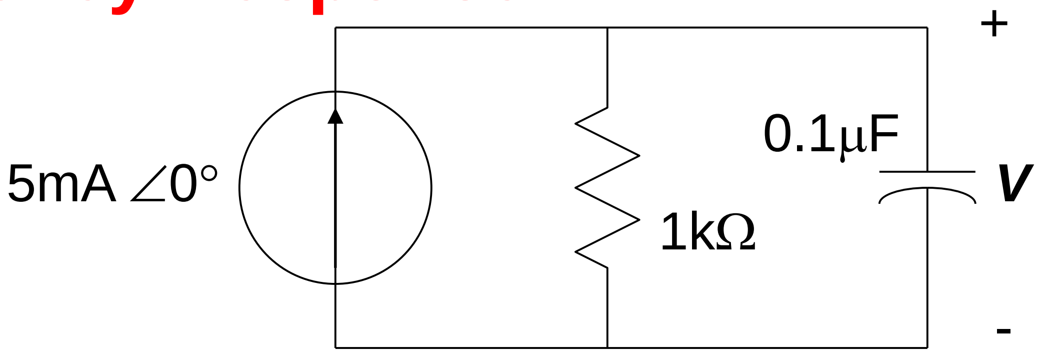
Lecture 12

- Frequency Response

Outline

- Frequency response
- Transfer function
- Bode plots (or diagram)
- Resonance

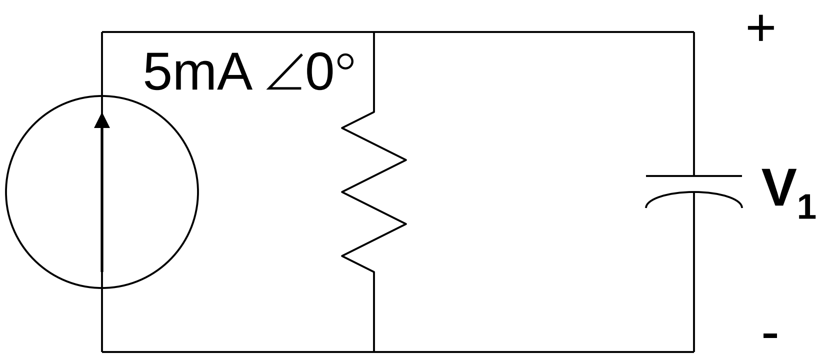
Frequency Response

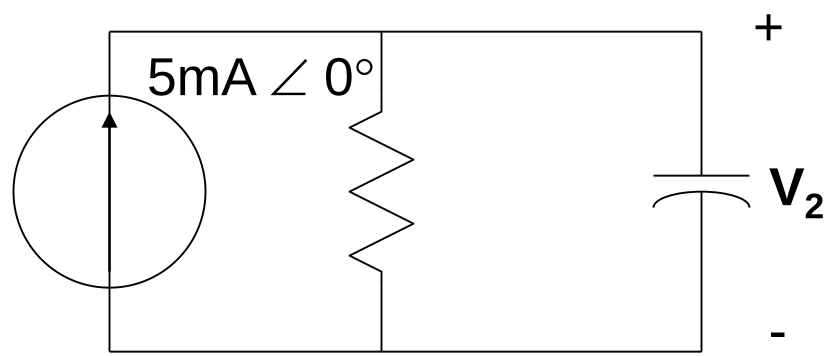


Find $v(t)$

Case 1: $\omega = 2\pi \times 3000$

Case 2: $\omega = 2\pi \times 455000$





$$\mathbf{Z}_{eq} = 468.2\angle -62.1°\Omega$$

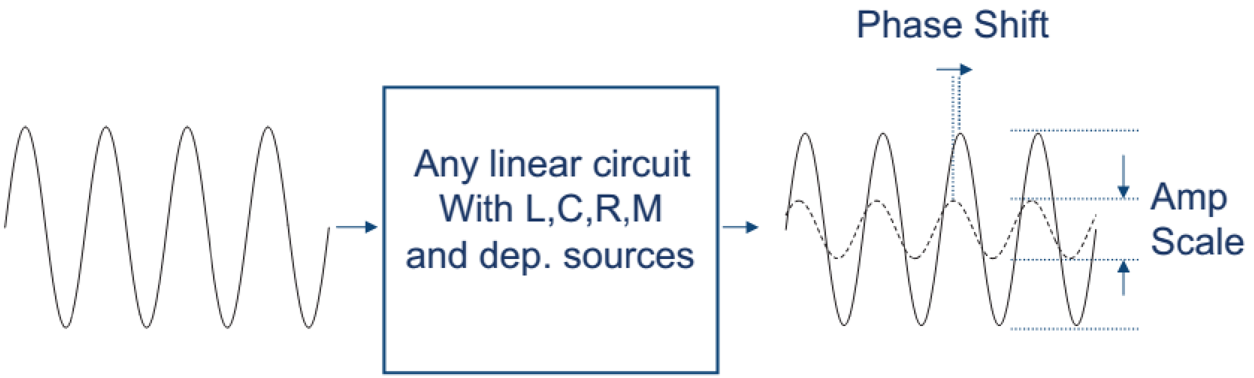
$$\mathbf{V}_1 = 2.34\angle -62.1°\text{V}$$

$$\mathbf{Z}_{eq} = 3.5\angle -89.8°\Omega$$

$$\mathbf{V}_2 = 17.5\angle -89.8°\text{mV}$$

[Source: Berkeley]

Frequency Response



- When a linear, time invariant (LTI) circuit is excited by a sinusoid, it's output is a sinusoid at the *same* frequency.
  - Only the magnitude and phase of the output differ from the input.
- The "Frequency Response" is a characterization of the input-output response for sinusoidal inputs at all frequencies.
  - Significant for applications, esp. in communications and control systems.

[Source: Berkeley]

Outline

- Frequency response
- Transfer function
- Bode plots (or diagram)
- Resonance

Transfer Function

- The transfer function *H(ω)* is the frequency-dependent ratio of a forced function *Y(ω)* to the forcing function *X(ω)*.

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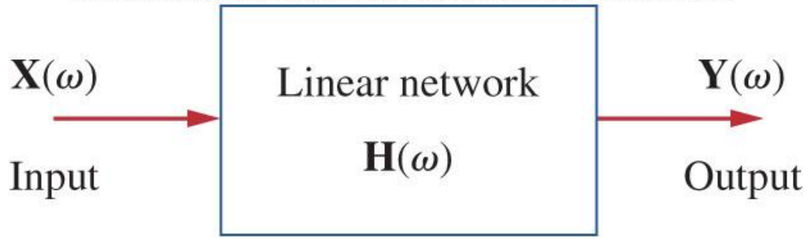

$$H(\omega) = \frac{Y(\omega)}{X(\omega)}$$

$$H(\omega) = \text{Voltage gain} = \frac{V_o(\omega)}{V_i(\omega)}$$

$$H(\omega) = \text{Current gain} = \frac{I_o(\omega)}{I_i(\omega)}$$

$$H(\omega) = \text{Transfer impedance} = \frac{V_o(\omega)}{I_i(\omega)}$$

$$H(\omega) = \text{Transfer admittance} = \frac{I_o(\omega)}{V_i(\omega)}$$

Transfer Function – Voltage Gain

- Complex quantity
- Both magnitude and phase are function of frequency

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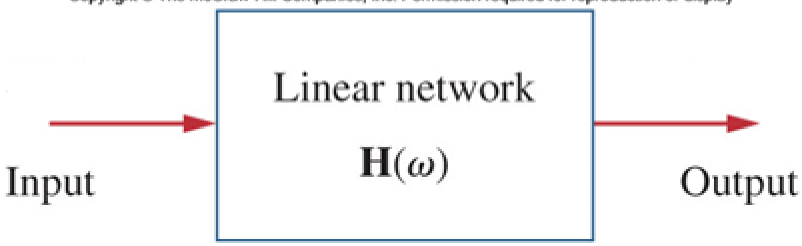
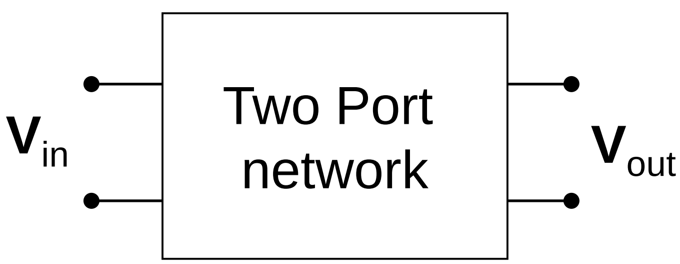
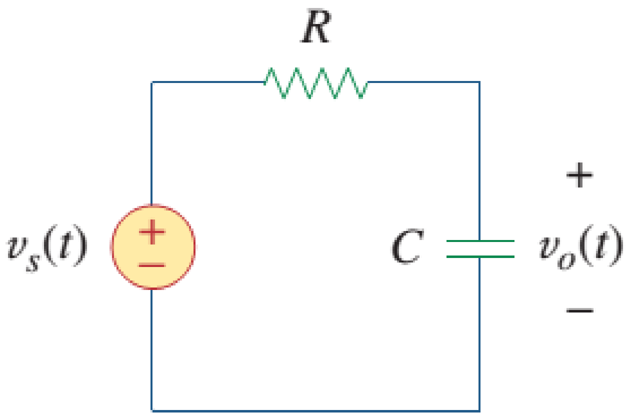


