廣東工業大學
Guangdong University of Technology

广东工业大学

第二章 高频基础电路

信息工程学院

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目录

2.1 选频网络

2.2 阻抗变换

2.1 选频网络

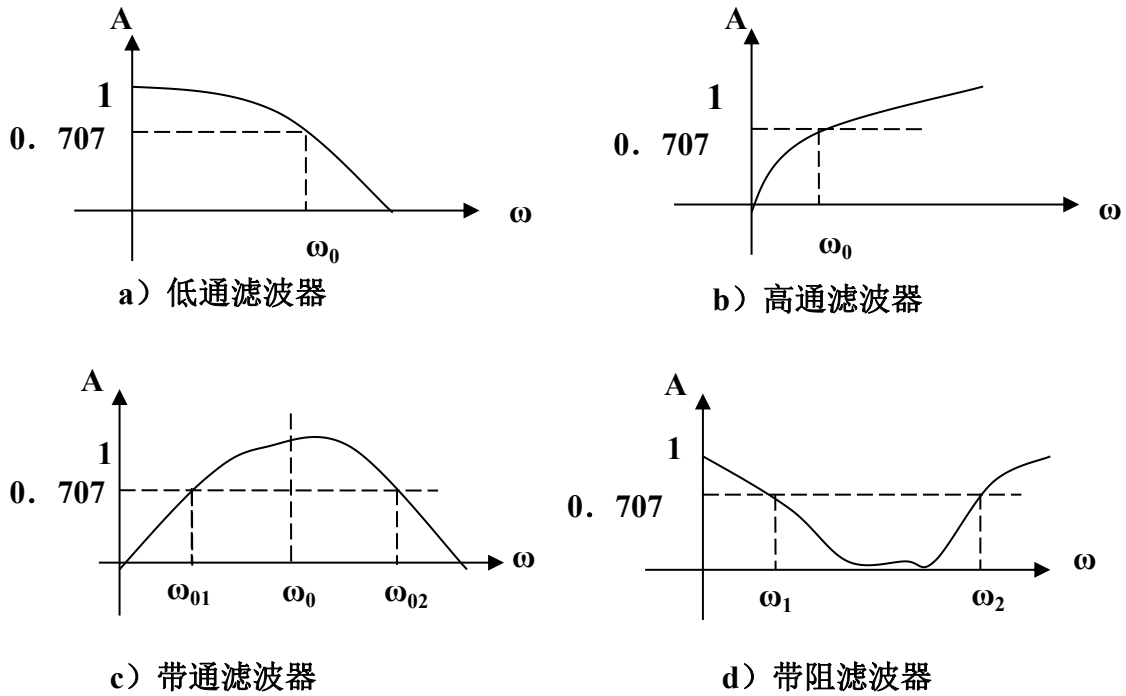
分类

- 按频率特性分：低通、高通、带通、带阻
- 按所用器件分：有源滤波器、无源滤波器
- 按处理信号分：模拟滤波器、数字滤波器、抽样数字滤波器

功能

- 具有选频特性：选出所需频率信号，滤除干扰信号

2.1 选频网络



滤波器的频率特性图

2.1 选频网络

- **LC谐振回路**
  - 单LC谐振回路（串联、并联）
  - 双谐振回路
- **各种滤波器**
  - LC集中滤波器
  - 石英晶体滤波器
  - 陶瓷滤波器
  - 声波表面滤波器

2.1 选频网络

电感品质因素

- 电感品质因素（Q值）

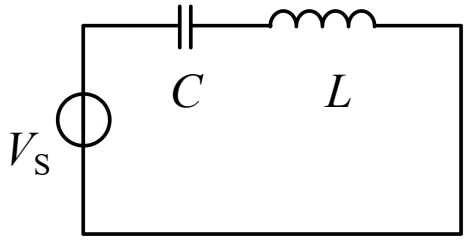
$$Q = \frac{\omega L}{R}$$

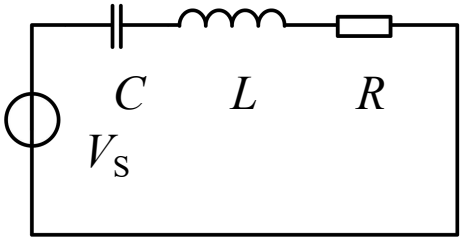
物理意义

- Q值反映了电感线圈损耗大小
- Q值越高，储能越强，功率损耗越小，电路效率越高

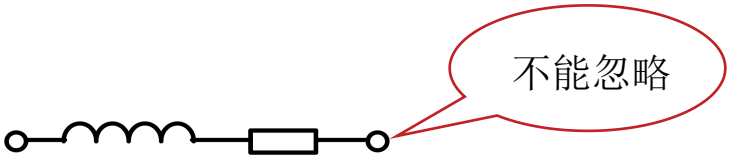
2.1 选频网络

串联谐振回路

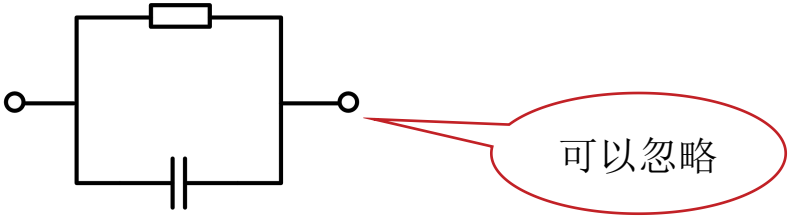




- 电感器=电感L 串 损耗电阻R

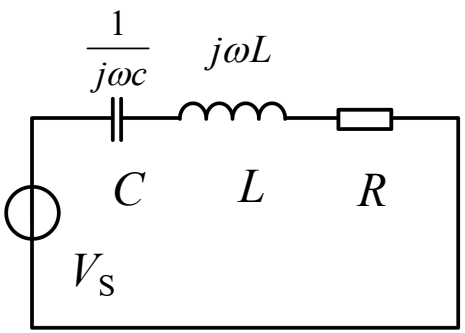


- 电容器=电容C 并 损耗电阻R



2.1 选频网络

串联谐振回路——阻抗Z~ω



$$X=\omega L-\frac{1}{\omega c}\Rightarrow Z=R+jX=R+j(\omega L-\frac{1}{\omega c})$$

