自动控制原理

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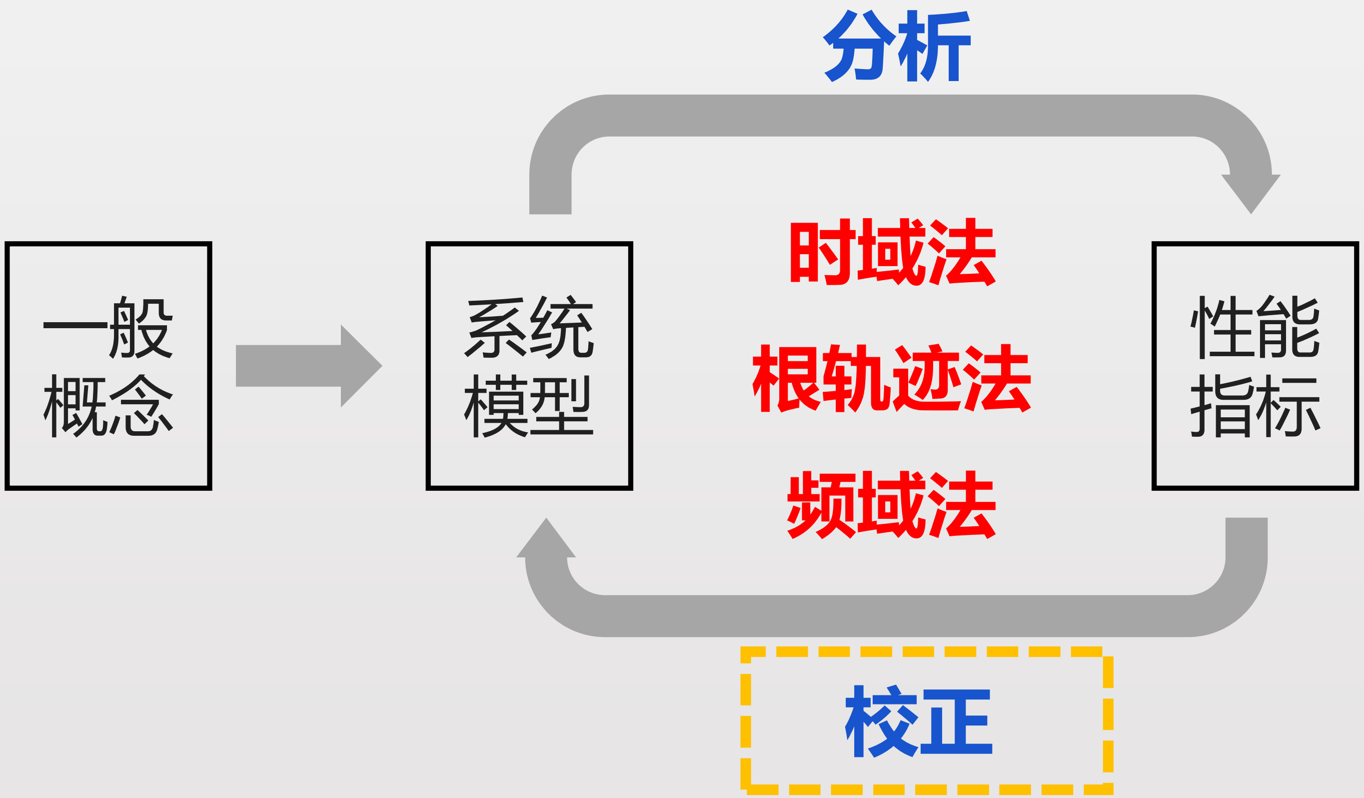
第六章 线性系统的校正

