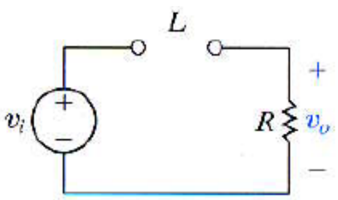


$\omega L \ll R$ $\Rightarrow$

- The output voltage and input voltage are equal both in magnitude and in phase angle.

- At high frequencies, the inductor's impedance is very large compared with the resistor's impedance

  i.e. the inductor functions as an open-circuit.



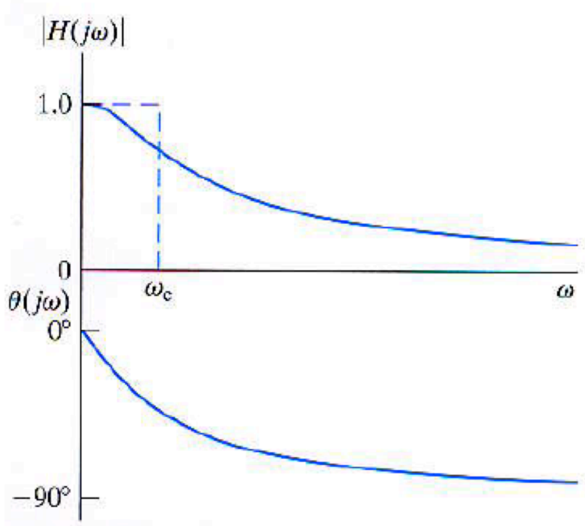
$\omega L \ll R$ $\Rightarrow$

- The phase angle of the output voltage is 90° more negative than that of the input voltage.

Hence ;

- This series RL circuit selectively passes low-frequency inputs to the output

  and blocks high-frequency inputs from reaching the output.



Note that ;

- Circuits acting as low-pass filters have a magnitude response

  that changes gradually from the passband to the stopband.

Defining the cutoff frequency

- The frequency for which the transfer function magnitude is decreased by the factor $1/\sqrt{2}$ from its maximum value :

$$|H(j\omega_c)| = \frac{1}{\sqrt{2}} H_{max}$$

why "$1/\sqrt{2}$" ?

- Define P_{max} as the value of the average power

  delivered to a load when its voltage is maximum

$$P_{max} = \frac{1}{2}\frac{V_{L_{max}}^2}{R}$$

- If we vary the frequency of the sinusoidal voltage source, $V_i(j\omega)$

  then $V_{L_{max}} = H_{max}|V_i|$

- Now when $\omega = \omega_c$ we have

$$\begin{aligned}|V_L(j\omega_c)| &= |H(j\omega_c)||V_i| \\ &= \frac{1}{\sqrt{2}} H_{max}|V_i| \\ &= \frac{1}{\sqrt{2}} V_{L_{max}}\end{aligned}$$

$$\Rightarrow \quad P(j\omega_c) = \frac{1}{2}\frac{|V_L(j\omega_c)|^2}{R}$$

$$= \frac{1}{2}\frac{\left|\frac{1}{\sqrt{2}} V_{L_{max}}\right|^2}{R} = \frac{P_{max}}{2}$$

Hence ;

- At the cutoff frequency ω_c, the average power delivered by the circuit is

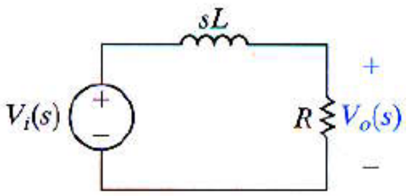
  one half the maximum average power.

- ω_c is also called the half-power frequency

  in the passband, the average power delivered to a load is at least 50% of the maximum average power.

Quantitative analysis

- Consider the s-domain equivalent of the series RL circuit



$$\Rightarrow \quad \frac{V_0(s)}{V_i(s)} = H(s) = \frac{R/L}{s + R/L}$$

- Let $s = j\omega$ for the frequency response

$$H(j\omega) = \frac{R/L}{j\omega + R/L}$$

$$\Rightarrow \quad |H(j\omega)| = \frac{R/L}{\sqrt{\omega^2 + (R/L)^2}} \quad , \quad \theta(j\omega) = -\tan^{-1}\left(\frac{\omega L}{R}\right)$$

$\omega \to \infty \quad \Rightarrow \; |H(j\omega)|$ decreases, $\theta(j\omega)$ becomes more negative.