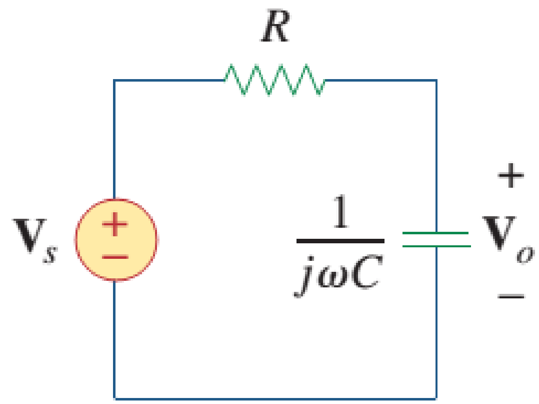


$$\mathbf{H}(f) = \frac{\mathbf{V_{out}}}{\mathbf{V_{in}}} = \frac{V_{out}}{V_{in}} \angle \left(\theta_{out} - \theta_{in} \right)$$

$$\mathbf{H(f)} = H(f) \angle \theta$$

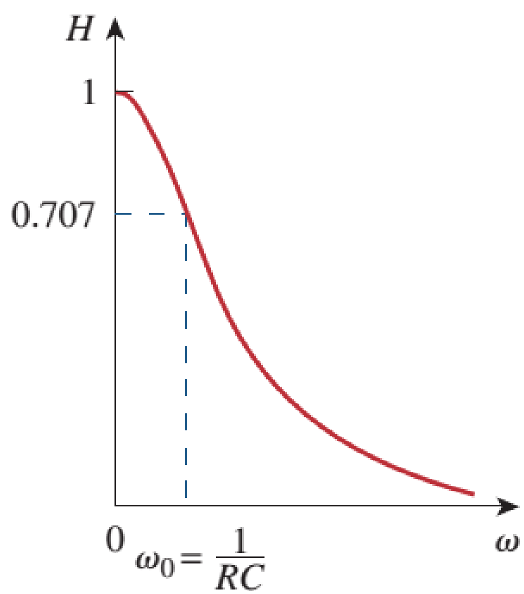
Example

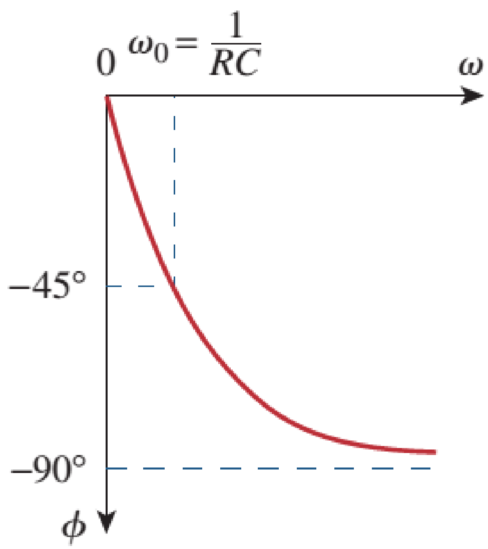




$$H = \frac{1}{\sqrt{1 + (\omega/\omega_0)^2}}, \qquad \phi = -\tan^{-1}\frac{\omega}{\omega_0}$$

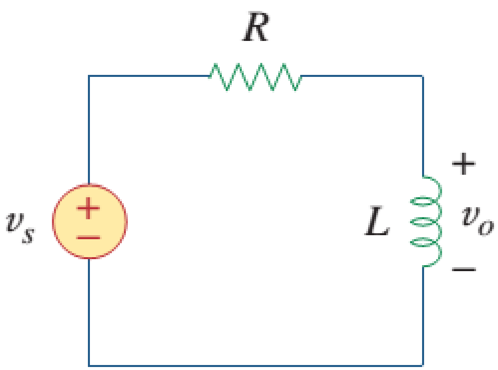
ω/ω_0	H	ϕ	ω/ω_0	H	ϕ
0	1	0	10	0.1	$-84°$
1	0.71	$-45°$	20	0.05	$-87°$
2	0.45	$-63°$	100	0.01	$-89°$
3	0.32	$-72°$	∞	0	$-90°$

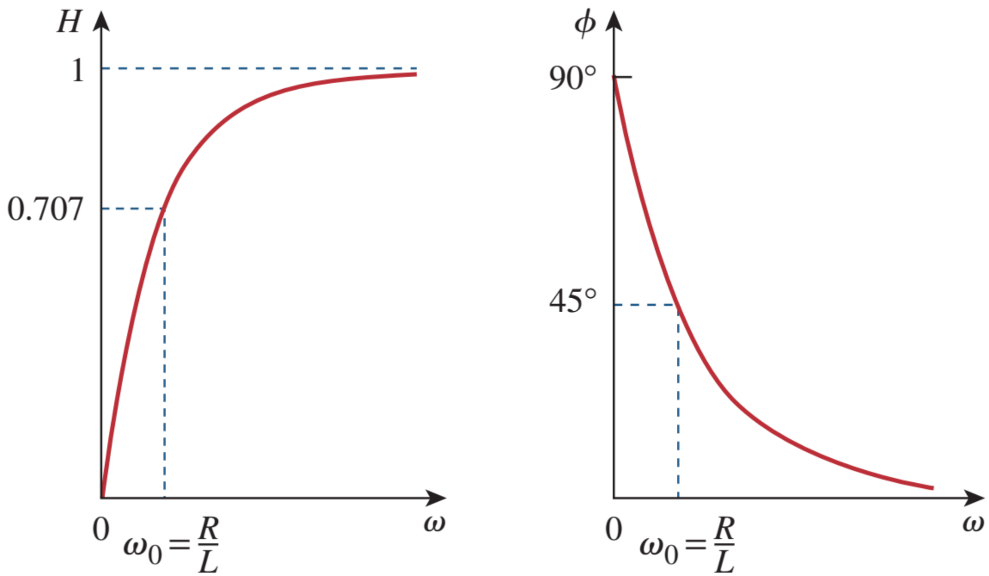




Exercise

- Obtain the transfer function $\mathbf{V_o}/\mathbf{V_s}$ of the RL circuit. Assuming $v_s = V_m \cos \omega t$.





Outline

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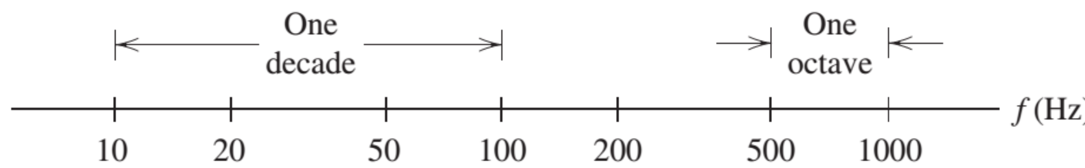
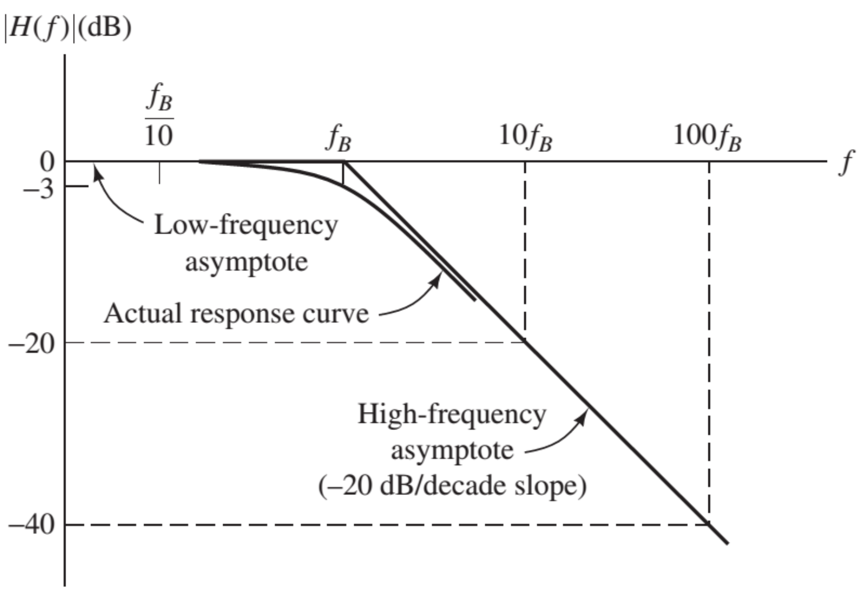
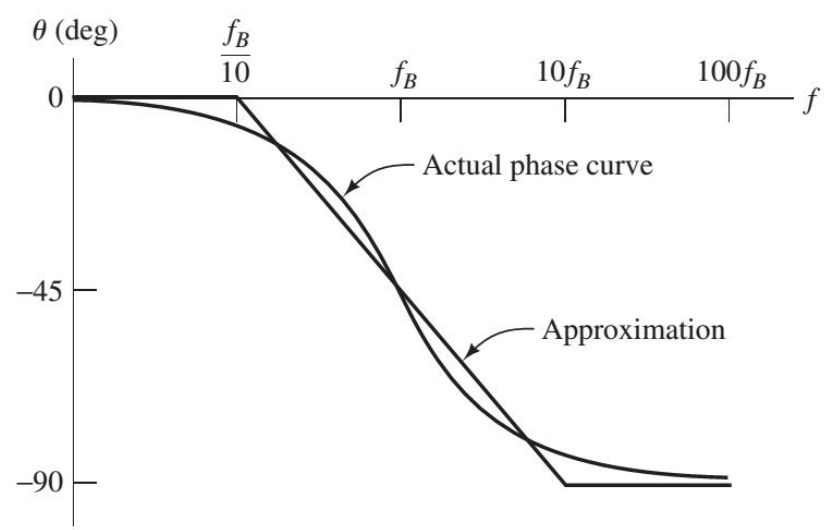
Bode Plots



Plotting the frequency response, magnitude or phase, on plots with

- Frequency X in log scale
- Y scale in dB (for magnitude) or degree (for phase)





Bel and Decibel (dB)

- A **bel** (symbol **B**) is a unit of measure of ratios of power levels, i.e. relative power levels.
  - The name was coined in the early 20th century in honor of Alexander Graham Bell, a telecommunication pioneer.
  - Definition of bel:

$$\text{Ratio with a unit of B} = \log_{10}(P_1/P_2)$$

  where P_1 and P_2 are power levels.