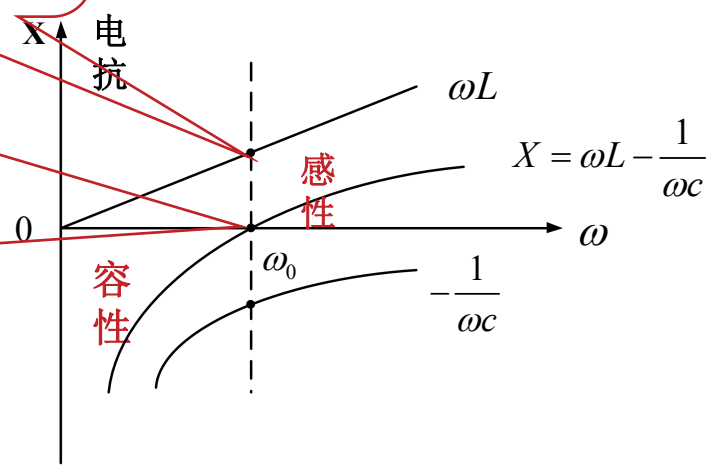
特性阻抗ρ：

$$\rho=\omega_0 L=\frac{1}{\omega_0 C}=\sqrt{\frac{L}{C}}$$

谐振频率ω_0：

$$X=\omega_0 L-\frac{1}{\omega_0 c}=0$$

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

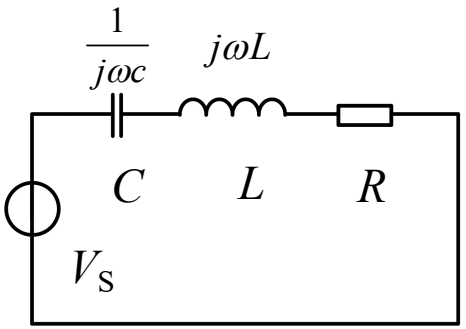


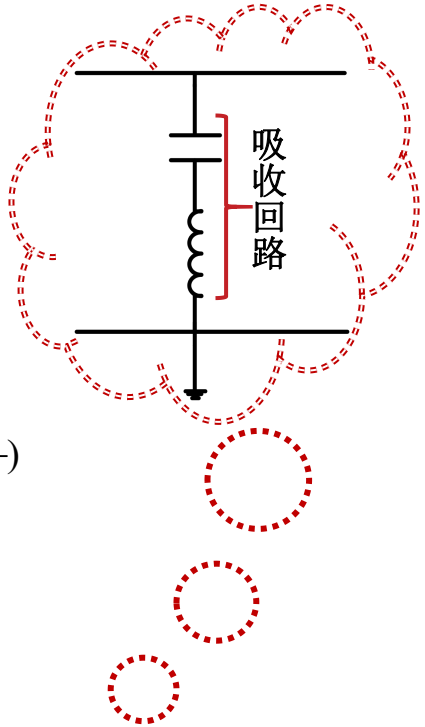
➢ 阻抗性质随频率的变化规律：

1）$\omega>\omega_0, X>0$ 呈感性，电压超前
2）$\omega<\omega_0, X<0$ 呈容性，电流超前
3）$\omega=\omega_0, X=0$ 呈纯阻性

2.1 选频网络

串联谐振回路——阻抗Z~ω





$$X = \omega L - \frac{1}{\omega c} \Rightarrow Z = R + jX = R + j(\omega L - \frac{1}{\omega c})$$

特性阻抗ρ：

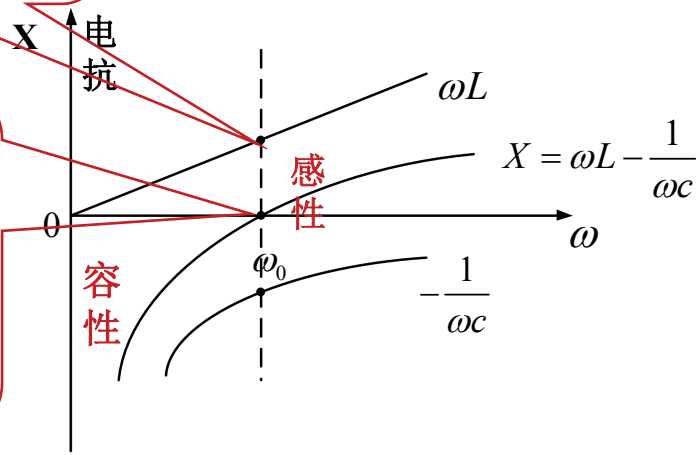
$$\rho = \omega_0 L = \frac{1}{\omega_0 C} = \sqrt{\frac{L}{C}}$$

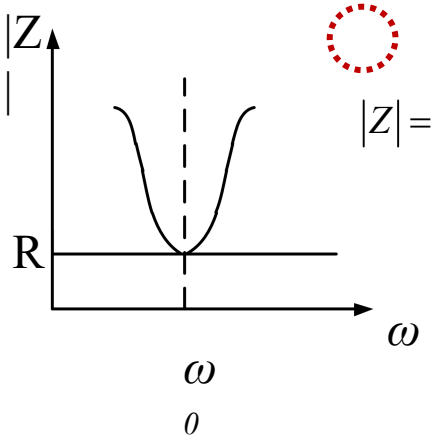
谐振频率

ω_0：

$$X = \omega_0 L - \frac{1}{\omega_0 c} = 0$$

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





$$|Z| = \sqrt{R^2 + X^2}$$

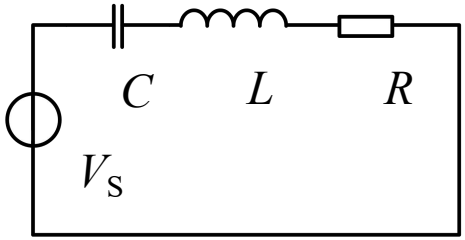
2.1 选频网络

串联谐振回路——品质因数

线圈的品质因数 $Q=\dfrac{\omega L}{R}$

回路的品质因数 $Q_0=\dfrac{\omega_0 L}{R}=\dfrac{\frac{1}{\omega_0 C}}{R}=\dfrac{\rho}{R}$

其中，阻抗特性 $\rho=\omega_0 L=\dfrac{1}{\omega_0 C}$



不同点：回路Q_0限定于谐振ω_0，线圈Q无限定ω

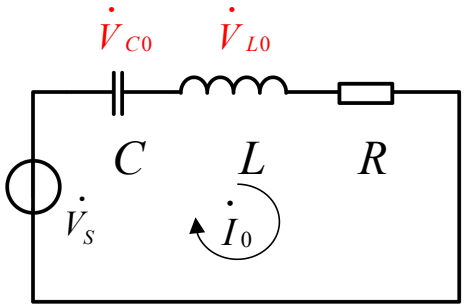
相同点：均表示能量损耗（源自损耗电阻R）

2.1 选频网络

串联谐振回路——电压谐振

电感两端电压:

$$\dot{V}_{L0}=\dot{I}_0\bullet j\omega_0 L=\frac{\dot{V}_S}{R}j\omega_0 L=j\boxed{\frac{\omega_0 L}{R}}\dot{V}_S=jQ_0\dot{V}_s$$