$\omega \to \infty \quad \Rightarrow \; |H(j\omega)| = 0 \;,\; \theta(j\infty) = -90°$

Moreover ;

$$|H(j\omega_c)| = \frac{1}{\sqrt{2}} H_{max}$$

$$= \frac{1}{\sqrt{2}}.1 = \frac{R/L}{\sqrt{\omega_c^2 + (R/L)^2}} \qquad \begin{aligned} &\Rightarrow \omega_c^2 + \left(\frac{R}{L}\right)^2 = 2\left(\frac{R}{L}\right)^2 \\ &\Rightarrow \omega_c = R/L \end{aligned}$$

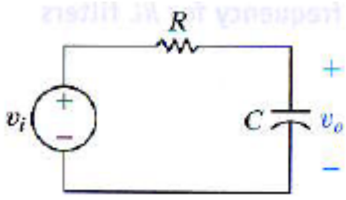
Therefore ;

- We can design a low pass filter

  with whatever cutoff frequency is needed.

A series RC circuit-qualitative analysis

- The following series RC circuit also behaves as a low-pass filter



- We consider three frequency regions

1. Zero frequency, $\omega = 0$: the impedance of the capacitor $\rightarrow \infty$ acting as an open-circuit

   the input and output voltages are same.

2. Increasing frequency, $\omega \uparrow \infty$: the impedance of the capacitor decreases relative to the resistor

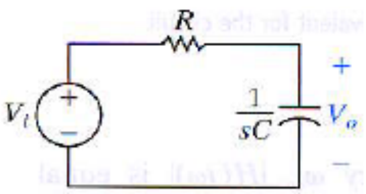
   the output voltage gets smaller than the source voltage.

3. Infinite frequency, $\omega = \infty$: the impedance of the capacitor is zero acting as a short circuit

   the output voltage is thus zero.

Quantitative analysis

- We consider the s-domain equivalent of the series RC circuit



$$\frac{V_0(s)}{V_i(s)} = H(s) = \frac{1/sC}{R + (1/sC)} = \frac{1/RC}{s + (1/RC)}$$

- and substituting $s = j\omega$ gives

$$|H(j\omega_c)| = \frac{1}{\sqrt{2}}\underbrace{|H(j0)|}_{1}$$

$$= \frac{1/RC}{\sqrt{\omega_c^2 + (1/RC)^2}}$$

$$\Rightarrow \omega_c^2 + \left(\frac{1}{RC}\right)^2 = 2\left(\frac{1}{RC}\right)^2$$

$$\Rightarrow \omega_c = \frac{1}{RC}$$

Genereal form of transfer function of low pass filters

- We shall write for both RL and RC low pass filters

$$H(s) = \frac{\omega}{s + \omega_c}$$

- Any circuit with $H(s)$ behaves as a low pass filter having cut off frequency, ω_c

High pass filters

- We consider series RL and RC circuits

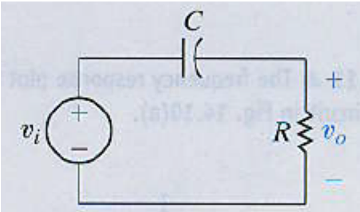
  ⮡ that function as high pass filters.

- The same circuit can act as either a low-pass or a high-pass filter

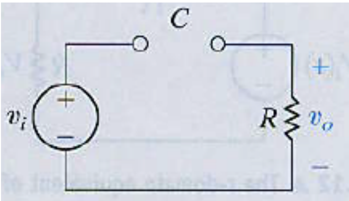
  ⮡ depending on where the output voltage is defined.