- One bel is too large for everyday use, so the **decibel (dB)**, equal to 0.1B, is more commonly used.

$$\text{Ratio with a unit of dB} = 10\log_{10}(P_1/P_2)$$

  - used to measure electric power, gain or loss of amplifiers, etc.

dB for Power

- To express a power in terms of decibels, one starts by choosing a reference power, $P_{reference}$, and write

$$\text{Power P in decibels} = 10 \log_{10}(P/P_{reference})$$

- Exercise: Express a power of 50 mW in decibels relative to 1 watt and 1mW.

  P (dB) =

[Source: Berkeley]

Decibel Scale

- The transfer function includes an expression of gain, which is typically expressed in log form.
  - in bels, or more commonly decibels

$$G_{dB} = 10\log_{10}\frac{P_2}{P_1}$$

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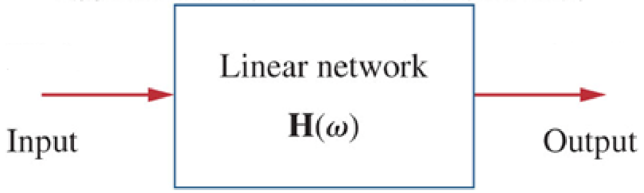

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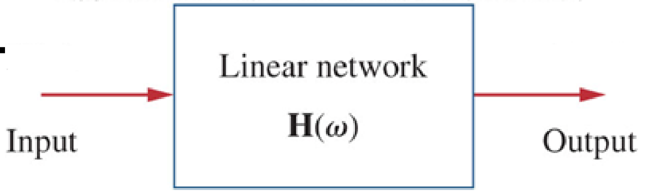


dB for Voltage or Current

- We can similarly relate the reference voltage or current to the reference power, as

$$P_{\text{reference}} = (V_{\text{reference}})^2/R \text{ or } P_{\text{reference}} = (I_{\text{reference}})^2 R$$

Hence,

$$\text{Voltage, V in decibels} = 20\log_{10}(V/V_{\text{reference}})$$
$$\text{Current, I, in decibels} = 20\log_{10}(I/I_{\text{reference}})$$

Question: How many decibels larger is the voltage of a 9-volt transistor battery than that of a 1.5-volt AA battery?

Question: The voltage gain of an amplifier with input = 0.2 mV and output = 0.5 V is ?

[Source: Berkeley]

Summary

If G is defined as the power gain,

$$G = \frac{P}{P_0},$$

then the corresponding gain in dB is defined as

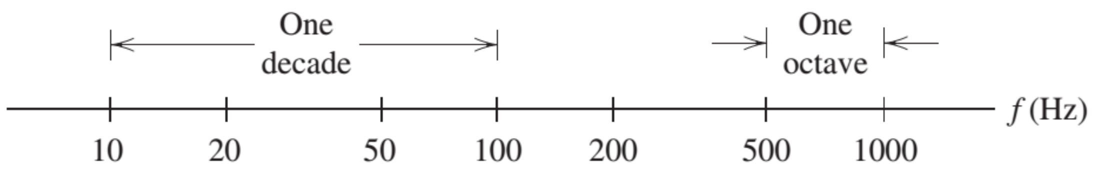
$$G\ [\text{dB}] = 10 \log G = 10 \log \left(\frac{P}{P_0} \right) \qquad (\text{dB}).$$

$$G\ [\text{dB}] = 10 \log \left(\frac{\frac{1}{2}|\mathbf{V}|^2/R}{\frac{1}{2}|\mathbf{V}_0|^2/R} \right) = 20 \log \left(\frac{|\mathbf{V}|}{|\mathbf{V}_0|} \right)$$

$\dfrac{P}{P_0}$	dB
10^N	$10N$ dB
10^3	30 dB
100	20 dB
10	10 dB
4	$\simeq 6$ dB
2	$\simeq 3$ dB
1	0 dB
0.5	$\simeq -3$ dB
0.25	$\simeq -6$ dB
0.1	-10 dB
10^{-N}	$-10N$ dB

$\left\lvert\dfrac{\mathbf{V}}{\mathbf{V}_0}\right\rvert$ or $\left\lvert\dfrac{\mathbf{I}}{\mathbf{I}_0}\right\rvert$	dB
10^N	$20N$ dB
10^3	60 dB
100	40 dB
10	20 dB
4	$\simeq 12$ dB
2	$\simeq 6$ dB
1	0 dB
0.5	$\simeq -6$ dB
0.25	$\simeq -12$ dB
0.1	-20 dB
10^{-N}	$-20N$ dB

Bode Plots



Plotting the frequency response, magnitude or phase, on plots with

- Frequency X in log scale
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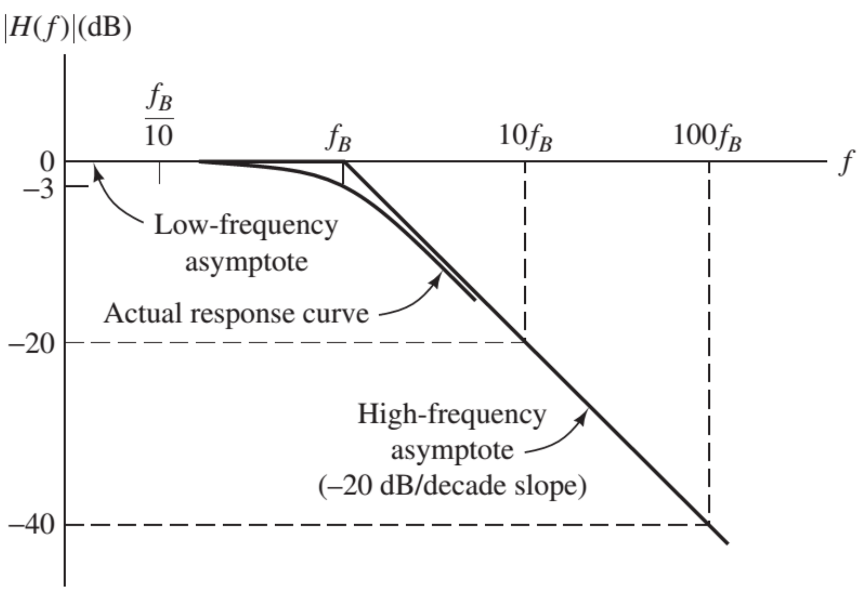
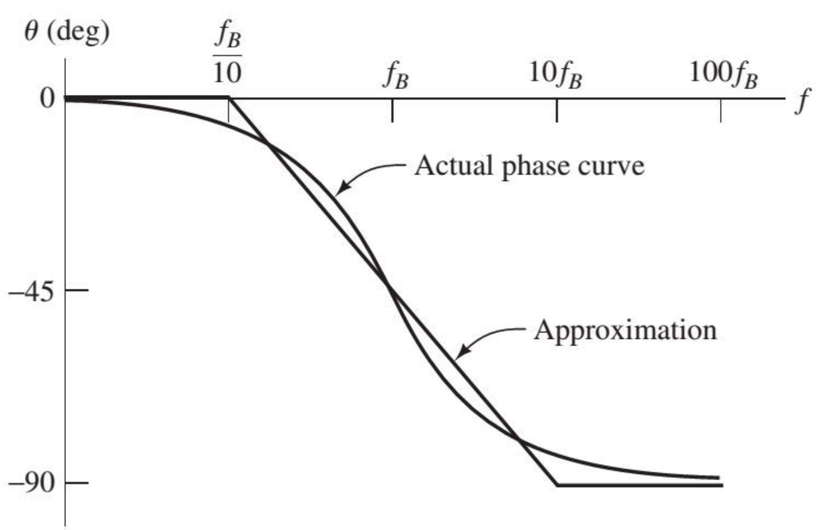




Bode Plots

- Bode plot is particularly useful for displaying transfer function-- a general form is displayed as:

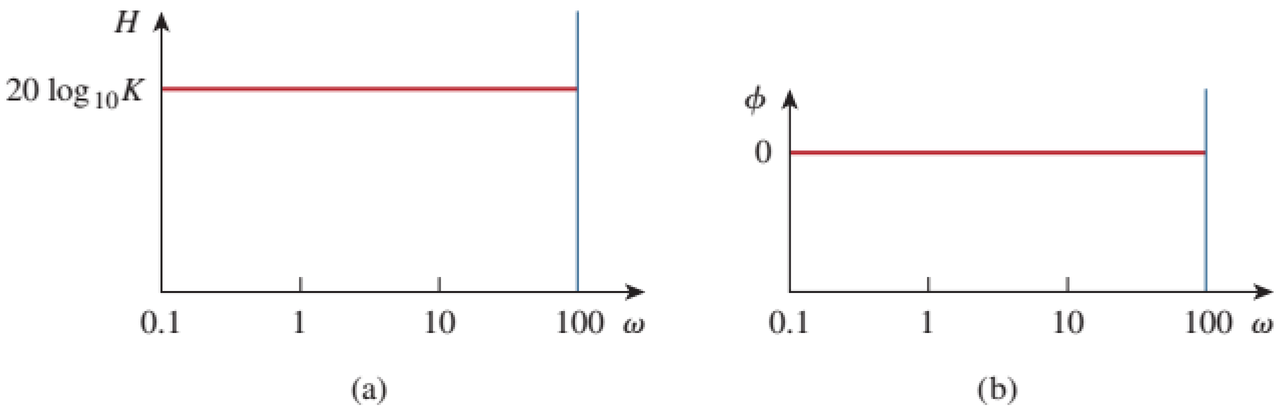
$$\mathbf{H}(\omega) = \frac{K(j\omega)^{\pm 1}(1 + j\omega/z_1)[1 + j2\zeta_1\omega/\omega_k + (j\omega/\omega_k)^2]\cdots}{(1 + j\omega/p_1)[1 + j2\zeta_2\omega/\omega_n + (j\omega/\omega_n)^2]\cdots}$$

In constructing a Bode plot, we plot each factor separately and then add them graphically. The factors can be considered one at a time and then combined additively because of the logarithms involved. It is this mathematical convenience of the logarithm that makes Bode plots a powerful engineering tool.

Constant term K

$$\mathbf{H}(\omega) = \frac{K(j\omega)^{\pm 1}(1 + j\omega/z_1)[1 + j2\zeta_1\omega/\omega_k + (j\omega/\omega_k)^2]\cdots}{(1 + j\omega/p_1)[1 + j2\zeta_2\omega/\omega_n + (j\omega/\omega_n)^2]\cdots}$$

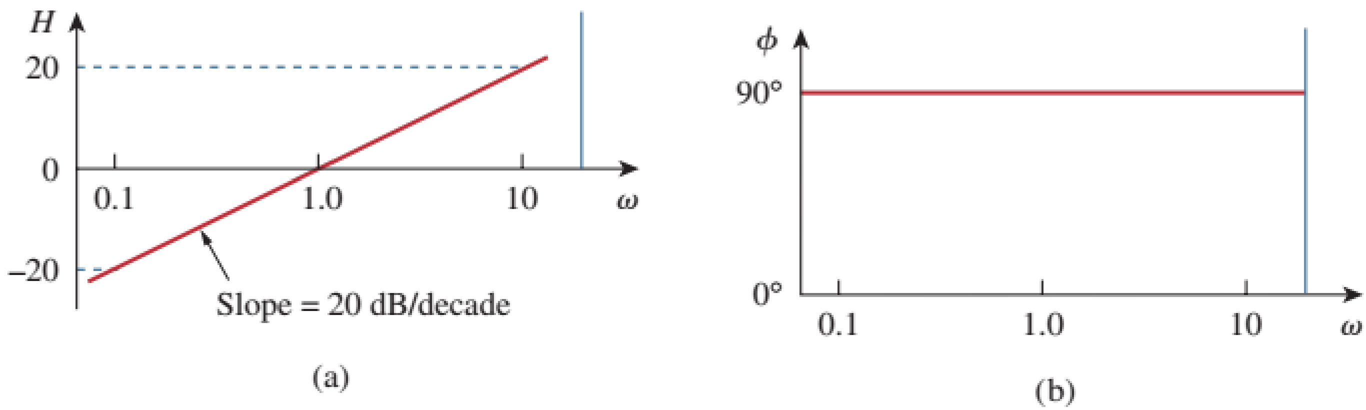
K>0



K<0

jω

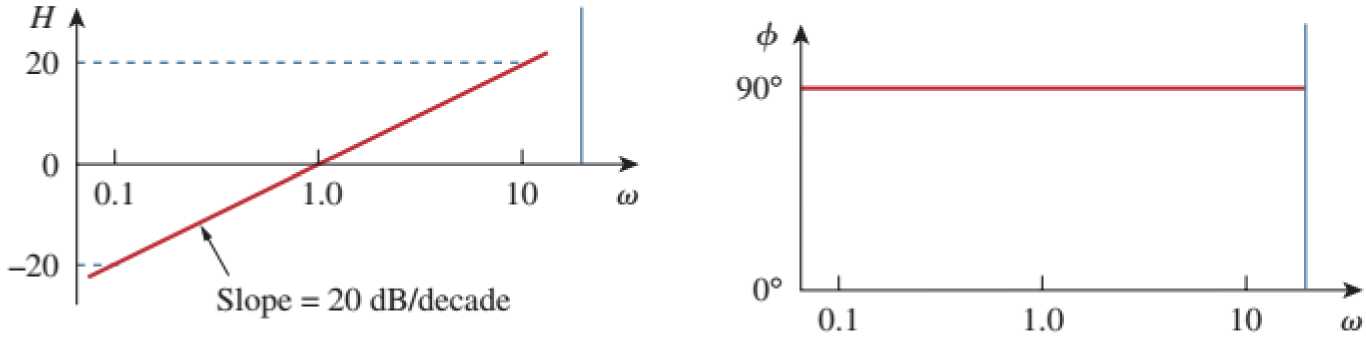
$$\mathbf{H}(\omega) = \frac{K(j\omega)^{\pm 1}(1 + j\omega/z_1)[1 + j2\zeta_1\omega/\omega_k + (j\omega/\omega_k)^2]\cdots}{(1 + j\omega/p_1)[1 + j2\zeta_2\omega/\omega_n + (j\omega/\omega_n)^2]\cdots}$$



(jω)⁻¹

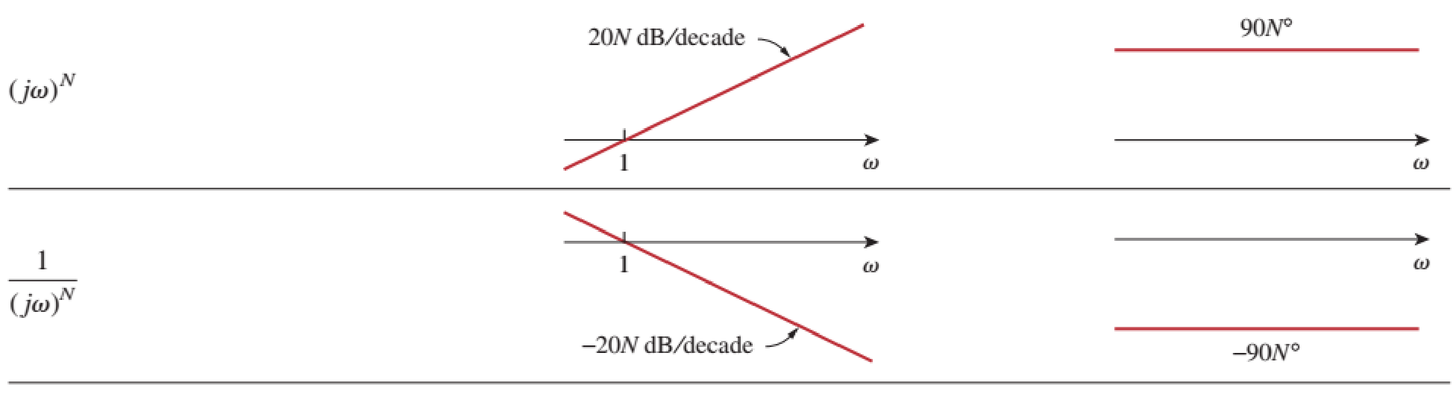
$j\omega$

$$\mathbf{H}(\omega) = \frac{K(j\omega)^{\pm 1}(1 + j\omega/z_1)[1 + j2\zeta_1\omega/\omega_k + (j\omega/\omega_k)^2]\cdots}{(1 + j\omega/p_1)[1 + j2\zeta_2\omega/\omega_n + (j\omega/\omega_n)^2]\cdots}$$



(a) (b)

- In general：



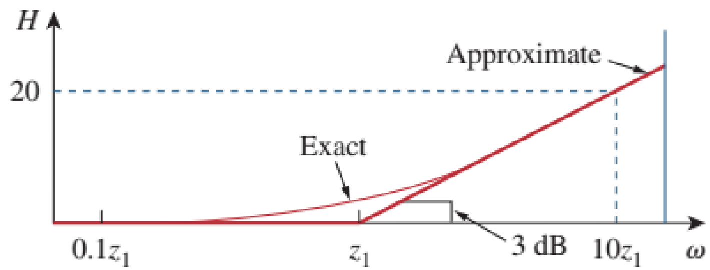
$1+j\omega/z_1$

$$\mathbf{H}(\omega) = \frac{K(j\omega)^{\pm 1}(1 + j\omega/z_1)[1 + j2\zeta_1\omega/\omega_k + (j\omega/\omega_k)^2]\cdots}{(1 + j\omega/p_1)[1 + j2\zeta_2\omega/\omega_n + (j\omega/\omega_n)^2]\cdots}$$