电容两端电压:

$$\dot{V}_{C0}=\dot{I}_0\bullet\frac{1}{j\omega_0 C}=\frac{\dot{V}_S}{R}\frac{1}{j\omega_0 C}=-j\boxed{\frac{\frac{1}{\omega_0 C}}{R}}\dot{V}_S=-jQ_0\dot{V}_s$$

$$Q_0=\frac{\omega_0 L}{R}=\frac{\frac{1}{\omega_0 C}}{R}$$

表明： $\dot{V}_{L0}=-\dot{V}_{C0}$

即电压大小相等，均等于信号源电压的Q_0倍

2.1 选频网络

串联谐振回路——广义失谐系数

谐振时 $$Q_0=\frac{(\text{电抗})\mathrm{X}}{(\text{电阻})\mathrm{R}}$$

若失谐不大ω≈ω0

失谐时 $$\xi=\frac{(\text{电抗和})\mathrm{X}}{(\text{电阻})\mathrm{R}}=\frac{\omega L-\frac{1}{\omega C}}{R}$$

$$=\frac{\omega_0 L}{R}\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)=\mathrm{Q}_0\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)=\frac{\cancel{(\omega+\omega_0)}(\omega-\omega_0)}{\omega_0\cancel{\omega}}$$

$$\xi\approx Q_0\frac{2(\omega-\omega_0)}{\omega_0}$$

物理意义：
ξ≠0表示失谐大小

$$\xi=Q_0\bullet\frac{2\Delta\omega}{\omega_0}\quad\text{或}\quad\xi=Q_0\bullet\frac{2\Delta f}{f_0}$$

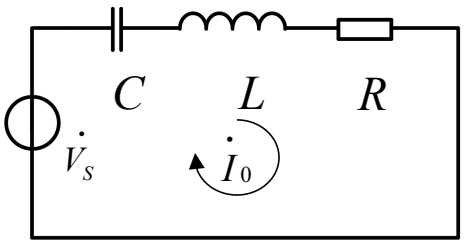
2.1 选频网络

串联谐振回路——谐振曲线

电流幅值：

$$\dot{I}=\frac{\dot{V}_S}{R+j(\omega L-\frac{1}{\omega C})}\sim\omega$$

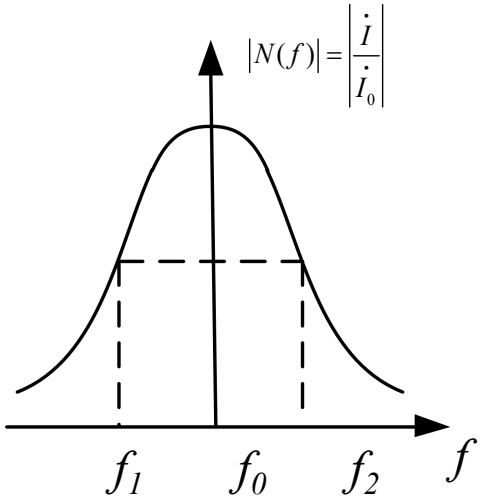
$$Z=R+jX=R+j(\omega L-\frac{1}{\omega C})$$



谐振曲线：

$$N(f)=\frac{\dot{I}}{\dot{I}_0}=\frac{\dfrac{\dot{V}_S}{R+j(\omega L-\frac{1}{\omega C})}}{\dfrac{\dot{V}_S}{R}}=\frac{R}{R+j(\omega L-\frac{1}{\omega C})}=\frac{1}{1+j(\frac{\omega L-\frac{1}{\omega C}}{R})}$$

$$\Rightarrow N(f)=\frac{\dot{I}}{\dot{I}_0}=\frac{1}{1+j\xi}$$



幅频曲线

2.1 选频网络

串联谐振回路——通频带

通频带：电流I下降到I_0的0.707时频率范围

$$B = 2\Delta f_{0.7} = | f_2 - f_1 |$$

谐振曲线

$$N(f) = \frac{\dot{I}}{\dot{I}_0} = \frac{1}{1 + j\xi}$$

幅频

$$|N(f)| = \frac{1}{\sqrt{1+\xi^2}} = \frac{1}{\sqrt{2}}$$

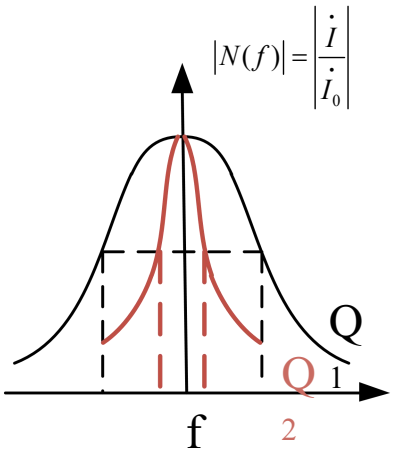
当 $2\Delta f_{0.7}$

$\xi = \pm 1$

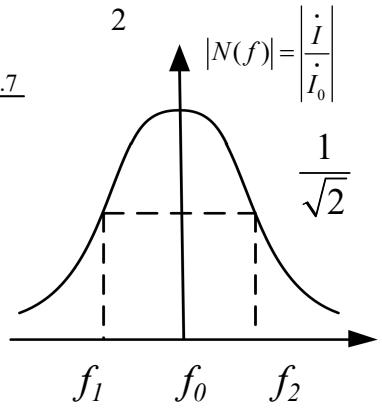
失谐系数 $\xi = Q_0 \cdot \frac{2\Delta f}{f_0}$