The series RC circuit-qualitative analysis

- We consider



1. At $\omega = 0$: the capacitor behaves like an open-circuit.



$\Rightarrow$

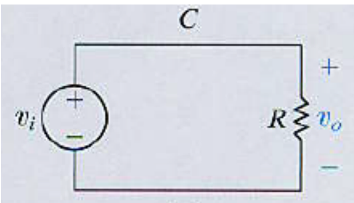
- no voltage drop across the resistor

  ⮡ filtering out the low-frequency source voltage.

2. Increasing frequency, $\omega \uparrow$: the impedance of the capacitor decreases relative to the resistor

   ⮡ the output voltage starts to increase.

3. When $\omega = \infty$: the capacitor behaves like a short-circuit



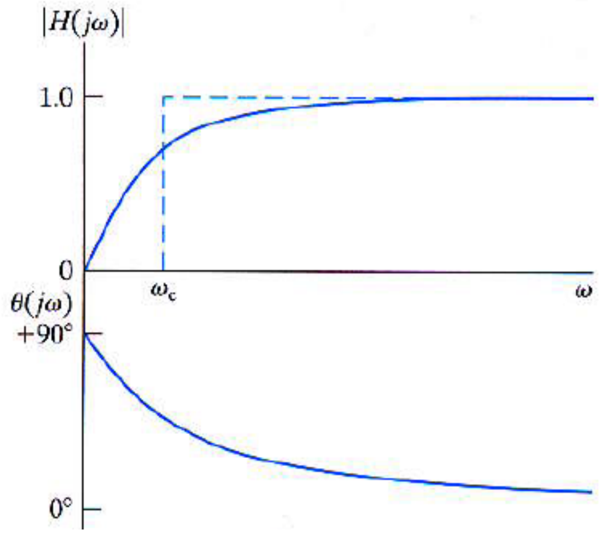
$\Rightarrow$

- no voltage across the capacitor

  ⮡ the output voltage is the same as input voltage.

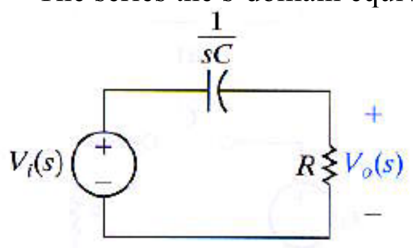
Phase angle difference

- For $\omega = \infty$, phase angle difference is zero.
- As ω decreases, the phase angle difference between the source and output voltages increases.
- When $\omega = 0$, this phase angle difference reaches its maximum of $+90°$



The series RC circuit-quantitative analysis

- The series the s-domain equivalent of series RC circuit



$$\Rightarrow \quad \frac{V_0(s)}{V_i(s)} = H(s) = \frac{R}{R + \frac{1}{sC}} = \frac{s}{s + \left(\frac{1}{RC}\right)}$$

- and letting $s = j\omega$ gives

$$H(j\omega) = \frac{j\omega}{j\omega + (1/RC)}$$

$$\Rightarrow \quad |H(j\omega)| = \frac{\omega}{\sqrt{\omega^2 + (1/RC)^2}} \quad , \quad \theta(j\omega) = 90° - \tan^{-1} \omega RC$$

$$H_{max} = |H(j\infty)| = 1$$

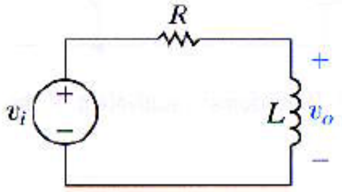
$$\Rightarrow \quad |H(j\omega_c)| = \frac{1}{\sqrt{2}}.1$$

$$= \frac{\omega_c}{\sqrt{\omega_c^2 + (1/RC)^2}} \qquad \Rightarrow 2\omega_c^2 = \omega_c^2 + (1/RC)^2$$