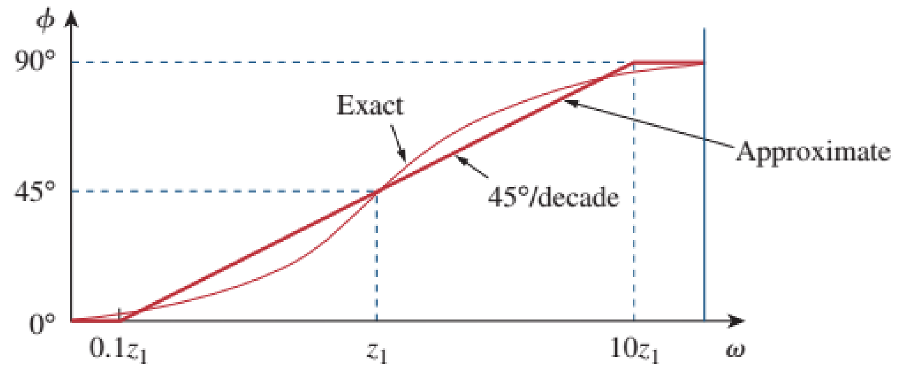
Simple pole/zero: For the simple zero $(1 + j\omega/z_1)$, the magnitude is $20\log_{10}|1 + j\omega/z_1|$ and the phase is $\tan^{-1}\omega/z_1$. We notice that

$$H_{dB} = 20\log_{10}\left|1 + \frac{j\omega}{z_1}\right| \quad \Rightarrow \quad 20\log_{10}1 = 0 \quad \text{as} \quad \omega \to 0$$

$$H_{dB} = 20\log_{10}\left|1 + \frac{j\omega}{z_1}\right| \quad \Rightarrow \quad 20\log_{10}\frac{\omega}{z_1} \quad \text{as} \quad \omega \to \infty$$



(a)



(b)

$1/(1+j\omega/p_1)$

$1/[1+2j\zeta_1\omega/\omega_n+(j\omega/\omega_n)^2]$

$$\mathbf{H}(\omega)=\frac{K(j\omega)^{\pm 1}(1+j\omega/z_1)[1+j2\zeta_1\omega/\omega_k+(j\omega/\omega_k)^2]\cdots}{(1+j\omega/p_1)[1+j2\zeta_2\omega/\omega_n+(j\omega/\omega_n)^2]\cdots}$$

Magnitude:

$$H_{\mathrm{dB}}=-20\log_{10}\left|1+\frac{j2\zeta_2\omega}{\omega_n}+\left(\frac{j\omega}{\omega_n}\right)^2\right| \quad\Rightarrow\quad 0$$

and

$$H_{\mathrm{dB}}=-20\log_{10}\left|1+\frac{j2\zeta_2\omega}{\omega_n}+\left(\frac{j\omega}{\omega_n}\right)^2\right| \quad\Rightarrow\quad -40\log_{10}\frac{\omega}{\omega_n}$$

as $\omega\to\infty$

the phase is $-\tan^{-1}(2\zeta_2\omega/\omega_n)/(1-\omega^2/\omega_n^2)$.

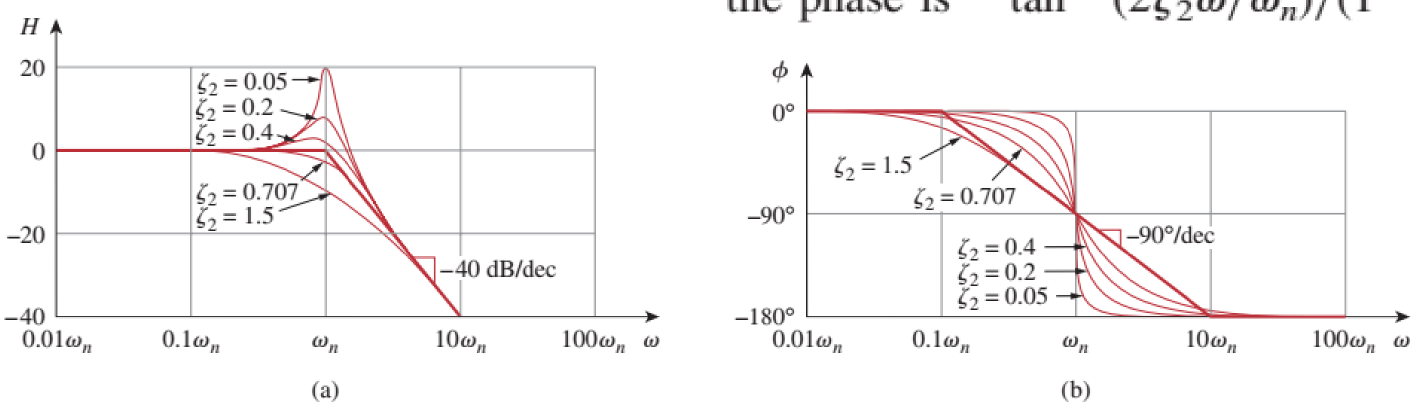
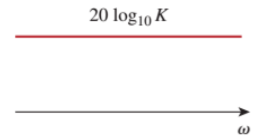
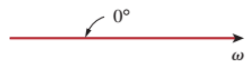
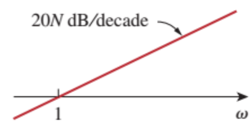
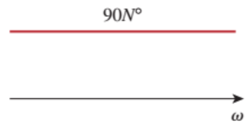
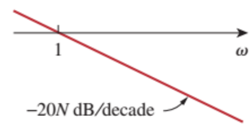
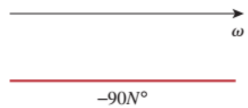
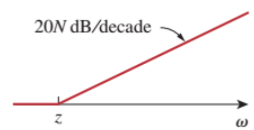
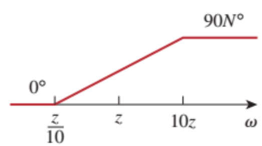
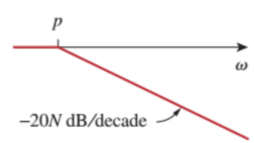
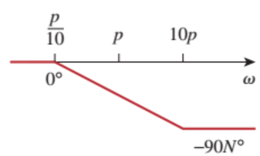
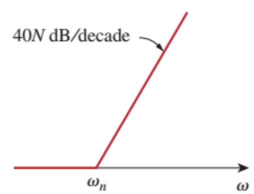
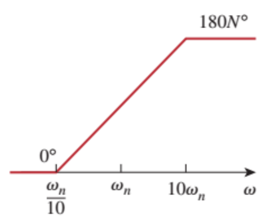
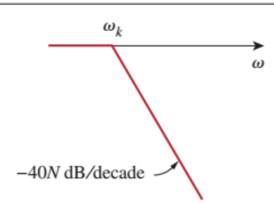
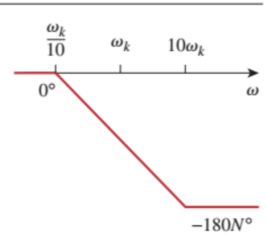


TABLE 14.3

Summary of Bode straight-line magnitude and phase plots.

Factor	Magnitude	Phase
K		
$(j\omega)^N$		
$\dfrac{1}{(j\omega)^N}$		
$\left(1+\dfrac{j\omega}{z}\right)^N$		
$\dfrac{1}{(1+j\omega/p)^N}$		
$\left[1+\dfrac{2j\omega\zeta}{\omega_n}+\left(\dfrac{j\omega}{\omega_n}\right)^2\right]^N$		
$\dfrac{1}{[1+2j\omega\zeta/\omega_k+(j\omega/\omega_k)^2]^N}$		

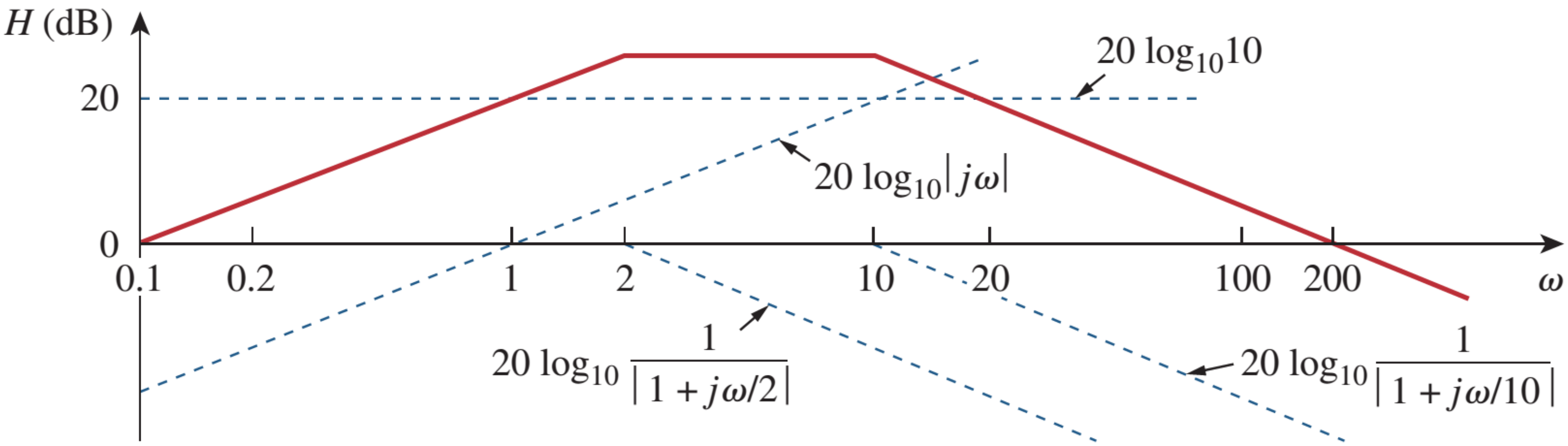
Example--Standard Form

$$\mathbf{H}(\omega) = \frac{200\,j\omega}{(j\omega + 2)(j\omega + 10)}$$

$$\mathbf{H}(\omega) = \frac{10\,j\omega}{(1 + j\omega/2)(1 + j\omega/10)}$$

Example - Magnitude

$$\mathbf{H}(\omega) = \frac{10j\omega}{(1 + j\omega/2)(1 + j\omega/10)}$$
$$= \frac{10|j\omega|}{|1 + j\omega/2||1 + j\omega/10|} \underline{/90^\circ - \tan^{-1}\omega/2 - \tan^{-1}\omega/10}$$