$$1 = Q_0 \cdot \frac{2\Delta f_{0.7}}{f_0}$$

$$1 = Q_0 \cdot \frac{B}{f_0}$$



$Q_1 < Q_2$



幅频曲线

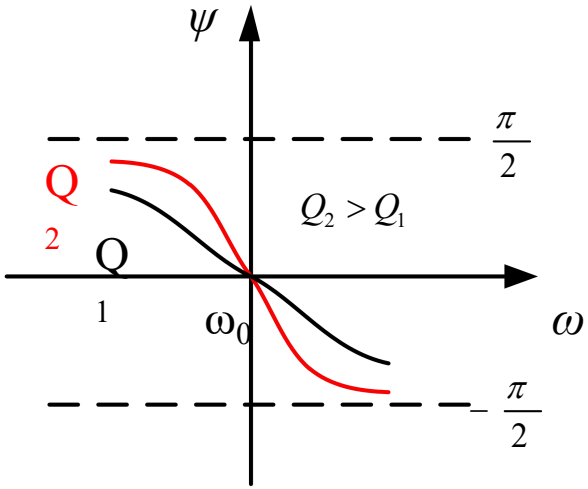
表明： 品质因数与带宽乘积为常数

$Q_0 \cdot B = f_0$

2.1 选频网络

串联谐振回路——相频曲线

谐振曲线 $N(f)=\dfrac{\dot{I}}{\dot{I}_0}=\dfrac{1}{1+j\xi}$



相频 $\psi=-\mathrm{arctg}\,\xi$

表明：

Q值愈大，谐振频率ω_0附近变化愈陡线性度愈差，线性范围愈窄

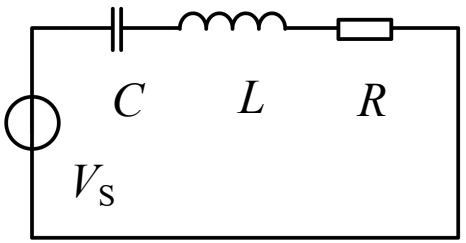
2.1 选频网络

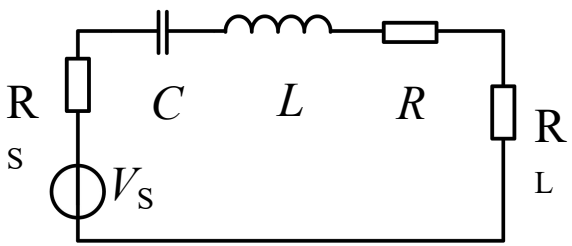
串联谐振回路——考虑信号源内阻和负载电阻

空载Q值：用Q_0表示 $Q_0 = \dfrac{\omega_0 L}{R}$ （未考虑信号源内阻和负载电阻)

有载Q值： $Q_L = \dfrac{\omega_0 L}{R + R_S + R_L}$ （考虑信号源内阻和负载电阻)

表明：
Q_L降低 ⟹通频带加宽





2.1 选频网络

串联谐振回路——串联谐振回路

谐振曲线：

$$N(f)=\frac{\dot{I}}{\dot{I}_0}=\frac{1}{1+j\xi}$$

电感品质因素：$Q=\frac{\omega L}{R}$

幅频：

$$|N(f)|=\left|\frac{\dot{I}}{\dot{I}_0}\right|$$

特性阻抗 $\rho=\omega_0 L=\frac{1}{\omega_0 C}$

$$Q_0=\frac{(\text{电抗})\mathrm{X}}{(\text{电阻})\mathrm{R}}=\frac{\omega_0 L}{R}=\frac{\frac{1}{\omega_0 C}}{R}=\frac{\rho}{R}$$

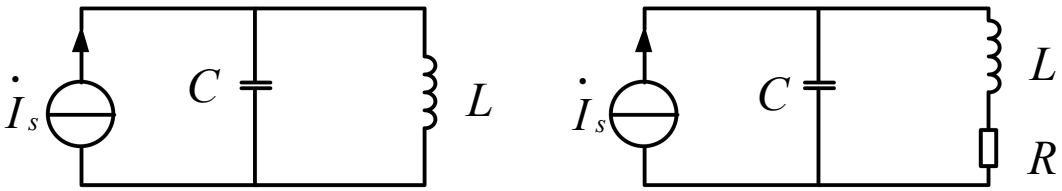
$$\xi=\frac{(\text{电抗和})\mathrm{X}}{(\text{电阻})\mathrm{R}}=\frac{\omega L-\frac{1}{\omega C}}{R}\approx Q_0\bullet\frac{2\Delta f}{f_0}\Rightarrow Q_0\bullet B=f_0$$

相频：

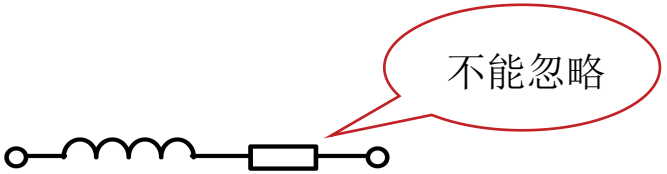
$$\psi=-\mathrm{arctg}\,\xi$$

2.1 选频网络

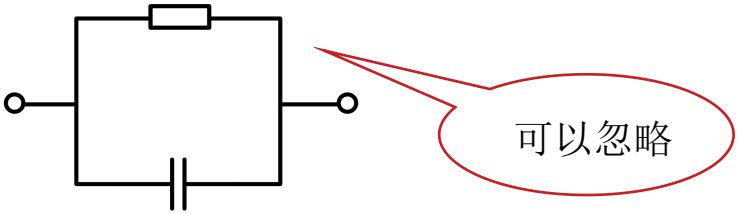
并联谐振回路



电感器=电感L 串 损耗电阻R



电容器=电容C 并 损耗电阻R



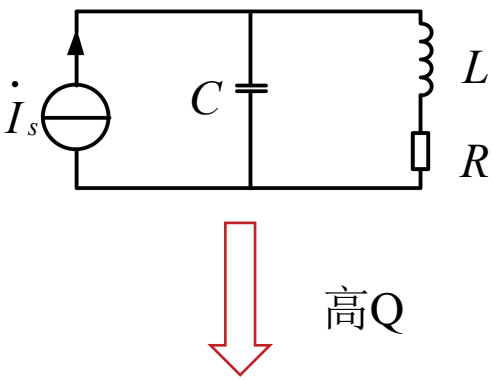
2.1 选频网络

并联谐振回路——阻抗Z、导纳Y

总阻抗

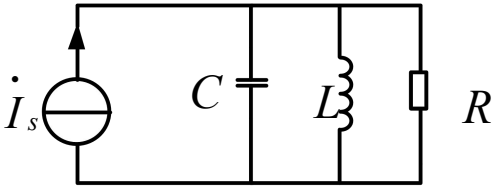
$$Z=\frac{(\mathrm{R}+\mathrm{j}\omega L)\frac{1}{j\omega C}}{(\mathrm{R}+j\omega L)+\frac{1}{j\omega C}}=\frac{\mathrm{j}\omega L\frac{1}{j\omega C}}{\mathrm{R}+j(\omega L-\frac{1}{\omega C})}$$

$$\approx\frac{\frac{L}{C}}{R+j(\omega L-\frac{1}{\omega C})}=\frac{1}{\frac{CR}{L}+j(\omega\mathrm{C}-\frac{1}{\omega L})}$$