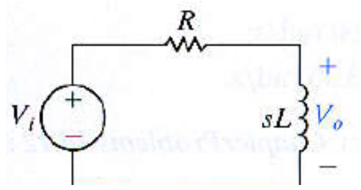
$$\Rightarrow \omega_c = 1/RC$$

A series RL high-pass filter

- We consider



$\Rightarrow$



$$\frac{V_0(s)}{V_i(s)} = H(s) = \frac{sL}{R + sL} = \frac{s}{s + (R/L)}$$

$$\Rightarrow \quad H(j\omega) = \frac{j\omega}{j\omega + (R/L)} \qquad \Rightarrow \qquad |H(j\omega)| = \frac{\omega}{\sqrt{\omega^2 + (R/L)^2}} \ , \qquad \theta(j\omega) = 90° - \tan^{-1}\frac{wL}{R}$$

$$H_{max} = |H(j\infty) = 1|$$

$$\Rightarrow \frac{1}{\sqrt{2}}.1 = \underbrace{\frac{\omega_c}{\sqrt{\omega_c^2 + (R/L)^2}}}_{|H(j\omega_c)|} \qquad \Rightarrow \qquad \omega_c = \frac{R}{L}$$

same as the cutoff frequency for the series RL low-pass filter.

General form of a high-pass filter transfer function

- We shall represent $H(s)$ as

$$H(s) = \frac{s}{s + \omega_c}$$

- Any circuit with the above $H(s)$ acts like a high-pass filter

having the cut-off frequency, ω_c

Bandpass filters

- Pass voltages within a band of frequencies to the output

while filtering out voltages at frequencies outside this band.

- Ideal bandpass filters have two cutoff frequencies, ω_{c_1} and ω_{c_2}

which identify the passband.

Center frequency, ω_0

- Defined as the frequency for which a circuit's transfer function is purely real

so called as "resonant frequency".

- Calculated as

$$\omega_0 = \sqrt{\omega_{c_1}\omega_{c_2}}$$

- The magnitude of the transfer function is maximum at the center frequency

$$H_{max} = |H(j\omega_0)|$$

Bandwidth, β

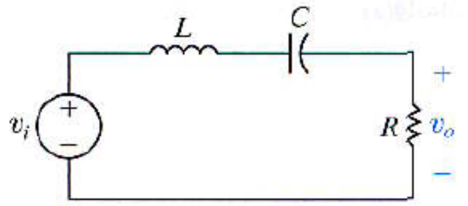
- Described as the width of the passband.

Quality factor

- Defined as the ratio of the center frequency to the bandwidth.

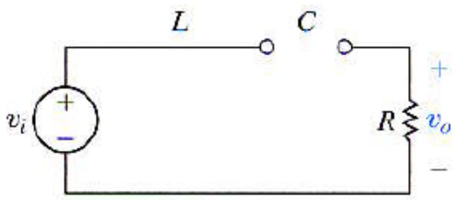
The series RLC circuit-qualitative analysis

- Depicted as



1. At $\omega = 0$, the capacitor behaves like an open circuit

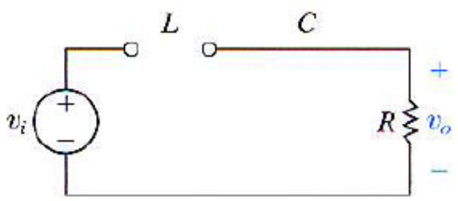
   and the inductor behaves like a short circuit.



$\Rightarrow$ the resulting output voltage is zero.

2. At $\omega = \infty$, the capacitor behaves like a short circuit,

   and the inductor behaves like n open circuit.



$\Rightarrow$ the output voltage is again zero.

3. $0 < \omega < \infty$, both the capacitor and inductor have finite impedances

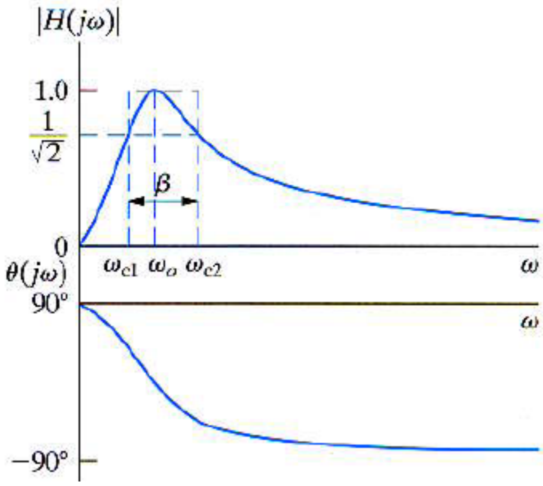
   some voltage will be reach the resistor.