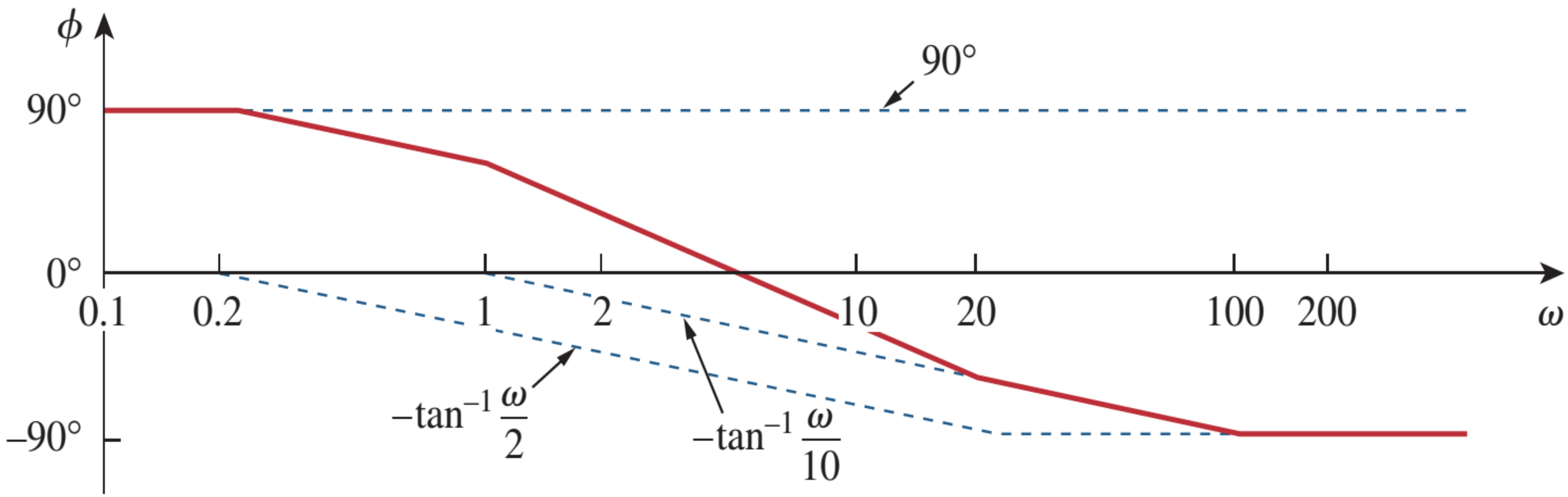
$$H_{\mathrm{dB}} = 20\log_{10}10 + 20\log_{10}|j\omega| - 20\log_{10}\left|1 + \frac{j\omega}{2}\right| - 20\log_{10}\left|1 + \frac{j\omega}{10}\right|$$

Example - Phase

$$\mathbf{H}(\omega) = \frac{10j\omega}{(1 + j\omega/2)(1 + j\omega/10)}$$

$$= \frac{10|j\omega|}{|1 + j\omega/2||1 + j\omega/10|} \underline{/90^\circ - \tan^{-1}\omega/2 - \tan^{-1}\omega/10}$$

$$\phi = 90^\circ - \tan^{-1}\frac{\omega}{2} - \tan^{-1}\frac{\omega}{10}$$



Exercises

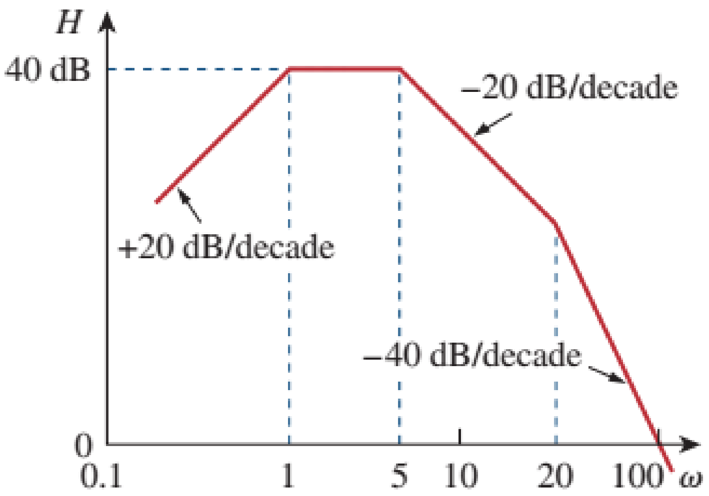
- $H(\omega) = K$
- $H(\omega) = (j\omega)^N$
- $H(\omega) = 1/(j\omega)^N$

Exercises

- $\mathbf{H}(\omega) = \dfrac{(20 + j4\omega)^2}{j40\omega(100 + j2\omega)}$

- $\mathbf{H}(\omega) = \dfrac{(j10\omega + 30)^2}{(300 - 3\omega^2 + j90\omega)}$

Obtain the transfer function



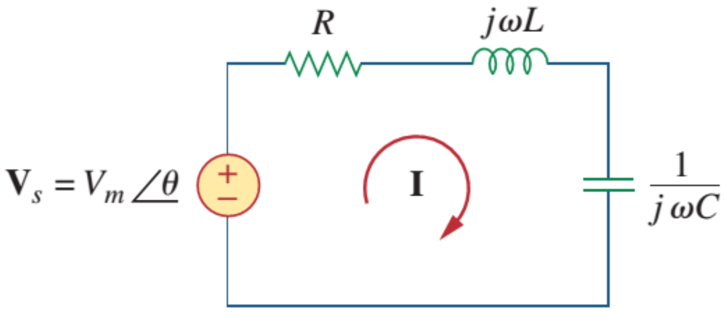
Outline

- Frequency response
- Transfer function
- Bode plots (or diagram)
- Resonance

Series Resonance

- A series resonant circuit consists of an inductor and capacitor in series.

$$H(\omega) = \frac{V}{I} = \mathbf{Z} = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

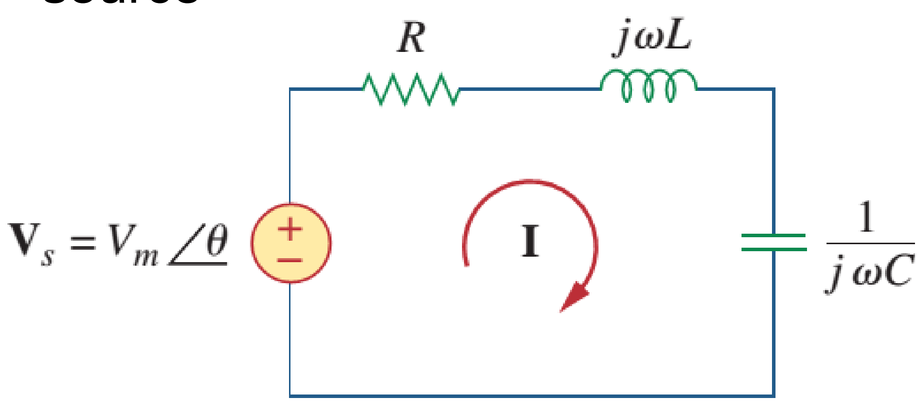


  - Resonance occurs when the imaginary part of *Z* is zero.
  - The value of ω that satisfies this is called the resonant frequency.

$$\omega_0 = \frac{1}{\sqrt{LC}} \text{ rad/s}$$

Series Resonance

- At resonance:
  - The impedance is purely resistive
  - The voltage V_s and the current I are in phase
  - The magnitude of the transfer function is minimum
  - The inductor and capacitor voltages can be much more than the source

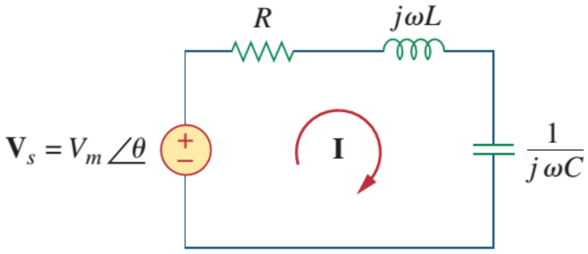


$$|\mathbf{V}_L| = \frac{V_m}{R}\omega_0 L$$

$$|\mathbf{V}_C| = \frac{V_m}{R}\frac{1}{\omega_0 C}$$

$$H(\omega) = \frac{V}{I} = \mathbf{Z} = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