总导纳

$$Y=G+jB=\frac{CR}{L}+j(\omega\mathrm{C}-\frac{1}{\omega L})$$



电导

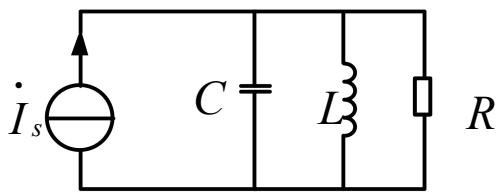
$$G=\frac{CR}{L}$$

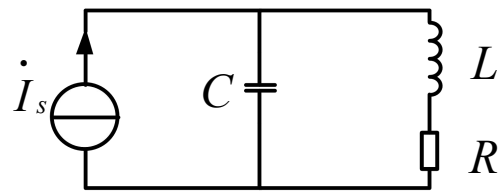
电纳

$$B=\omega C-\frac{1}{\omega L}$$

2.1 选频网络

并联谐振回路——R_p与R关系



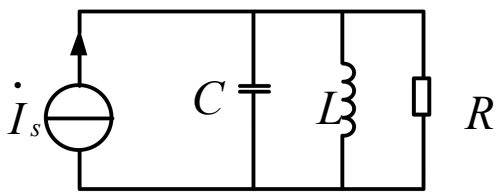


$$R_\rho = \frac{1}{G} = \frac{L}{CR}$$

思考题：R_p与R关系

2.1 选频网络

并联谐振回路——导纳Y



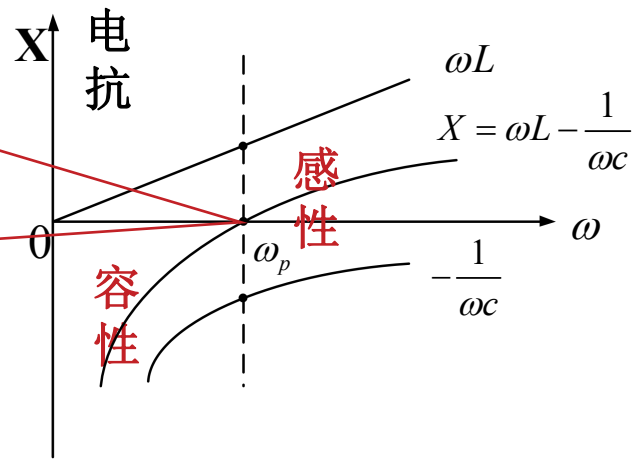
电纳 $B=\omega C-\dfrac{1}{\omega L}$ ⇦ $Y=G+jB=\dfrac{CR}{L}+j(\omega C-\dfrac{1}{\omega L})$

谐振频率

ω_0:

$$X=\omega_0 L-\frac{1}{\omega_0 c}=0$$

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



➢ 阻抗性质随频率的变化规律：

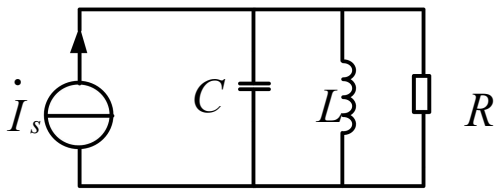
1）$\omega>\omega_0, X>0$ 呈感性，电压超前

2）$\omega<\omega_0, X<0$ 呈容性，电流超前

3）$\omega=\omega_0, X=0$ 呈纯阻性

2.1 选频网络

并联谐振回路——导纳Y



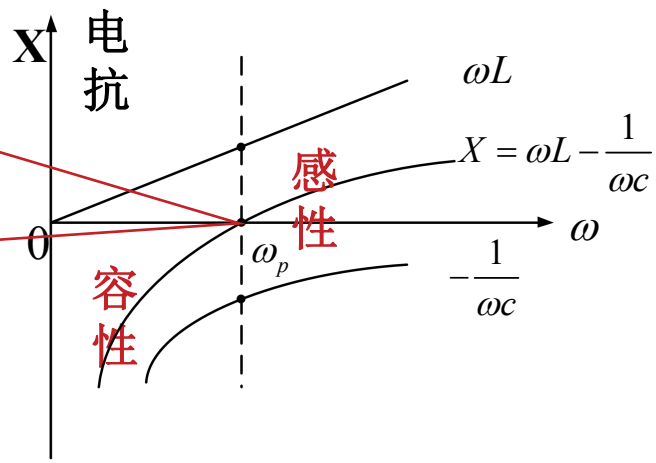
电纳 $B=\omega C-\dfrac{1}{\omega L}$ ⇦ $Y=G+jB=\dfrac{CR}{L}+j(\omega C-\dfrac{1}{\omega L})$

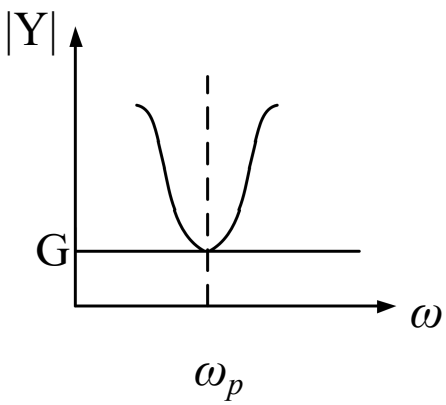
谐振频率

ω_0:

$$X=\omega_0 L-\frac{1}{\omega_0 c}=0$$

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



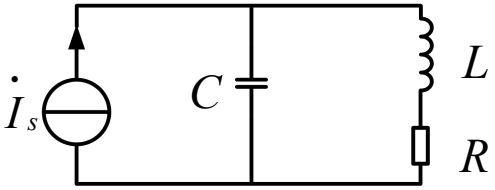


2.1 选频网络

并联谐振回路——品质因数

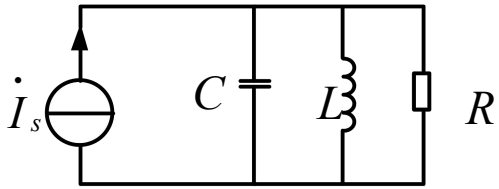
$$Q_p=\frac{\omega_p L}{R}=\frac{\frac{1}{\omega_p C}}{R}=\frac{\rho}{R}=\frac{(\text{电抗})\mathrm{X}}{(\text{电阻})\mathrm{R}}$$