- At some frequency, the impedance of the capacitor and that of inductor cancel out each other

  ↳ the output voltage becomes equal to the source voltage.

Hence ;

- We have



Phase angle difference

- At $\omega = \omega_0$, phase angle difference is zero.

- As the frequency decreases, the phase angle contribution from the capacitor is larger than that of inductor

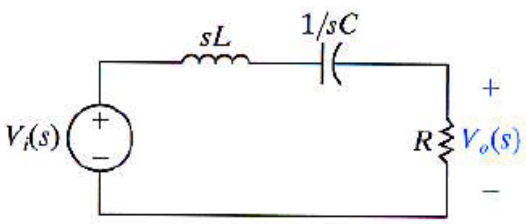
  ↳ the net phase angle is positive approaching to $+90°$

- If the frequency increases from ω_0, then the phase angle contribution of the inductor dominates that of capacitor

  ↳ the net phase angle is negative reaching to $-90°$

Quantitative analysis

- We first draw the s-domain equivalent



$$\Rightarrow \quad \frac{V_0(s)}{V_i(s)} = H(s) = \frac{(R/L)s}{s^2 + (R/L)s + (1/LC)}$$

- Substituting $s = j\omega$ gives

$$|H(j\omega)| = \frac{\omega(R/L)}{\sqrt{[(1/LC) - \omega^2]^2 + [\omega(R/L)]^2}}$$

$$\theta(j\omega) = 90° - \tan^{-1}\left[\frac{\omega(R/L)}{(1/LC) - \omega^2}\right]$$

Calculating the filter characteristics

- For the center frequency, ω_0 , we have

$$j\omega_0 L + \frac{1}{j\omega_0 L} = 0$$

$$\Rightarrow \qquad \omega_0 = \sqrt{\frac{1}{LC}}$$

- Then for the cutoff frequencies

$$H_{max} = |H(j\omega_0)|$$

$$= \frac{\omega_0(R/L)}{\sqrt{[(1/LC) - \omega_0^2] + [\omega_0(R/L)]^2}}$$

$$= 1$$

$$\Rightarrow \quad \frac{1}{\sqrt{2}} = \frac{\omega_c(R/L)}{\sqrt{[(1/LC) - \omega_c^2]^2 + (\omega_c R/L)^2}}$$

$$= \frac{1}{\sqrt{[(\omega_c L/R) - (1/\omega_c RC)]^2 + 1}}$$

$$\Rightarrow \ \pm 1 = \omega_c \frac{L}{R} - \frac{1}{\omega_c RC}$$

$$\Rightarrow \quad \omega_c^2 L \pm \omega_c R - 1/C = 0$$

$$\omega_{c_1} = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \left(\frac{1}{LC}\right)}$$

$$\omega_{c_2} = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \left(\frac{1}{LC}\right)}$$

- The bandwidth is calculated as

$$\beta = \omega_{c_2} - \omega_{c_1}$$

$$= \frac{R}{L}$$

- and finally the quality factor is computed as

$$Q = \omega_0/\beta$$

$$= \frac{\sqrt{1/LC}}{R/L}$$

$$= \sqrt{\frac{L}{CR^2}}$$

Alternative forms of these characteristics

$$\omega_{c_1} = -\frac{\beta}{2} + \sqrt{\left(\frac{\beta}{2}\right)^2 + \omega_0^2}$$

$$\omega_{c_2} = \frac{\beta}{2} + \sqrt{\left(\frac{\beta}{2}\right)^2 + \omega_0^2}$$

OR

$$\omega_{c_1} = \omega_0 \left[-\frac{1}{2Q} + \sqrt{1 + \left(\frac{1}{2Q}\right)^2} \right]$$

$$\omega_{c_2} = \omega_0 \left[\frac{1}{2Q} + \sqrt{1 + \left(\frac{1}{2Q}\right)^2} \right]$$

Note that ;

- only two of the parameters (β, ω_0, Q) are sufficient

  ↳ to design the filter independently.