本章知识点：

- ■校正的基本概念
- ■线性系统的基本控制规律
- ■常用校正装置及其特性
- ■串联相位超前校正
- ■串联相位滞后校正
- ■串联相位滞后-超前校正


分析
一般概念
系统模型
时域法
根轨迹法
频域法
性能指标
校正

第一节 校正的基本概念

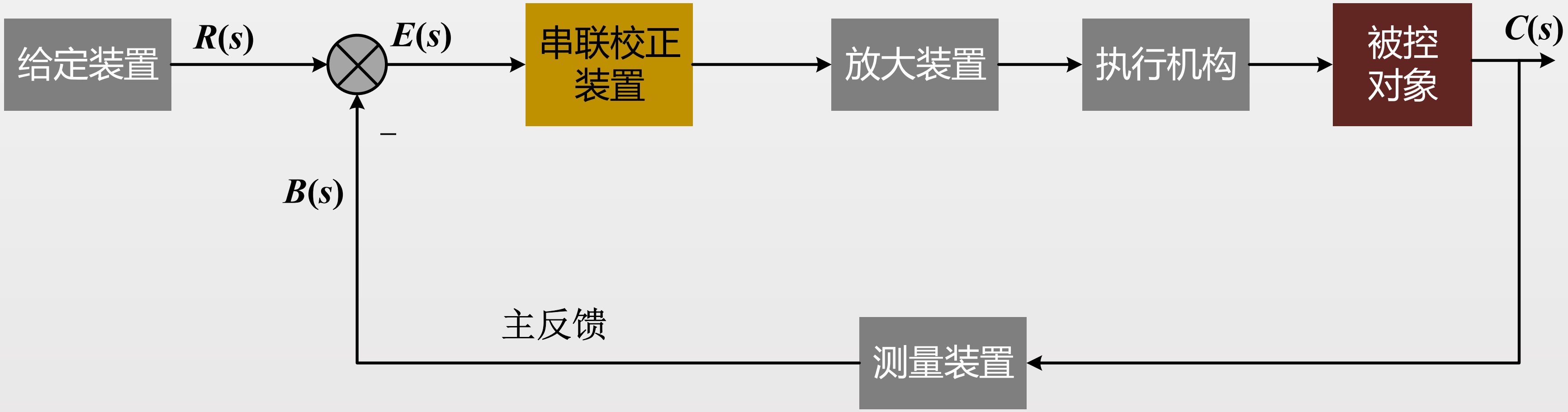
校正：

调整控制器中放大器增益；

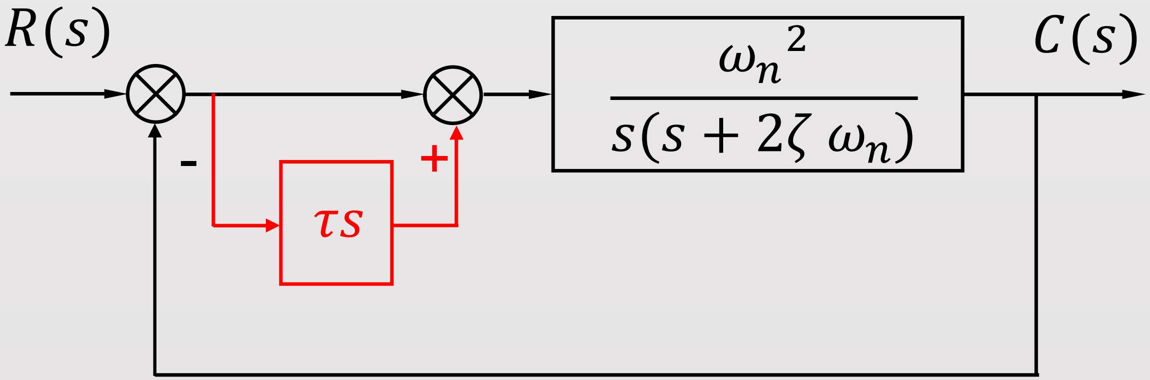
在系统中引入**附加装置**。

校正装置

串联校正： 校正装置一般接在系统误差检测点之后和放大元件之前，串联于系统前向通道之中

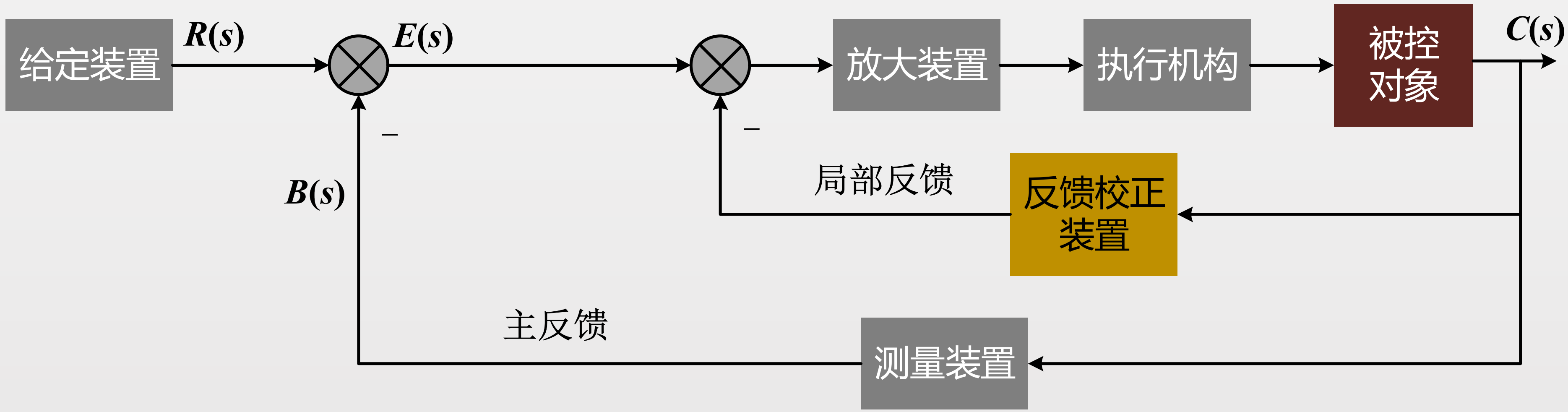


例：

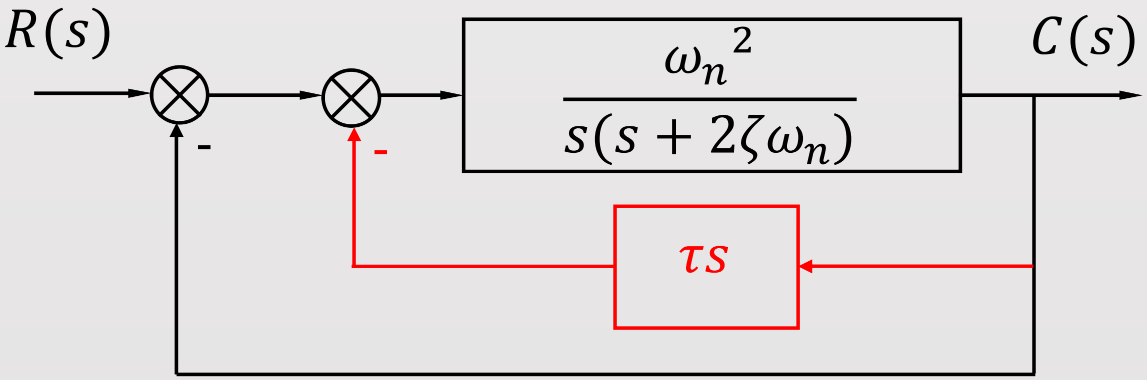


比例微分控制的二阶系统框图

反馈校正： 接在系统局部反馈通道之中



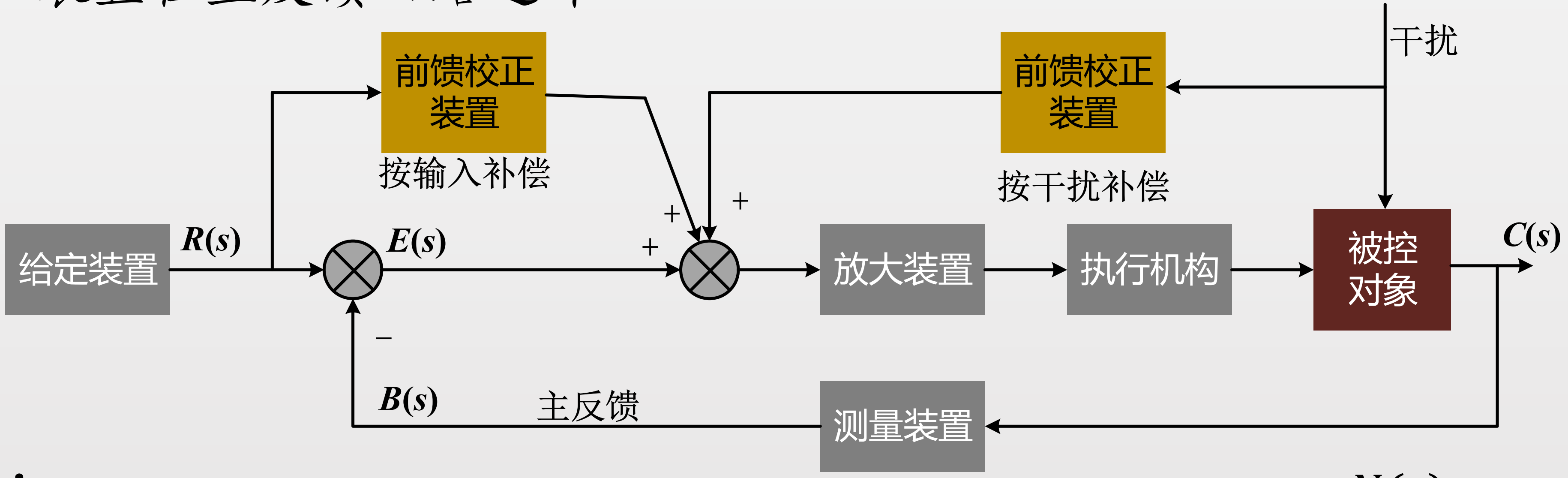
例：