R形式的Q_p



$$Q_p=\frac{1}{\omega_p L}\bullet R_p=\omega_p C\bullet R_p$$

R_p形式的Q_p



$$Q_p=\frac{\frac{1}{\omega_p L}}{G}=\frac{\omega_p C}{G}=\frac{(\text{电纳})\mathrm{B}}{(\text{电导})\mathrm{G}}$$

G形式的Q_p

$$R_\rho=\frac{1}{G}=\frac{L}{CR}$$

本质：损耗电阻R，还有并联形式R_p(G是R_p的倒数)

2.1 选频网络

串联谐振回路——电流谐振

并联谐振时，电感和电容支路的电流：

$$\dot{I}_{Cp} = j\omega_p C \cdot R_p \dot{I}_S = j\omega_p C \cdot R_p \dot{I}_S = jQ_P \dot{I}_S$$

$$\dot{I}_{Lp} = \frac{1}{j\omega_p L} \cdot R_p \dot{I}_S = -j\frac{1}{\omega_p L} \cdot R_p \dot{I}_S = -jQ_P \dot{I}_S$$

$$\dot{I}_{Cp} = -\dot{I}_{Lp}$$

电流大小相等，均等于信号源电流的Q_p倍

2.1 选频网络

并联谐振回路——广义失谐系数

谐振时，

$$Q_p = \frac{(\text{电纳})\mathrm{B}}{(\text{电导})\mathrm{G}}$$

失谐时，

$$\xi = \frac{(\text{电纳和})\mathrm{B}}{(\text{电导})\mathrm{G}} = \frac{\omega C - \frac{1}{\omega L}}{G}$$

$$= \frac{\omega_p C}{G}\left(\frac{\omega}{\omega_p} - \frac{\omega_p}{\omega}\right) = Q_p\left(\frac{\omega}{\omega_p} - \frac{\omega_p}{\omega}\right) = Q_p \frac{(\omega + \omega_p)(\omega - \omega_p)}{\omega\omega_p}$$

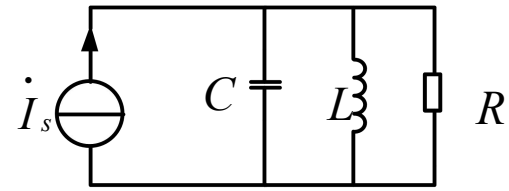
$$\xi \approx Q_p \frac{2(\omega - \omega_p)}{\omega_p}$$

$$\xi = Q_p \cdot \frac{2\Delta\omega}{\omega_p} \quad \text{或} \quad \xi = Q_p \cdot \frac{2\Delta f}{f_p}$$

2.1 选频网络

并联谐振回路——谐振曲线

$$Y=\frac{CR}{L}+j(\omega C-\frac{1}{\omega L})=G_p+j(\omega C-\frac{1}{\omega L})$$

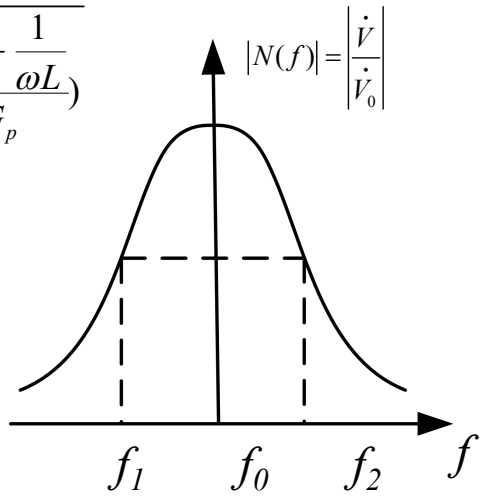


电压： $\dot{V}=\frac{\dot{I}_S}{Y}=\frac{\dot{I}}{G_p+j(\omega C-\frac{1}{\omega L})}\sim\omega$

$$N(f)=\frac{\dot{V}}{\dot{V}_0}=\frac{\frac{\dot{I}}{G_p+j(\omega C-\frac{1}{\omega L})}}{\frac{\dot{I}_s}{G_p}}=\frac{G_p}{G_P+j(\omega C-\frac{1}{\omega L})}=\frac{1}{1+j(\frac{\omega C-\frac{1}{\omega L}}{G_p})}$$