General form of a bandpass filter transfer function

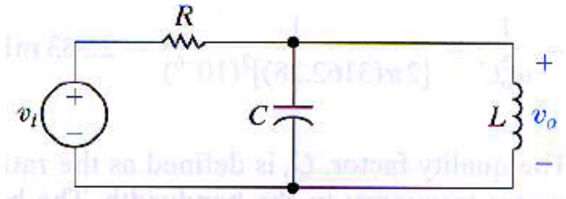
- Can be represented as

$$H(s) = \frac{\beta s}{s^2 + \beta s + \omega_0^2}$$

- Thus any circuit with the transfer function $H(s)$

  ↳ acts as a bandpass filter with a center frequency, ω_0 and a bandwidth, β

Example. Consider the following RLC circuit



a. Show that this circuit is also a bandpass filter by deriving an expression for $H(s)$.

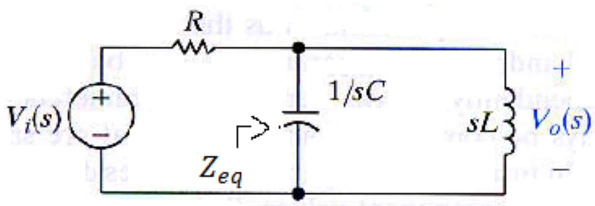
b. Compute the center frequency, ω_0.

c. Calculate the cutoff frequencies, ω_{c_1} and ω_{c_2}, the bandwidth, β and the quality factor, Q.

d. Compute the values for R and L to yield a bandpass filter with a center frequency of 5kHz and a bandwidth of 200Hz using a $5\mu F$ capacitor.

Solution.

- We first draw the s-domain equivalent



$$Z_{eq} = \frac{(1/sC)sL}{sL + \frac{1}{sC}} = \frac{L/C}{sL + \frac{1}{sC}}$$

- and

a.

$$\frac{V_0(s)}{V_i(s)} = \frac{\frac{L/C}{sL + (1/sC)}}{R + \frac{L/C}{sL + (1/sC)}} = \frac{L/C}{sRL + \frac{R}{sC} + \frac{L}{C}}$$

$$= \frac{sL}{s^2RLC + R + sL} = \frac{s/RC}{s^2 + \frac{s}{RC} + \frac{1}{LC}}$$

b. We need to calculate where the transfer function magnitude is maximum

$$|H(j\omega)| = \frac{\frac{\omega}{RC}}{\sqrt{\left(\frac{1}{LC} - \omega^2\right)^2 + \left(\frac{\omega}{RC}\right)^2}}$$

$$= \frac{1}{\sqrt{1 + \underbrace{\left(\omega RC - \frac{1}{\omega \frac{L}{R}}\right)}_{=0}^{2}}} \qquad \Rightarrow \qquad \omega_0 = \sqrt{\frac{1}{LC}}$$

- and

$$H_{max} = |H(j\omega_0| = 1$$

c. At the cutoff frequencies, $|H(j\omega_c| = \frac{1}{\sqrt{2}}$

$$\Rightarrow \quad \left(\omega_c RC - \frac{1}{\omega_c \frac{L}{R}}\right)^2 = 1$$

$$\Rightarrow \quad \omega_c RC - \frac{1}{\omega_c \frac{L}{R}} = \pm 1 \qquad \begin{cases} \omega_{c_1} = -\frac{1}{2RC} + \sqrt{\left(\frac{1}{2RC}\right)^2 + \frac{1}{LC}} \\ \omega_{c_2} = \frac{1}{2RC} + \sqrt{\left(\frac{1}{2RC}\right)^2 + \frac{1}{LC}} \end{cases}$$

d. We have

$$\beta = \omega_{c_1} - \omega_{c_2} = \frac{1}{RC} \qquad \Rightarrow \qquad R = \frac{1}{\beta C} = \frac{1}{(2\pi)(200)5.10^{-6}} = 159.15\ \Omega$$

$$L = \frac{1}{\omega_0^2 C} = \frac{1}{[(2\pi).5000]^2.5.10^{-6}} = 202.64\ \mu H$$