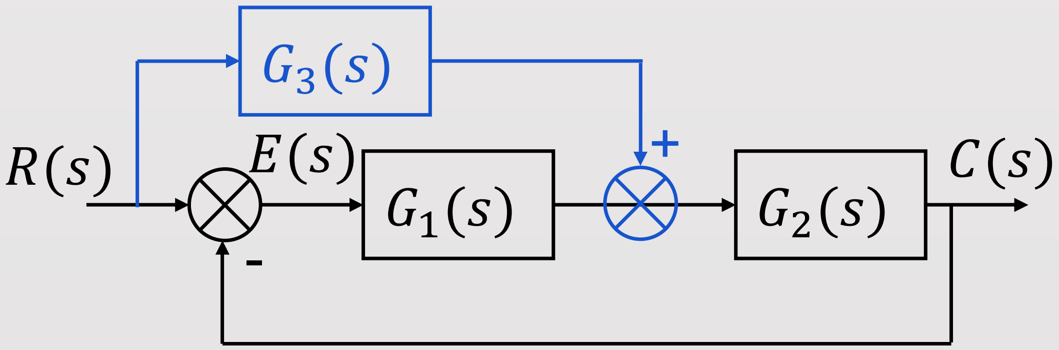
测速反馈的二阶系统框图

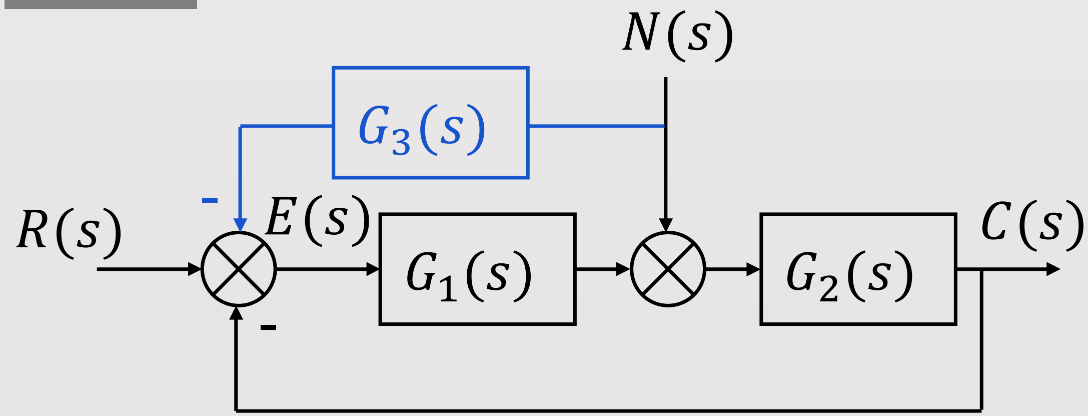
前馈校正（顺馈校正、前馈补偿、复合校正）：

校正装置在主反馈回路之外



例：

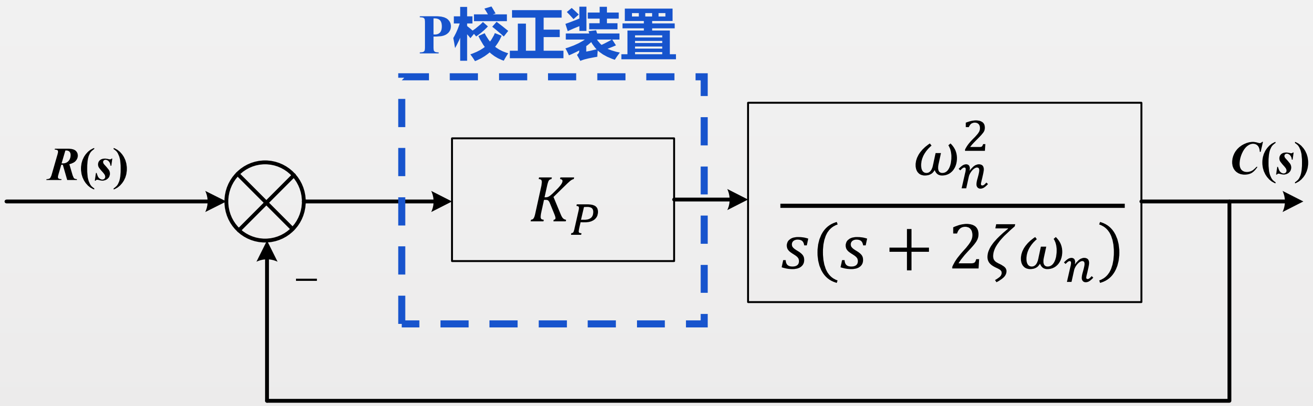




第二节 线性系统的基本控制规律

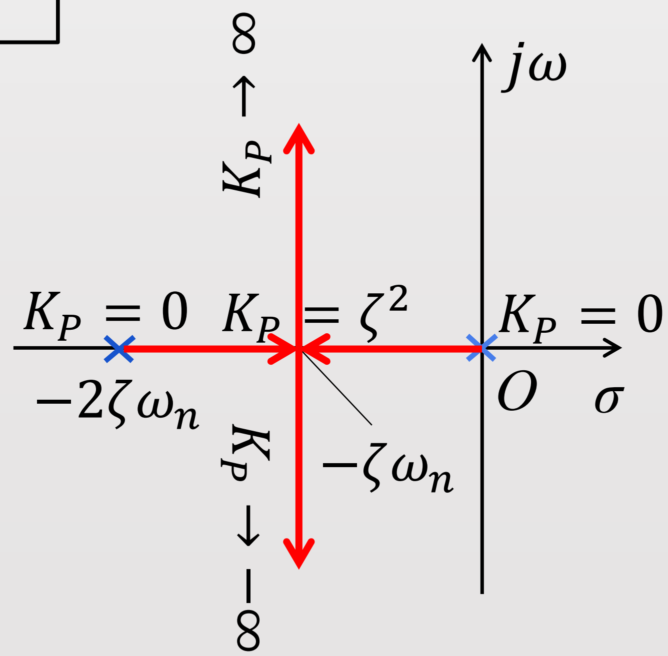
比例控制(**P**)	Proportional
积分控制(**I**)	Integral
微分控制(**D**)	Derivative

一、比例控制(P)

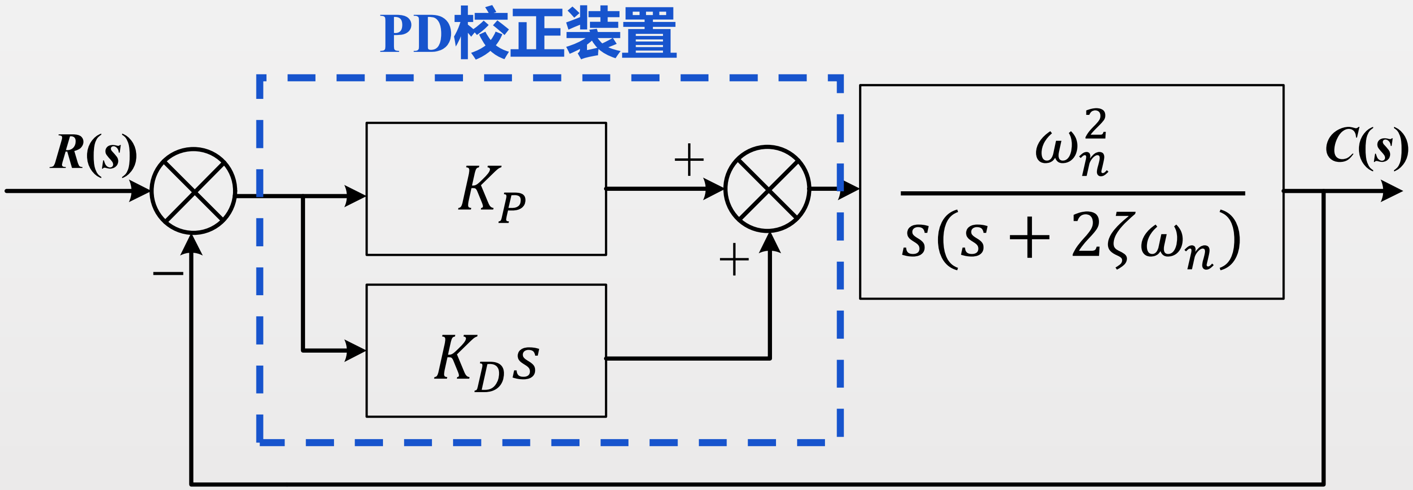


采用比例控制器的二阶系统

$$G(s) = K_P \frac{\omega_n^2}{s(s+2\zeta\omega_n)}$$



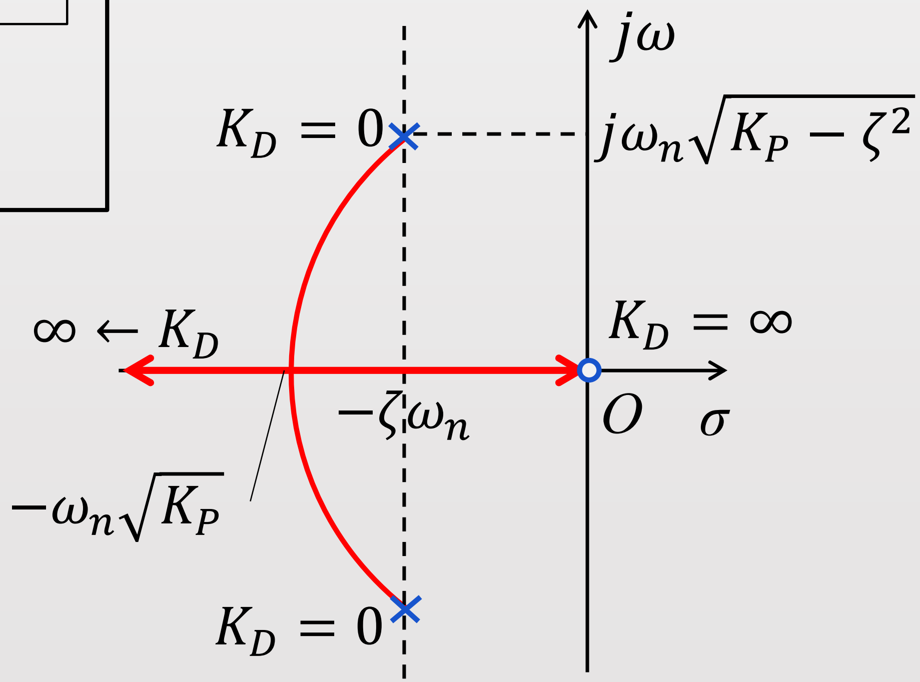
二、比例微分控制(**PD**)