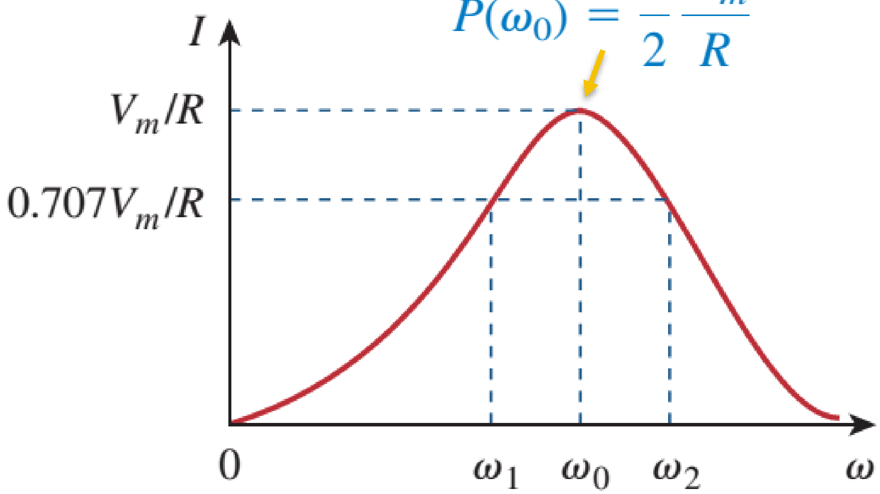
Half-Power Frequencies



- the current magnitude:

$$I = |\mathbf{I}| = \frac{V_m}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}}$$

$$P(\omega_0) = \frac{1}{2}\frac{V_m^2}{R}$$



$$\omega_0 = \frac{1}{\sqrt{LC}} \text{ rad/s}$$

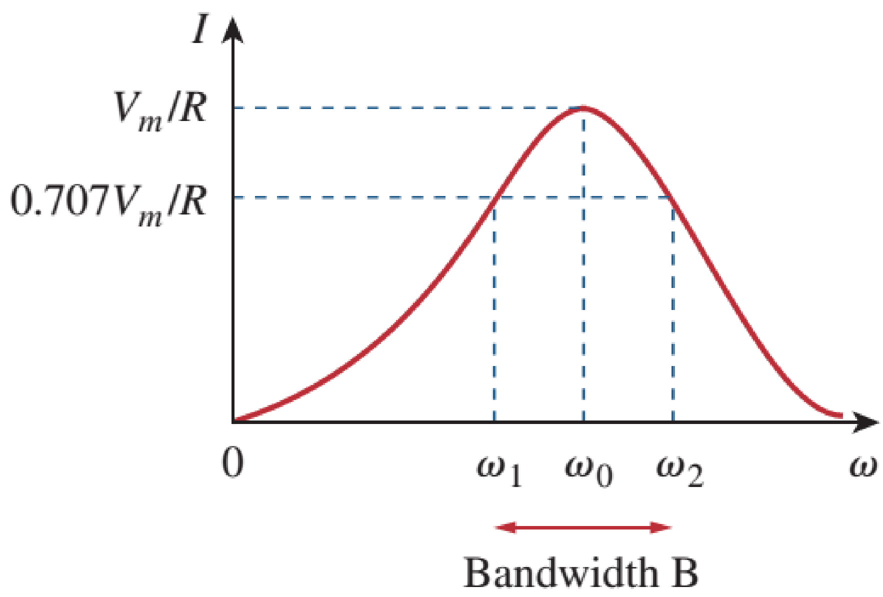
$$P(\omega_1) = P(\omega_2) = \frac{1}{2}P(\omega_0)$$

$$\omega_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$\omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$\omega_0 = \sqrt{\omega_1\omega_2}$$

Bandwidth



$$\omega_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

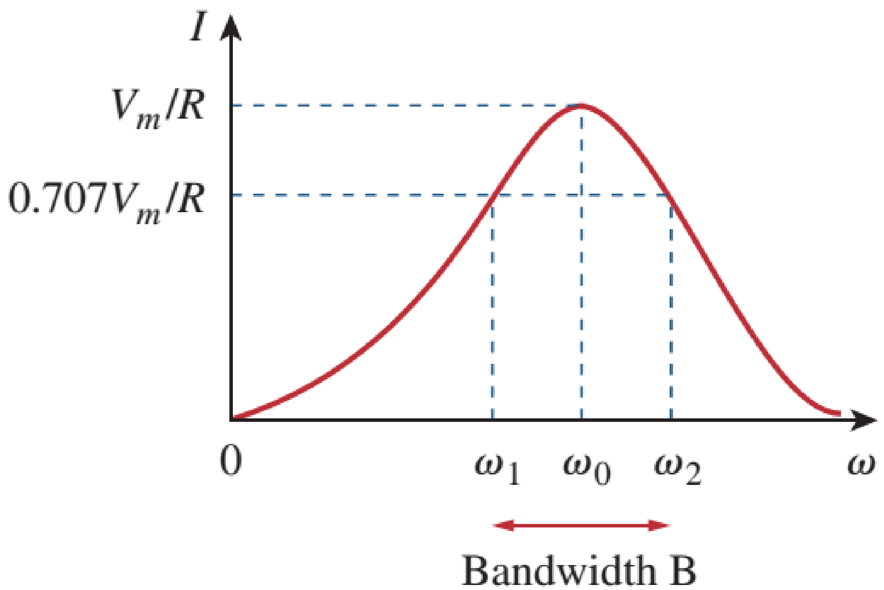
$$\omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

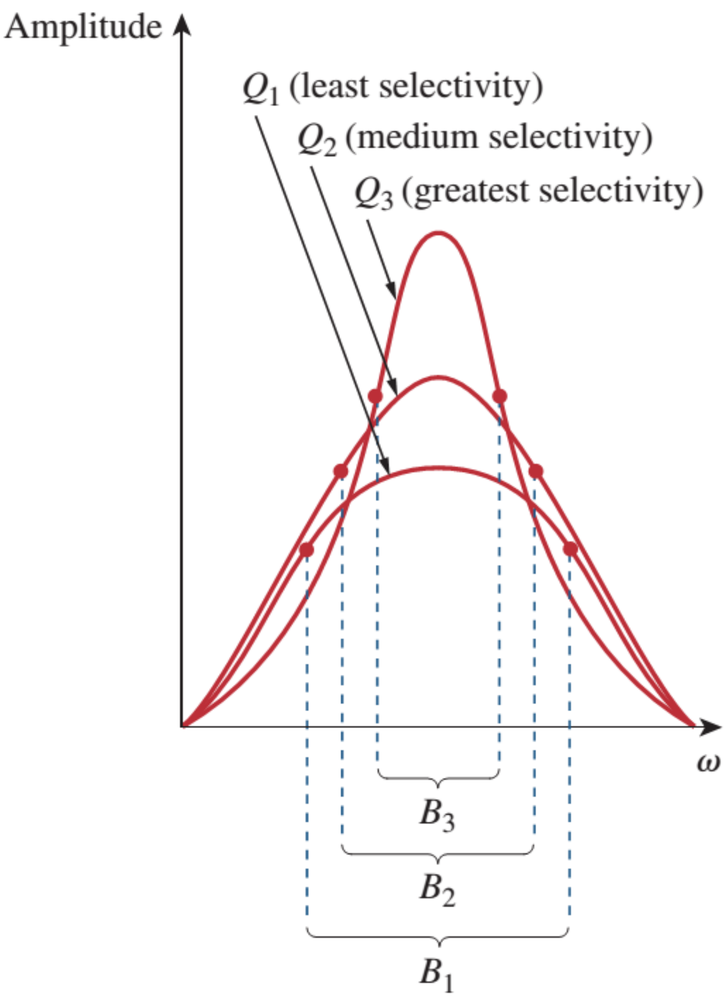
$$B = \omega_2 - \omega_1 = \frac{R}{L}$$

- Bandwidth: the difference between the two half-power frequencies

Quality Factor Q

- Quality factor Q: measure the "sharpness" of the resonance.