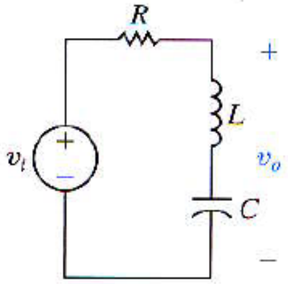
Bandreject filters

- The filter passes source voltages outside the band between the two cutoff frequencies to the output.
- Characterized by the same five parameters as bandpass filters

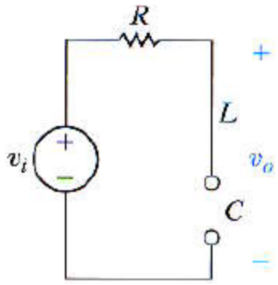
  ⮡ only two of these five parameters can be specified independently.

The series RLC circuit-qualitative analysis

- We consider the following circuit

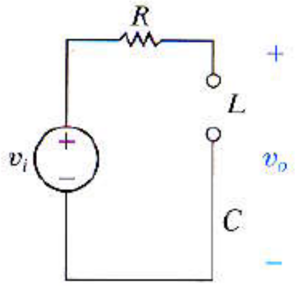


1. At $\omega = 0$, the inductor behaves like a short circuit and a capacitor acts as an open circuit.



$\Rightarrow$ output voltage is same as the input voltage.

2. At $\omega = \infty$, the roles of inductor and capacitor switch



$\Rightarrow$ output and input voltages have the same magnitude.

- This series RLC circuit has two passbands

  one below a lower cutoff frequency and the other above an upper cutoff frequency.

phase angle difference

- As the frequency is increased from zero

  the impedance of the inductor increases and that of the capacitor decreases.

- The phase shift between input and output approaches $-90°$

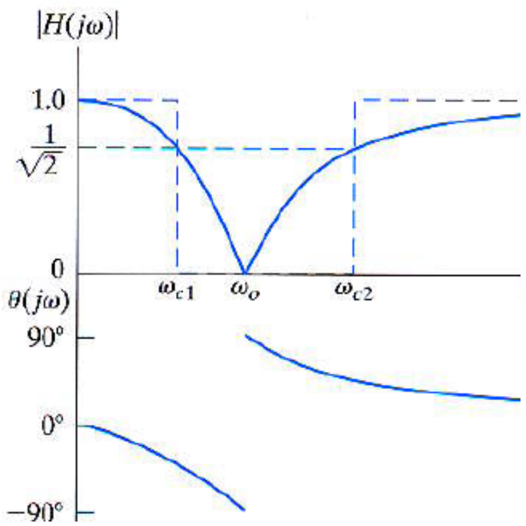
  as ωL approaches $1/\omega C$

- As ωL exceeds $1/\omega C$, the phase shift jumps to $+90°$

  then approaches zero as ω continues to increase.

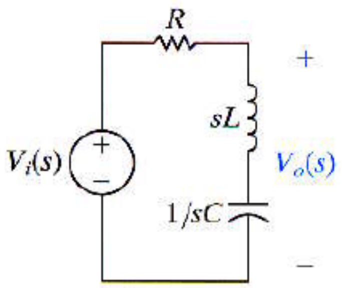
- At some frequency the impedances of inductor and capacitor are equal but of opposite sign.

  the output voltage is just zero at this center frequency.



Quantitative analysis

- We take into account the s-domain equivalent of the series RLC circuit



$$V_0(s) \Rightarrow \frac{V_0(s)}{V_i(s)} = H(s) = \frac{sL + \frac{1}{sC}}{R + sL + \frac{1}{sC}} = \frac{s^2 + \frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

- Substituting $s = j\omega$ gives

$$|H(j\omega)| = \frac{\left|\frac{1}{LC} - \omega^2\right|}{\sqrt{\left(\frac{1}{LC} - \omega^2\right)^2 + \left(\frac{\omega R}{L}\right)^2}}$$

$$\theta(j\omega) = -\tan^{-1}\left(\frac{\omega \frac{R}{L}}{\frac{1}{LC} - \omega^2}\right)$$