$$\Rightarrow N(f)=\frac{1}{1+j\xi}$$

$$\xi=\frac{\omega C-\frac{1}{\omega L}}{G}$$



幅频曲线

2.1 选频网络

并联谐振回路——通频带

通频带：电流I下降到I_0的0.707时频率范围

$$B = 2\Delta f_{0.7} = |f_2 - f_1|$$

$$N(f) = \frac{\dot{V}}{\dot{V}_0} = \frac{1}{1 + j\xi}$$

$$|N(f)| = \frac{1}{\sqrt{1+\xi^2}} = \frac{1}{\sqrt{2}}$$

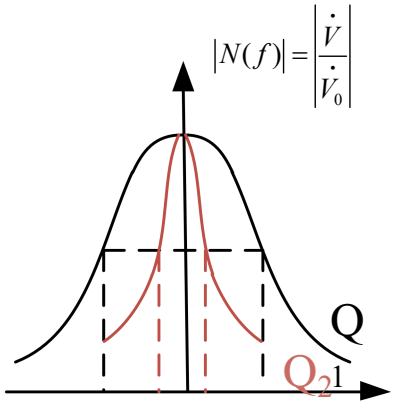
当$2\Delta f_{0.7}$
$\xi=1$

失谐系数 $\xi = Q_p \cdot \frac{2\Delta f}{f_p}$

$$1 = Q_p \cdot \frac{2\Delta f_{0.7}}{f_p}$$

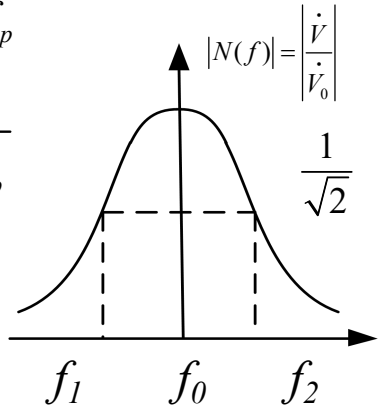
$$1 = Q_p \cdot \frac{B}{f_p}$$

表明：$Q_p \cdot B = f_p$ 品质因数与带宽乘积为常数



f_0

$Q_1 < Q_2$



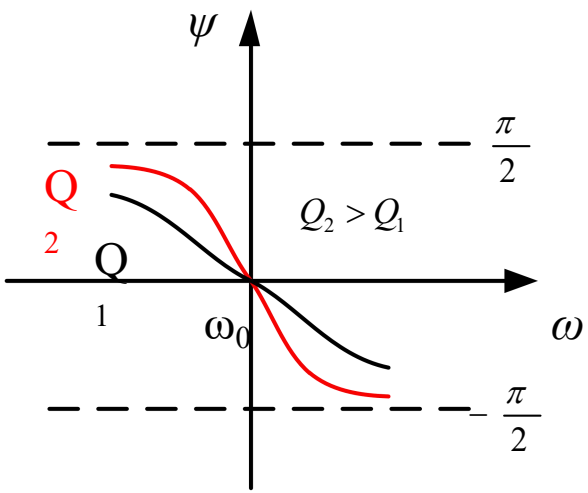
幅频曲线

2.1 选频网络

并联谐振回路——相频曲线

$$N(f)=\frac{\dot{V}}{\dot{V}_0}=\frac{1}{1+j\xi}$$

相频 $\psi=-\mathrm{arctg}\,\xi$



表明：

Q值愈大，谐振频率ω_0附近变化愈陡线性度愈差，线性范围愈窄

2.1 选频网络

并联谐振回路——考虑信号源内阻和负载电阻

空载Q值：

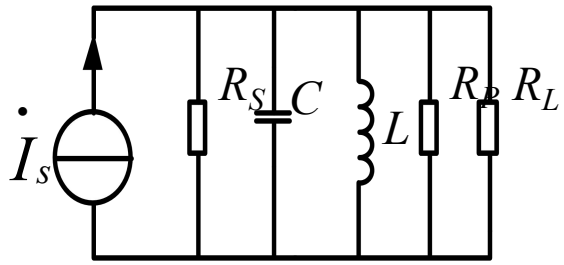
$$Q_0 = \frac{\omega_0 L}{R} = \frac{1}{\omega_p L} \cdot R_p = \frac{1}{\omega_p L} \cdot \frac{1}{G_p}$$ (未考虑信号源内阻和负载电阻)

有载Q值：

$$Q_L = \frac{1}{\omega_p L} \cdot \frac{1}{G_p + G_s + G_L}$$ (考虑信号源内阻和负载电阻)

表明：

Q_L降低 ⟹通频带加宽



2.1 选频网络

要点提示——并联谐振回路

阻抗特性：$\rho=\omega_p L=\dfrac{1}{\omega_p c}$

谐振曲线： $N(f)=\dfrac{\dot{I}}{\dot{I}_0}=\dfrac{1}{1+j\xi}$

幅频： $|N(f)|=\left|\dfrac{\dot{V}}{\dot{V}_0}\right|$

$$Q_p=\frac{\omega_p L}{R}=\frac{\frac{1}{\omega_p C}}{R}=\frac{\rho}{R}=\frac{(\text{电抗})\mathrm{X}}{(\text{电阻})\mathrm{R}}$$

R形式的Q_p

$$Q_p=\frac{1}{\omega_p L}\bullet R_p=\omega_p C\bullet R_p$$

R_p形式的Q_p

$$Q_p=\frac{\frac{1}{\omega_p L}}{G}=\frac{\omega_p C}{G}=\frac{(\text{电纳})\mathrm{B}}{(\text{电导})\mathrm{G}}$$

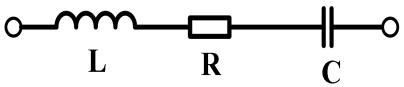
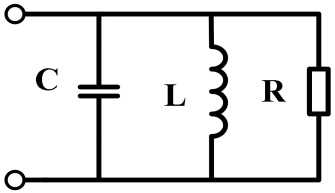
G形式的Q_p

相频 $\psi=-\mathrm{arctg}\,\xi$

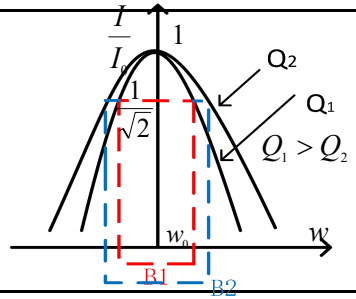
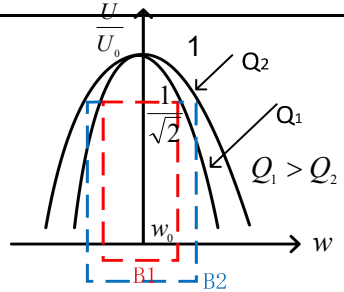
失谐 $\xi=\dfrac{(\text{电纳和})\mathrm{B}}{(\text{电导})\mathrm{G}}=\dfrac{\omega C-\frac{1}{\omega L}}{G}\approx Q_p\cdot\dfrac{2\Delta f}{f_p}\Rightarrow Q_P\cdot B=f_p$

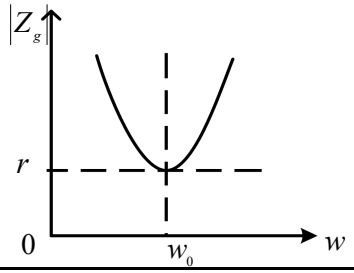
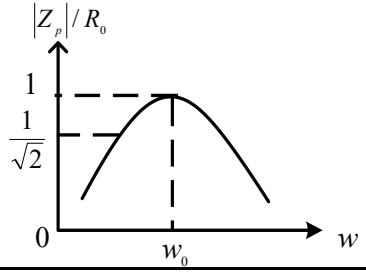
2.1 选频网络

LC串并联相比较

	串联谐振回路	并联谐振回路
电路		
谐振频率	$w_0 = \frac{1}{\sqrt{LC}}$	$w_0 = \frac{1}{\sqrt{LC}}$
空载品质因数	$Q_0 = \frac{w_0 L}{r}$	$Q_0 = \frac{R_0}{w_0 L} = \frac{w_0 L}{r}$
有载品质因数	$Q_L = \frac{w_0 L}{R_\Sigma}$	$Q_L = \frac{R_\Sigma}{w_0 L}$