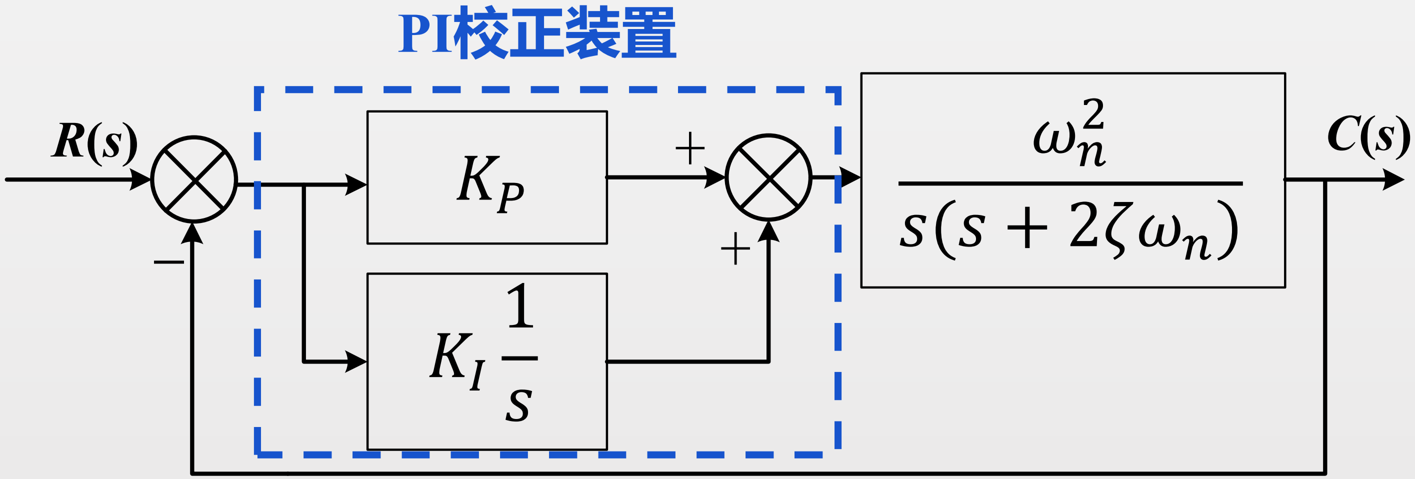
采用串联比例-微分控制器的二阶系统

$$G(s)=\frac{\omega_n^2(K_P+K_D s)}{s(s+2\zeta\omega_n)}$$

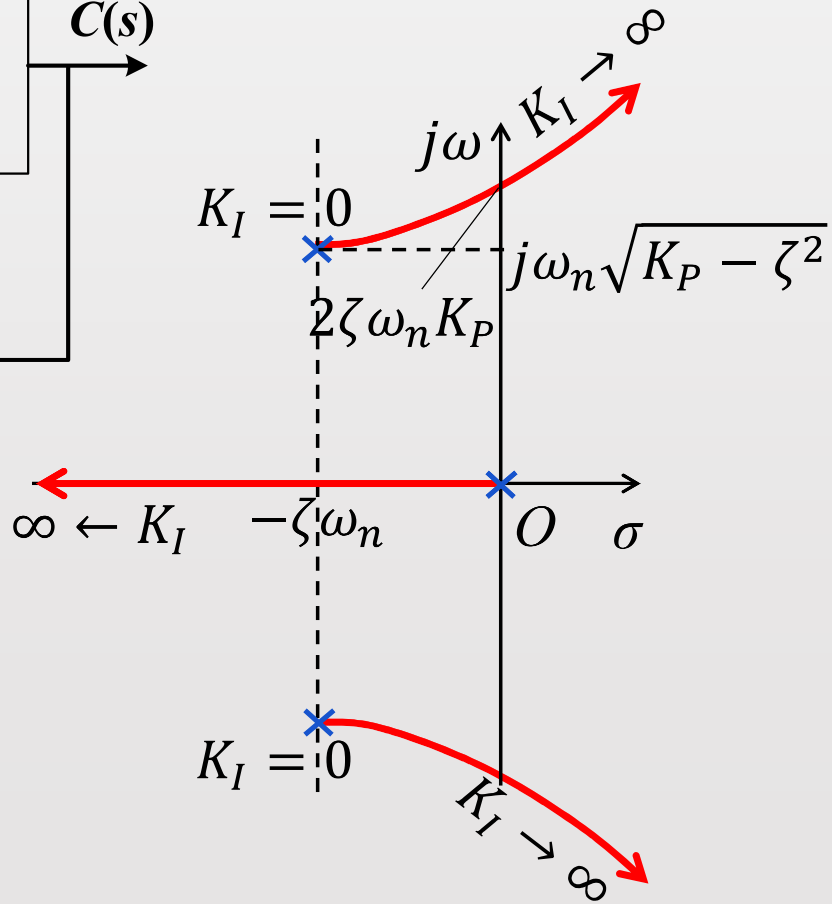
$$K_D\frac{\omega_n^2 s}{s^2+2\zeta\omega_n s+K_P\omega_n^2}=-1$$



三、比例积分控制(PI)



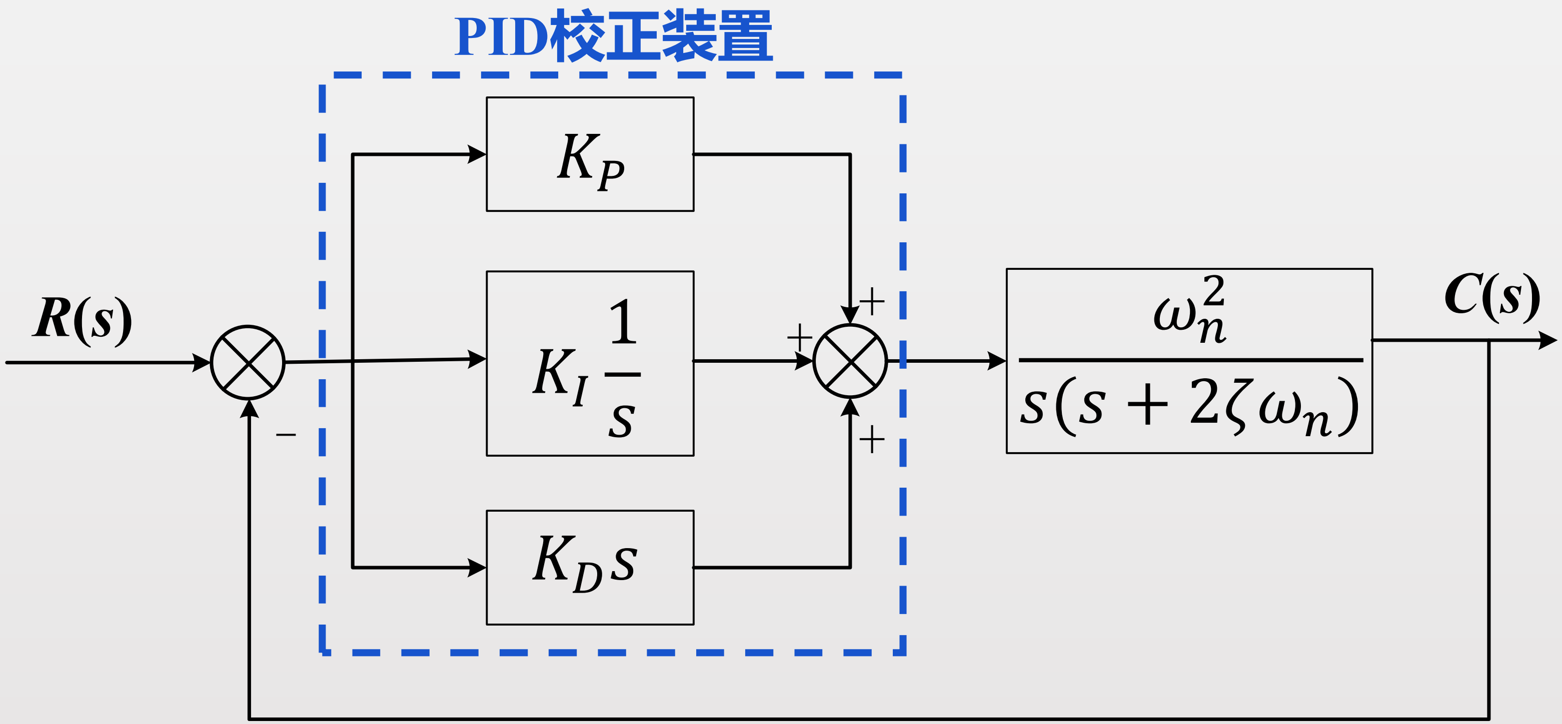
采用串联比例-积分控制器的二阶系统



$$G(s) = \frac{\omega_n^2(K_P s + K_I)}{s^2\,(s+2\zeta\omega_n)}$$

$$K_I \frac{\omega_n^2}{s(s^2 + 2\zeta\omega_n s + K_P\omega_n^2)} = -1$$

四、比例积分微分控制(PID)