- For the center frequency, we have

$$j\omega_0 L + \frac{1}{j\omega_0 C} = 0 \qquad \Rightarrow \qquad \omega_0 = \sqrt{\frac{1}{LC}}$$

- At the center frequency, $|H(j\omega_0)| = 0$
- For the cutoff frequencies, we have

$$\frac{1}{\sqrt{2}} = \frac{\left|\frac{1}{LC} - \omega_c^2\right|}{\sqrt{\left(\frac{1}{LC} - \omega_c^2\right)^2 + \left(\frac{\omega_c R}{L}\right)^2}}$$

$$\omega_{c_1} = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$\omega_{c_2} = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

- and the bandwidth is

$$\beta = \omega_{c_2} - \omega_{c_1} = \frac{R}{L}$$

- and the quality factor is

$$Q = \sqrt{\frac{L}{R^2 C}}$$

- As an alternative representation we obtain

$$\omega_{c_1} = -\frac{\beta}{2} + \sqrt{\left(\frac{\beta}{2}\right)^2 + \omega_0^2}$$

$$\omega_{c_2} = \frac{\beta}{2} + \sqrt{\left(\frac{\beta}{2}\right)^2 + \omega_0^2}$$

OR

$$\omega_{c_1} = \omega_0 \left[-\frac{1}{2Q} + \sqrt{1 + \left(\frac{1}{2Q}\right)^2}\right]$$

$$\omega_{c_2} = \omega_0 \left[\frac{1}{2Q} + \sqrt{1 + \left(\frac{1}{2Q}\right)^2}\right]$$

Example. Using the series RLC circuit, compute the component values that yield a bandreject filter with a bandwidth of 250 Hz and a center frequency of 750 Hz. Use a 100 nF capacitor. Compute values for $R, L, \omega_{c_1}, \omega_{c_2}$ and Q.

Solution. We calculate

$$Q = \frac{\omega_0}{\beta} = \frac{750}{250} = 3$$

$$\Rightarrow \qquad L = \frac{1}{\omega_0^2 C} = \frac{1}{(2\pi.750)^2.100.10^{-9}} = 450\ mH$$

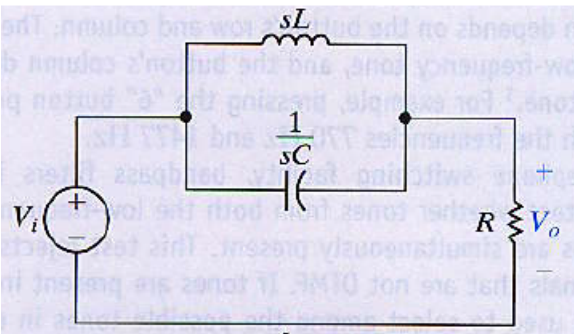
$$\Rightarrow \qquad R = \beta L = 2\pi.250.(450.10^{-3}) = 707\ \Omega$$

$$\omega_{c_1} = -\frac{2\pi.250}{2} + \sqrt{\left(\frac{2\pi.250}{2}\right)^2 + (2\pi.750)^2} = 3992.0\ rad/s \quad \rightarrow \quad 653.3\ Hz$$

$$\omega_{c_2} = \frac{2\pi.250}{2} + \sqrt{\left(\frac{2\pi.250}{2}\right)^2 + (2\pi.750)^2} = 5562.8\ rad/s \quad \rightarrow \quad 885.3\ Hz$$

General form of a band reject filter transfer function

- A parallel RLC circuit also acts as a bandreject filter



$$H(s) = \frac{s^2 + 1/LC}{s^2 + s/RC + 1/LC} \quad , \quad \omega_0 = \sqrt{1/LC} \quad , \quad \beta = 1/RC$$

- We can state a general form of the transfer function of bandreject filters

$$H(s) = \frac{s^2 + \omega_0^2}{s^2 + \beta s + \omega_0^2}$$

Hence ;

- any circuit with the above transfer function

   can be used as a bandreject filter.