2.1 选频网络

	串联谐振回路	并联谐振回路
负载影响	适宜带小负载	适宜带大负载
谐振曲线		

	串联谐振回路	并联谐振回路
阻抗特性		
作用	陷波器	选频

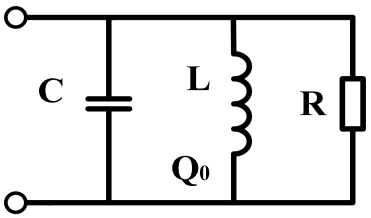
2.1 选频网络

例6：LCR并联谐振回路如下图，已知谐振频率为

$$f_0 = 10\ MHz\ ,L = 4uH\ ,Q_0 = 100\ ,R = 4k\Omega$$ ，试求：

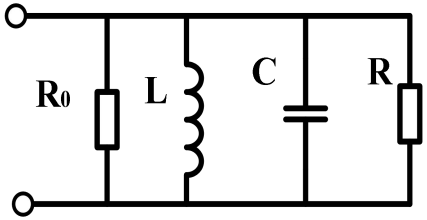
(1) 通频带

(2) 若要增大通频带为原来的2倍，还应并联一个多大的电阻。



2.1 选频网络

解：等效电路如下：



$$(1)R_0 = Q_0\omega_0 L = 100\times 2\pi\times 10\times 10^6\times 4\times 10^{-6} = 25.12(k\Omega)$$

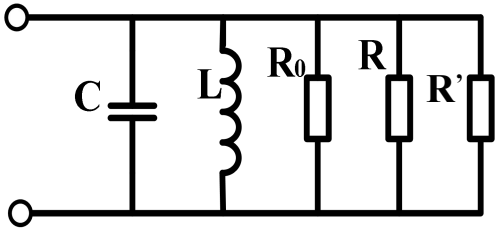
$$R_\Sigma = \frac{R_0 R}{R_0 + R} = 3.450(k\Omega)$$

$$Q_L = \frac{R_\Sigma}{\omega_0 L} = \frac{3.450\times 10^3}{2\pi\times 10\times 10^6\times 4\times 10^{-6}} = 13.74$$

$$2\Delta f_{0.7} = \frac{f_0}{Q_L} = \frac{10\times 10^6}{13.74} = 0.728\times 10^6(Hz) = 0.728(MHz)$$

2.1 选频网络

(2)设并联电阻为R'



若要求通频带增大一倍,则有载品质因数应减小一倍

$$Q_L' = \frac{1}{2}Q_L = 6.87$$

对应的 R_Σ' 应减小一倍

$$R_\Sigma' = \frac{1}{2}R_\Sigma = 1.725(k\Omega)$$

$$\frac{1}{R'} = \frac{1}{R_\Sigma'} - (\frac{1}{R} + \frac{1}{R_0}) = \frac{1}{R_\Sigma'} - \frac{1}{R_\Sigma} = 289.8\times10^{-6}(S)$$

$$\therefore R' = 3.45(k\Omega)$$

2.1 选频网络

串谐 $N(f)=\dfrac{\dot{I}}{\dot{I}_s}=\dfrac{1}{1+j\varsigma}$

幅频曲线

谐振时：$Q_0=\dfrac{(\text{电抗})X}{(\text{电阻})R}=\dfrac{w_0L}{R}=\dfrac{\frac{1}{w_0C}}{R}=\dfrac{\rho}{R}$

$$\rho=\sqrt{\frac{L}{C}}$$

$$Q_L=\frac{w_0L}{R_S+R+R_L}=\frac{\frac{1}{w_0C}}{R_S+R+R_L}$$

失谐时：$\varsigma=\dfrac{(\text{电抗差})X}{R}=\dfrac{wL-\frac{1}{wC}}{R}\approx Q_0\cdot\dfrac{2\Delta f}{f_0}$

$$Q_L\cdot 2\Delta f_{0.7}=Q_L\cdot B=f_0$$

相频曲线 $\psi=-arctg\zeta$

并谐 $N(f)=\dfrac{\dot{V}}{\dot{V}_0}=\dfrac{1}{1+j\varsigma}$

幅频曲线

谐振时：$Q_0=\dfrac{(\text{电抗})X}{(\text{电阻})R}=\dfrac{w_0L}{R}=\dfrac{\frac{1}{w_0C}}{R}=\dfrac{\rho}{R}$

$$\rho=\sqrt{\frac{L}{C}}$$

$$=R_p\cdot\frac{1}{w_pL}=R_p\cdot w_pC=\frac{R_p}{\rho}$$

$$R_p=\frac{L}{C}\frac{1}{R}=\frac{\rho^2}{R}=Q_p^2R$$

$$=\frac{(\text{电纳})B}{(\text{电导})G}=\frac{\frac{1}{w_pL}}{G_p}=\frac{w_pC}{G_p}$$

$$Q_L=\frac{\frac{1}{w_pC}}{G_S+G_p+G_L}=\frac{w_pL}{G_S+G_p+G_L}$$

失谐时：$\varsigma=\dfrac{(\text{电纳差})B}{(\text{电导})G_p}=\dfrac{wC-\frac{1}{wL}}{G_p}\approx Q_p\cdot\dfrac{2\Delta f}{f_p}$

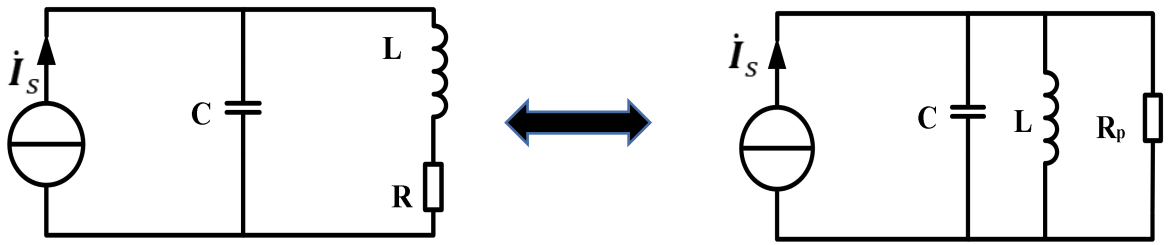
$$Q_L\cdot 2\Delta f_{0.7}=Q_L\cdot B=f_0$$

相频曲线 $\psi=-arctg\zeta$

2.1 选频网络

回顾与讨论

并谐时Q_p值：



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

电感损耗电阻

$$Q_p = \frac{R_p}{w_p L}$$

$$Q_p^2 \cdot R = R_p$$

串联形式R ⟷ 并联形式R_p

END!