采用串联比例-积分-微分控制器的二阶系统

$$G(s)=\frac{\omega_n^2(K_D s^2+K_P s+K_I)}{s^2\,(s+2\zeta\omega_n)}$$

第三节 常用校正装置及其特性

无源校正装置

有源校正装置

比例控制器

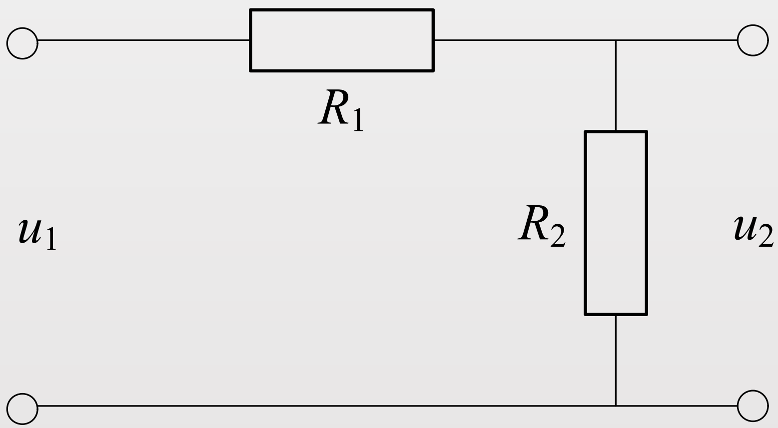
相位滞后校正装置

相位超前校正装置

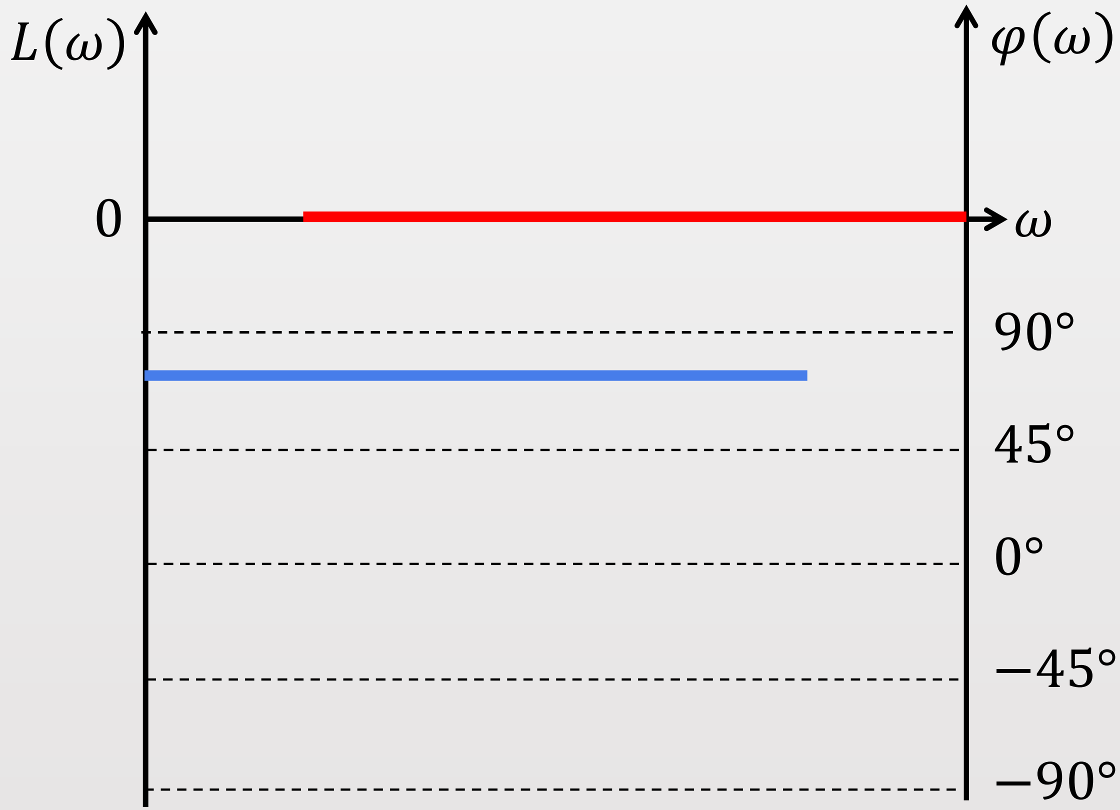
相位滞后-超前校正装置

无源校正装置

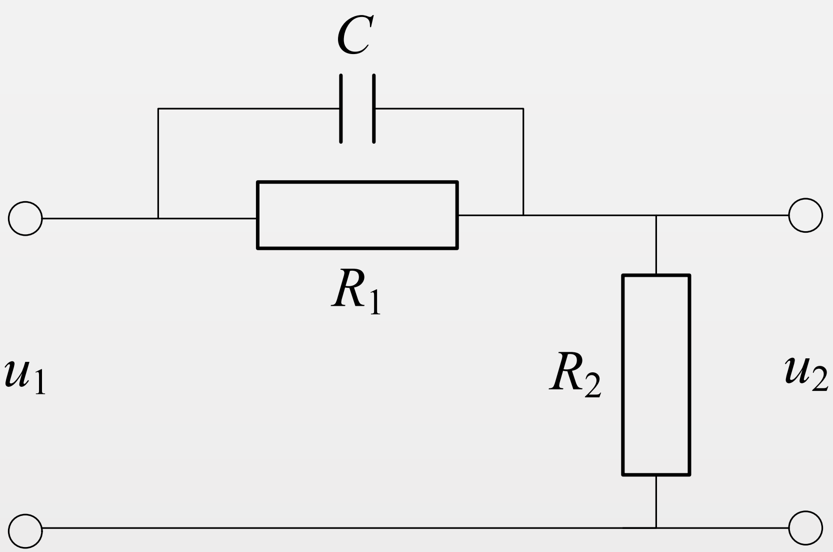
（一）比例控制器



$$K=\frac{U_2(s)}{U_1(s)}=\frac{R_2}{R_2+R_1}<1$$



（二）相位超前校正装置



$$\frac{U_2(s)}{U_1(s)} = \frac{R_2}{R_2 + \frac{1}{\frac{1}{R_1} + Cs}} = \frac{R_2(CR_1 s + 1)}{R_1 R_2 C s + R_1 + R_2}$$

$$\xRightarrow{\tau = R_1 C} \frac{R_2(\tau s + 1)}{R_2 \tau s + R_1 + R_2} = \frac{R_2}{R_1 + R_2} \cdot \frac{\tau s + 1}{\frac{R_2}{R_1 + R_2}\tau s + 1}$$

$$\xRightarrow{\alpha = \frac{R_2}{R_1 + R_2}} \alpha\left(\frac{\tau s + 1}{\alpha \tau s + 1}\right)$$

$$\boxed{\boldsymbol{G_c(s) = \frac{\tau s + 1}{\alpha \tau s + 1}}}$$

$$\varphi(\omega) = \arctan(\tau\omega) - \arctan(\alpha\tau\,\omega)$$
$$= \arctan\frac{\tau\omega(1-\alpha)}{1+\alpha\tau^2\omega^2}$$

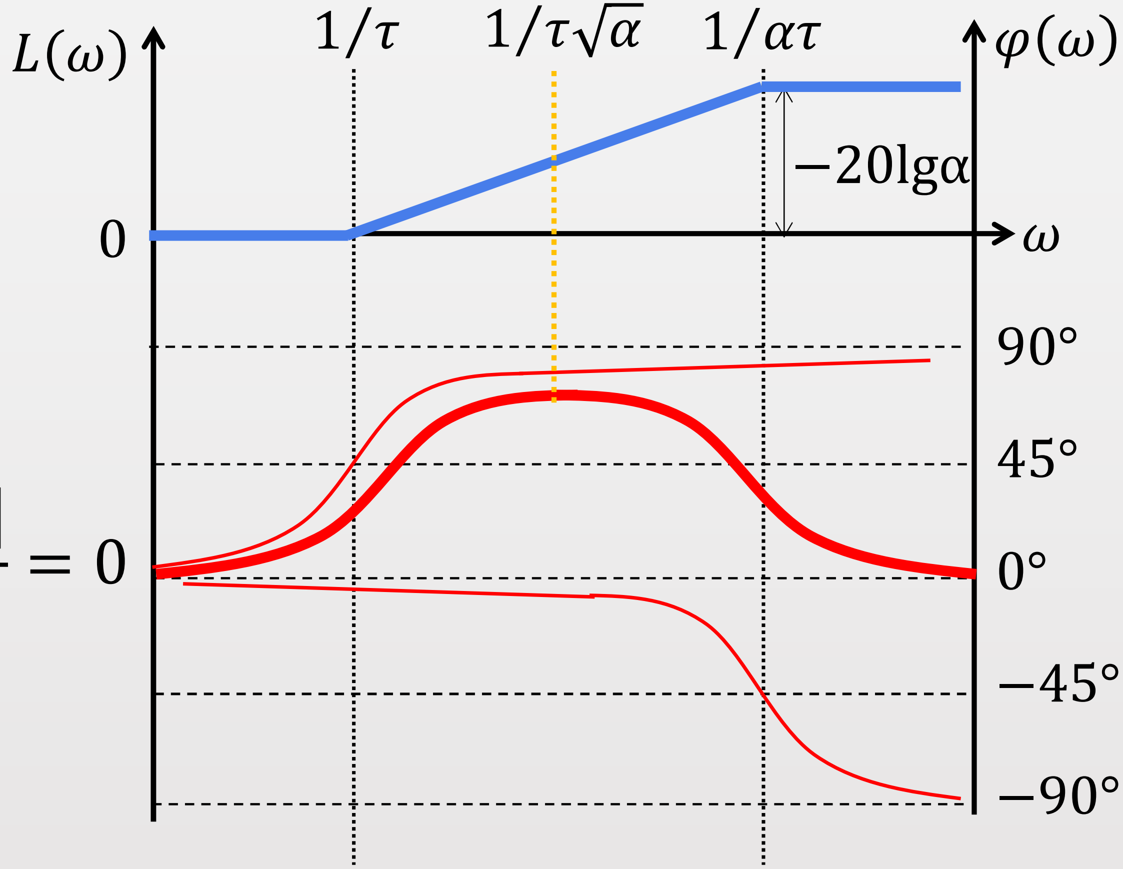
$$\frac{d\varphi(\omega)}{d\omega} = 0 \quad \Rightarrow \quad \frac{d}{d\omega}[\tan\varphi\,(\omega)] = 0$$