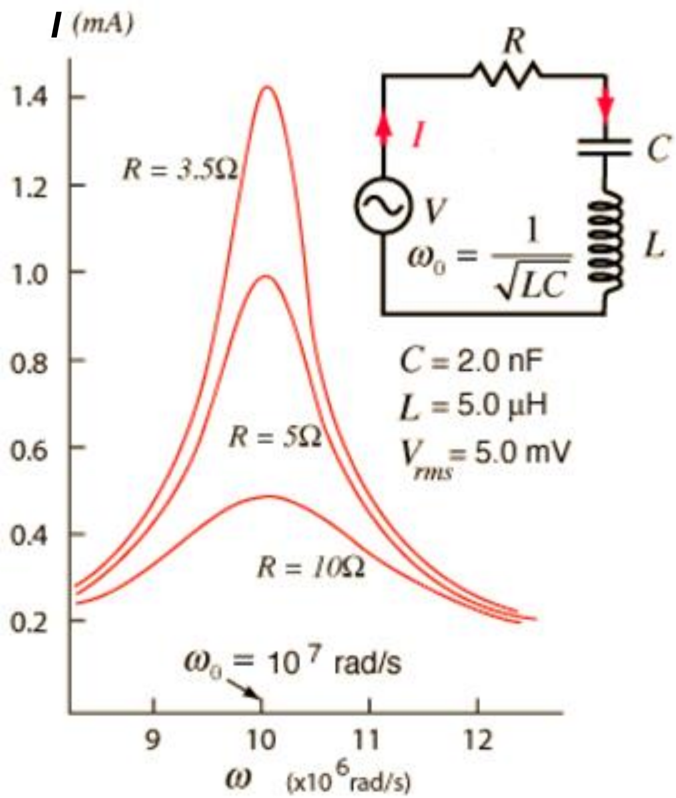
The smaller the B, the higher the Q.

$$Q = \frac{\omega_0}{B}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad B = \omega_2 - \omega_1 = \frac{R}{L}$$

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 CR}$$

Quality Factor *Q*



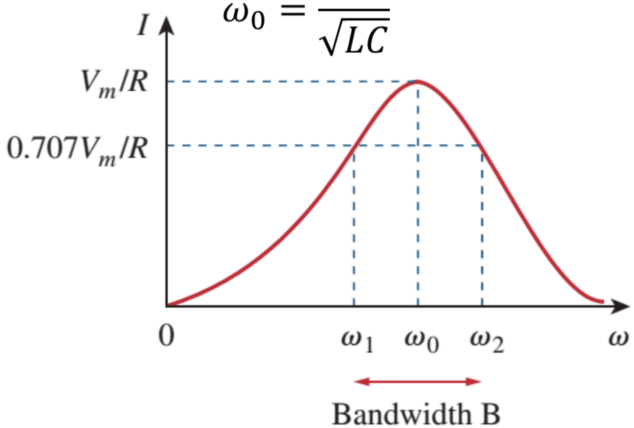
[Source: Georgia State U]

$$Q = \frac{\omega_0}{B}$$

$$\boxed{Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R}}$$

Approximation of Half-Power Frequencies

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



$$\omega_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$\omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$\frac{R}{L} = B \qquad B = \frac{\omega_0}{Q}$$

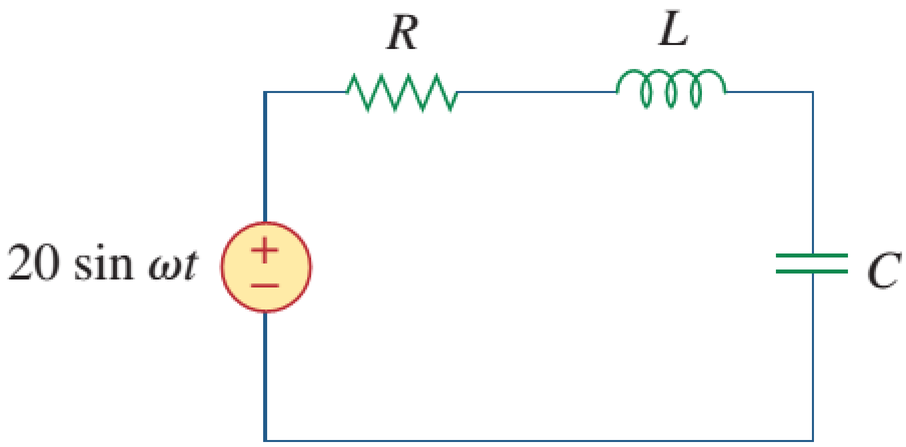
$$\omega_1 = -\frac{\omega_0}{2Q} + \omega_0\sqrt{1 + \frac{1}{4Q^2}}$$

$$\omega_2 = \frac{\omega_0}{2Q} + \omega_0\sqrt{1 + \frac{1}{4Q^2}}$$

- For high-Q ($Q \geq 10$) circuits, half-power frequencies can be approximated as

$$\boxed{\omega_1 \simeq \omega_0 - \frac{B}{2}, \qquad \omega_2 \simeq \omega_0 + \frac{B}{2}}$$

Example



In the circuit, $R = 2\Omega$, $L = 1\text{mH}$ and $C = 0.4\mu\text{F}$

- Find resonant frequency ω_0.
- Calculate *Q* and bandwidth *B*.
- Find half-power frequencies.
- Determine the amplitude of the current at ω_0, ω_1 and ω_2.

$$\omega_0 = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{10^{-3} \times 0.4 \times 10^{-6}}} = 50 \text{ krad/s}$$

$$B = \omega_2 - \omega_1 = 2 \text{ krad/s}$$

$$Q = \frac{\omega_0}{B} = \frac{50}{2} = 25$$

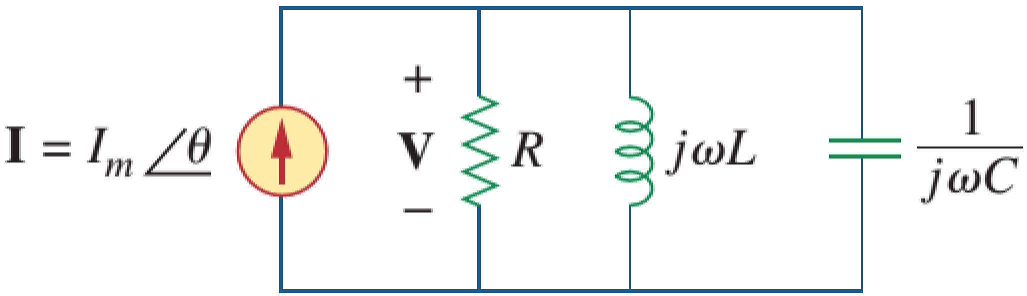
At $\omega = \omega_0$,

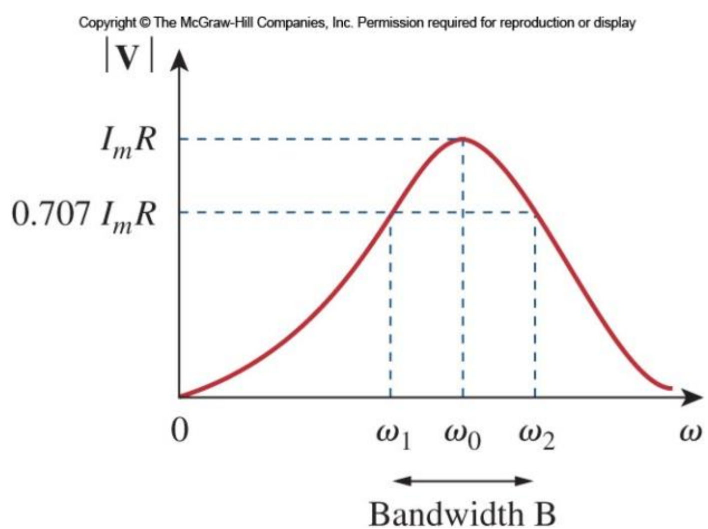
$$I = \frac{V_m}{R} = \frac{20}{2} = 10 \text{ A}$$

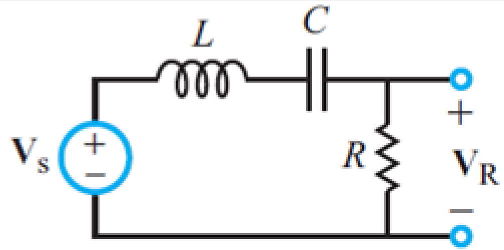
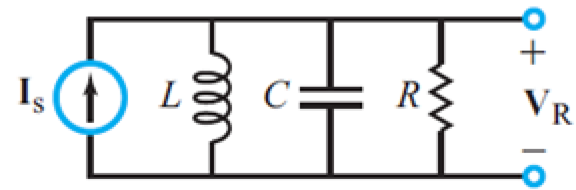
At $\omega = \omega_1, \omega_2$,

$$I = \frac{V_m}{\sqrt{2}R} = \frac{10}{\sqrt{2}} = 7.071 \text{ A}$$

Parallel resonance





RLC Circuit		
Transfer Function	$\mathbf{H} = \dfrac{\mathbf{V}_R}{\mathbf{V}_s}$	$\mathbf{H} = \dfrac{\mathbf{V}_R}{\mathbf{I}_s}$
Resonant Frequency, ω_0	$\dfrac{1}{\sqrt{LC}}$	$\dfrac{1}{\sqrt{LC}}$
Bandwidth, B	$\dfrac{R}{L}$	$\dfrac{1}{RC}$
Quality Factor, Q	$\dfrac{\omega_0}{B} = \dfrac{\omega_0 L}{R}$	$\dfrac{\omega_0}{B} = \dfrac{R}{\omega_0 L}$
Lower Half-Power Frequency, ω_1	$\left[-\dfrac{1}{2Q} + \sqrt{1 + \dfrac{1}{4Q^2}}\right]\omega_0$	$\left[-\dfrac{1}{2Q} + \sqrt{1 + \dfrac{1}{4Q^2}}\right]\omega_0$
Upper Half-Power Frequency, ω_2	$\left[\dfrac{1}{2Q} + \sqrt{1 + \dfrac{1}{4Q^2}}\right]\omega_0$	$\left[\dfrac{1}{2Q} + \sqrt{1 + \dfrac{1}{4Q^2}}\right]\omega_0$

Notes: (1) The expression for Q of the series RLC circuit is the inverse of that for Q of the parallel circuit. (2) For $Q \geq 10$, $\omega_1 \simeq \omega_0 - \frac{B}{2}$, and $\omega_2 \simeq \omega_0 + \frac{B}{2}$.

[Source: Berkeley]