$$\frac{d}{d\omega}\left[\frac{\tau\omega(1-\alpha)}{1+\alpha\tau^2\omega^2}\right] = \frac{\tau(1-\alpha)[1-\alpha\tau^2\omega^2]}{(1+\alpha\tau^2\omega^2)^2} = 0$$

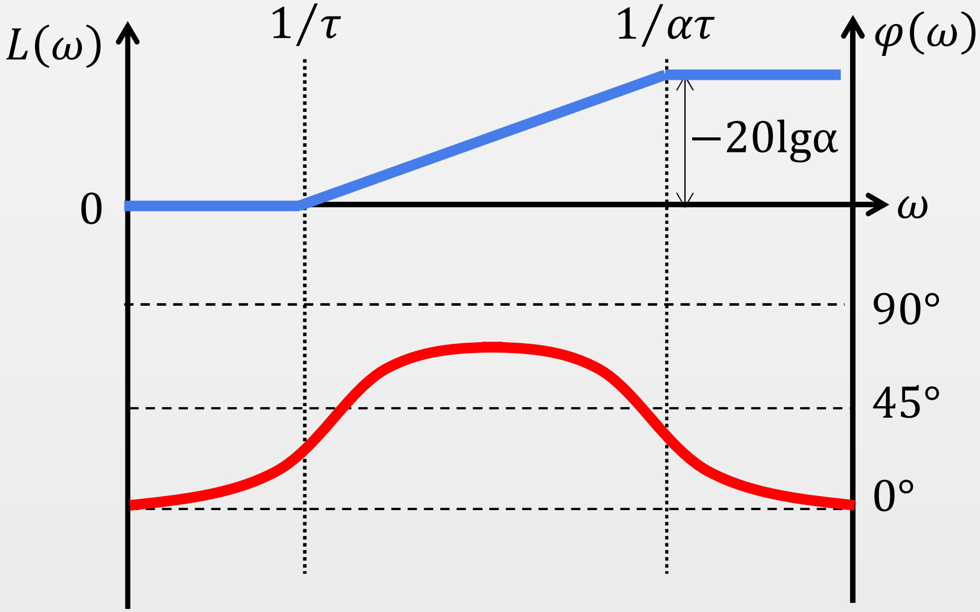
最大超前相位频率： $\omega_m = \dfrac{1}{\tau\sqrt{\alpha}}$

$$\varphi_m = \arctan\frac{1-\alpha}{2\sqrt{\alpha}} = \arcsin\frac{1-\alpha}{1+\alpha}$$

$$L(\omega_m) = -10\lg\alpha$$



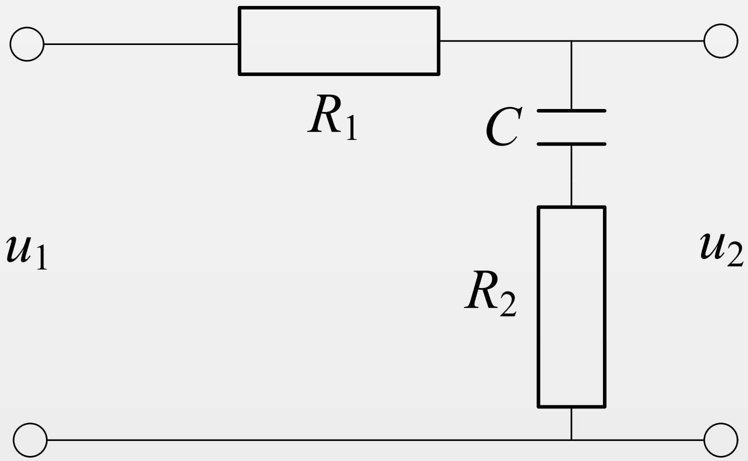
$$G_c(j\omega) = \frac{j\omega\tau + 1}{j\alpha\omega\tau + 1}$$



作用:

- 相位超前，即适当选择校正装置参数，使最大超前角频率ω_m置于校正后系统的剪切频率处，就可以有效增加系统的相角裕度，提高系统的相对稳定性。
- 幅值增加，即将校正装置的对数幅频特性叠加到原系统开环对数幅频特性上，会使系统的剪切频率右移（增大），有利于提高系统响应的快速性。

（三）相位滞后校正装置



$$\frac{U_2(s)}{U_1(s)} = \frac{R_2 + \frac{1}{Cs}}{R_1 + R_2 + \frac{1}{Cs}} = \frac{R_2Cs + 1}{(R_1 + R_2)Cs + 1}$$

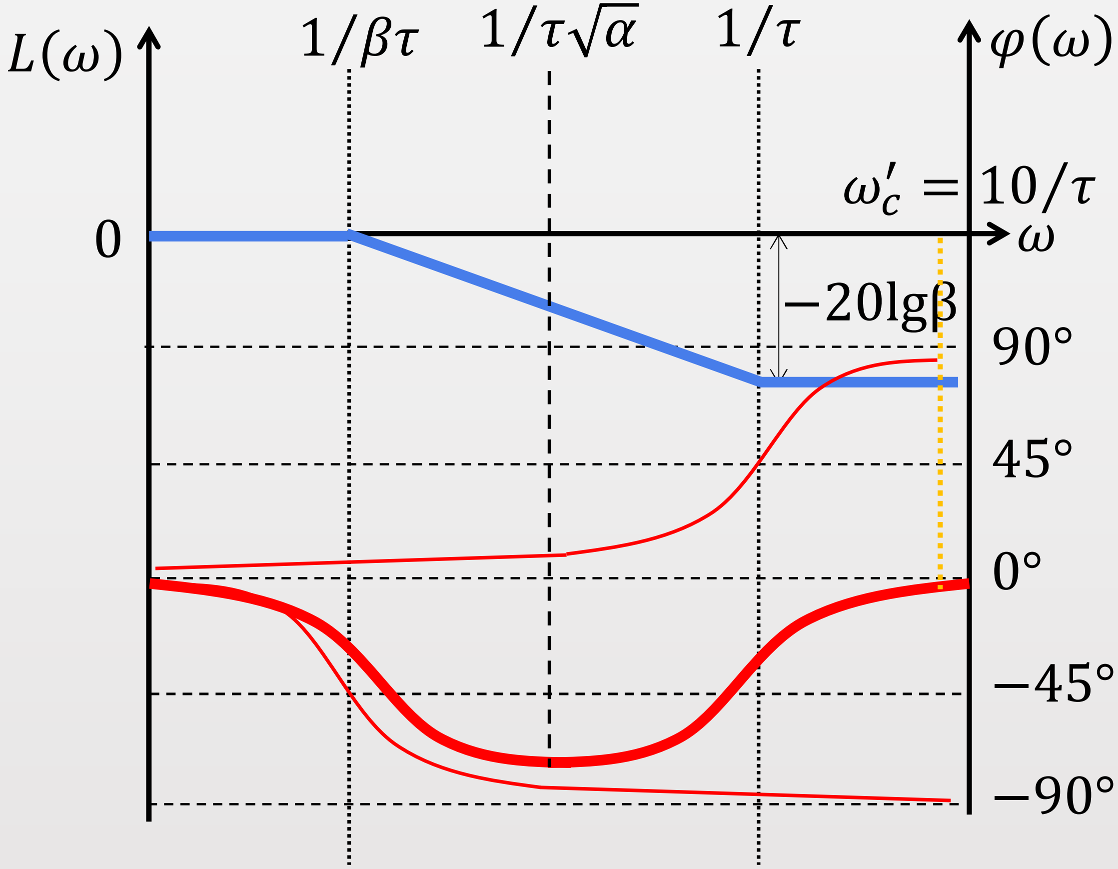
$$\xRightarrow{\tau = R_2C} \frac{\tau s + 1}{(R_1 + R_2)Cs + 1} = \frac{\tau s + 1}{\frac{R_1 + R_2}{R_2}\tau s + 1}$$

$$\xRightarrow{\beta = \frac{R_1 + R_2}{R_2}} \frac{\tau s + 1}{\beta\tau s + 1}$$

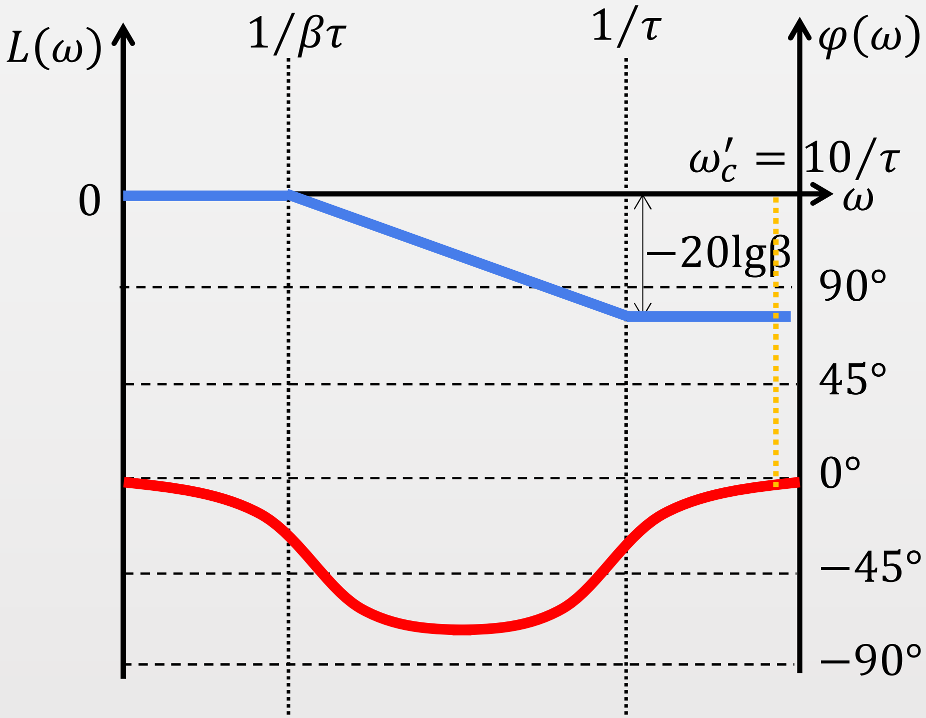
$$\boxed{\boldsymbol{G_c(s) = \frac{\tau s + 1}{\beta\tau s + 1}}}$$

$$\varphi\left(\frac{10}{\tau}\right) = \arctan(10) - \arctan(10\beta)$$
$$= \arctan\frac{10(1-\beta)}{1+100\beta}$$

$$\lim_{\beta\to\infty}\varphi\left(\frac{10}{\tau}\right) = \lim_{\beta\to\infty}\arctan\frac{10(1-\beta)}{1+100\beta}$$
$$= \arctan\frac{-1}{10} = -5.7106° > -6°$$



$$G_c(j\omega) = \frac{j\omega\tau + 1}{j\beta\omega\tau + 1}$$



作用：

- 利用幅值衰减特性，可以挖掘原系统自身的相位储备量，提高系统的稳定裕度；
- 压低了高频段，相应提高了校正后系统的抗高频干扰能力。

（四）相位滞后-超前校正装置

$$\frac{U_2(s)}{U_1(s)}=\frac{(\tau_1 s+1)(\tau_2 s+1)}{\tau_1\tau_2 s^2+(\tau_1+\tau_2+\tau_{12})s+1}$$

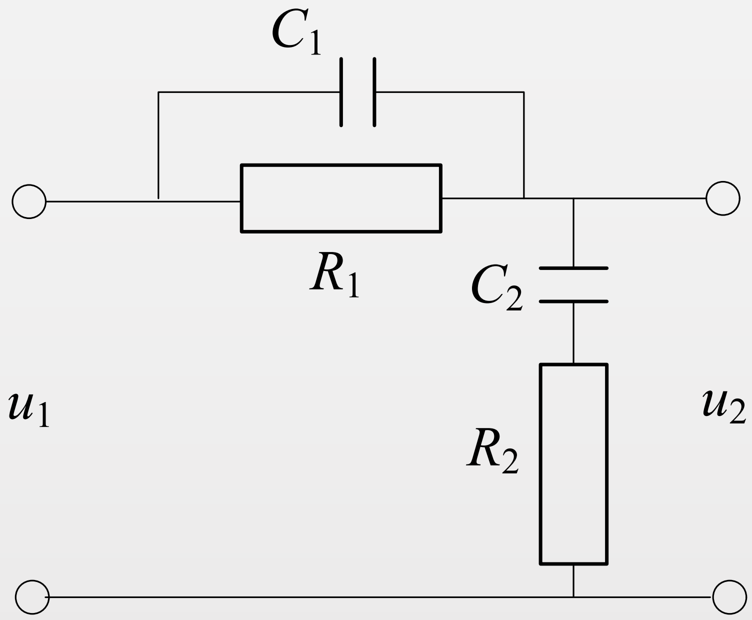
$$\begin{cases}\tau_1=R_1C_1\\ \tau_2=R_2C_2\\ \tau_{12}=R_1C_2\end{cases}$$

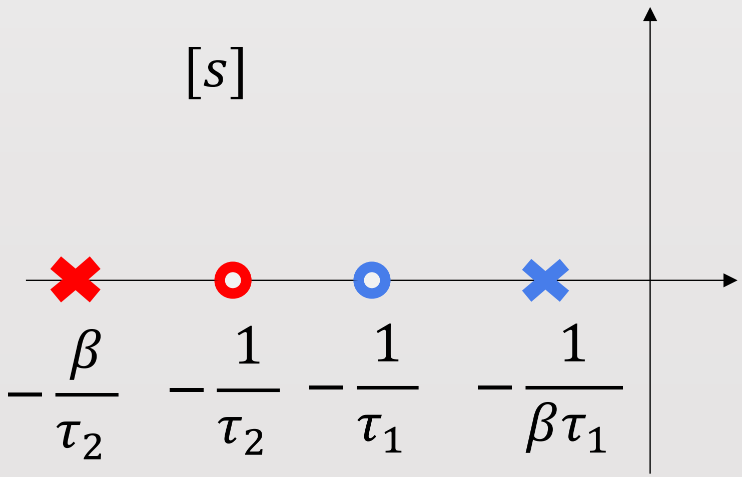
$$\beta\tau_1+\frac{\tau_2}{\beta}=\tau_1+\tau_2+\tau_{12}\qquad(\beta>1)$$

$$\beta\tau_1>\tau_1>\tau_2>\frac{\tau_2}{\beta}$$

$$=\boxed{\left(\frac{\tau_1 s+1}{\beta\tau_1 s+1}\right)}\boxed{\left(\frac{\tau_2 s+1}{\frac{\tau_2}{\beta}s+1}\right)}$$

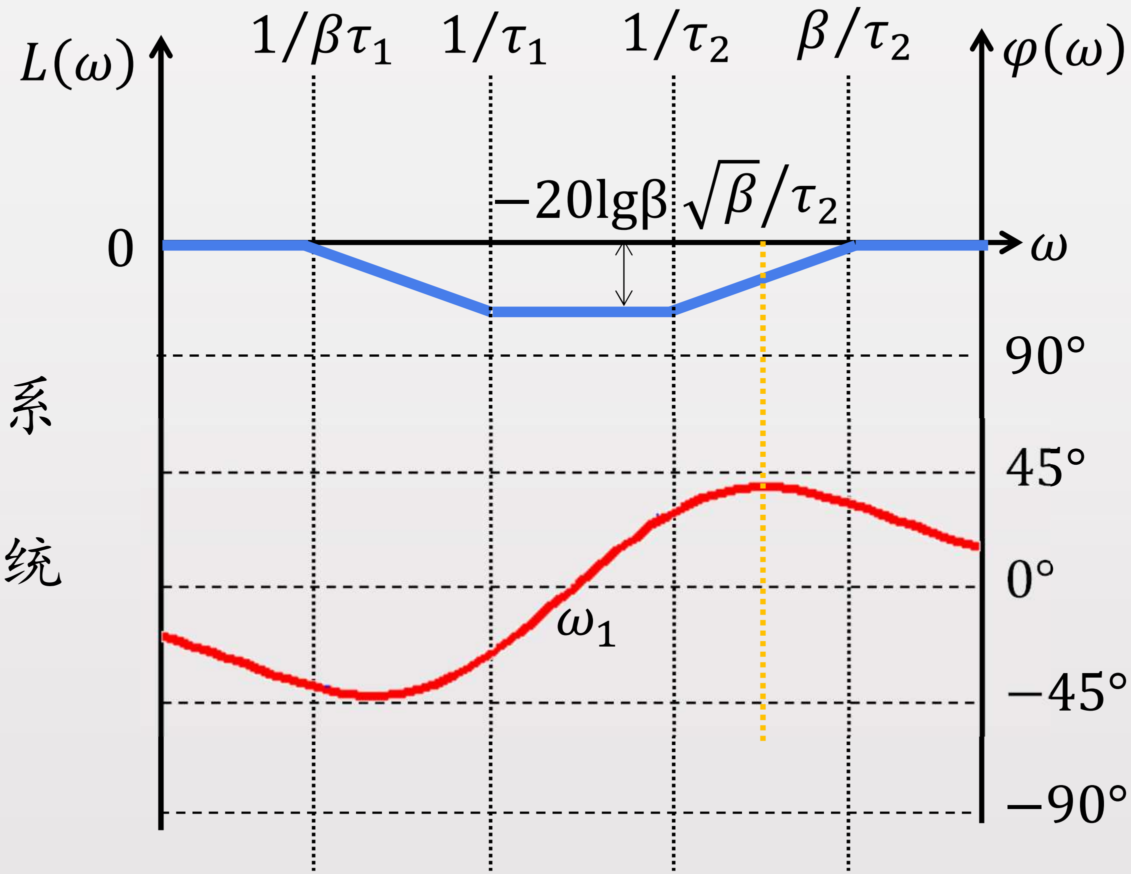
滞后部分　超前部分





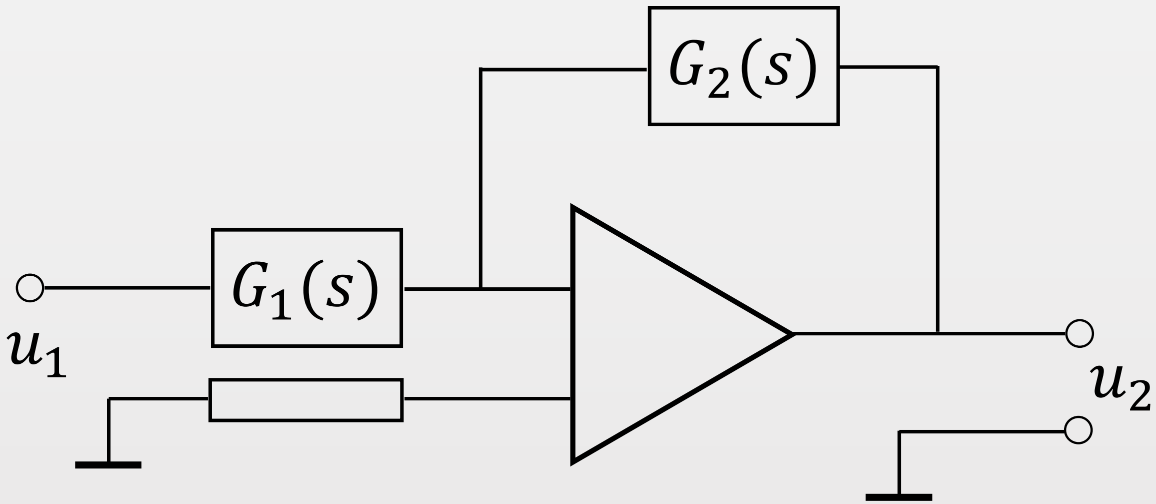
作用:

- 利用相位超前特性，有效增加系统的相角裕度；
- 利用幅值衰减特性，挖掘原系统自身的相位储备量。



$$G_c(s) = \frac{(j\omega\tau_1 + 1)(j\omega\tau_2 + 1)}{(j\omega\beta\tau_1 + 1)(\frac{j\omega\tau_2}{\beta} + 1)}$$

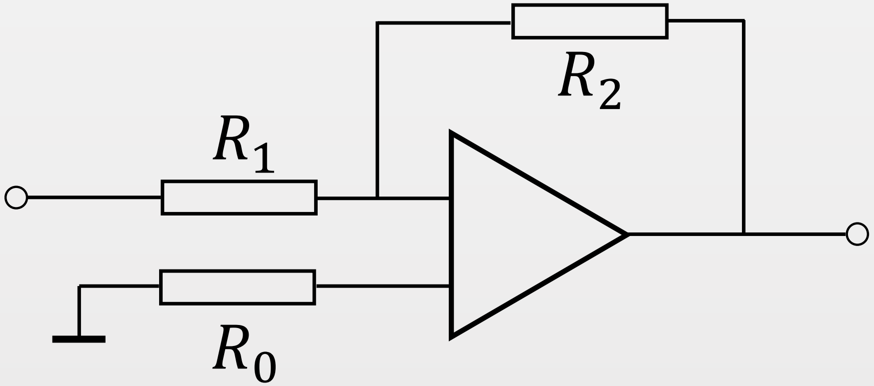
有源校正装置



有源校正装置示意图

$$G_c(s) = \frac{G_2(s)}{G_1(s)}$$

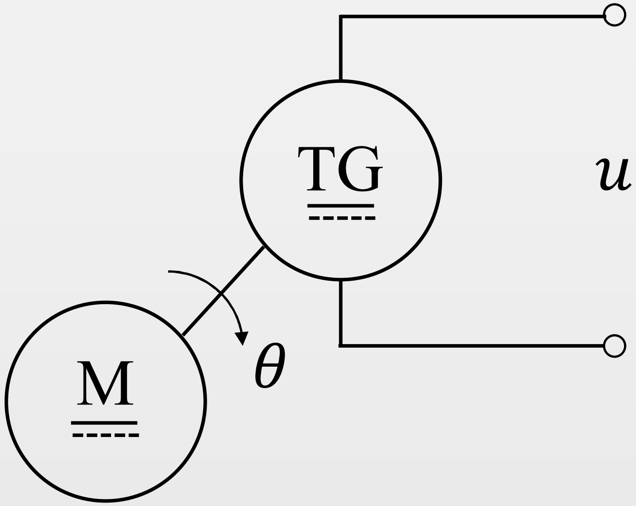
比例(P)



$$G_c(s) = K$$

$$K = \frac{R_2}{R_1}$$

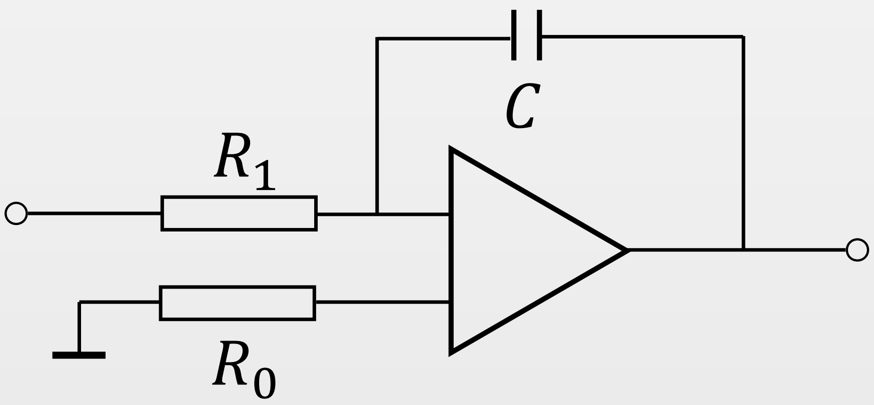
微分(D)



$$G_c(s) = Ks$$

$$u = K\frac{d\theta}{dt}$$

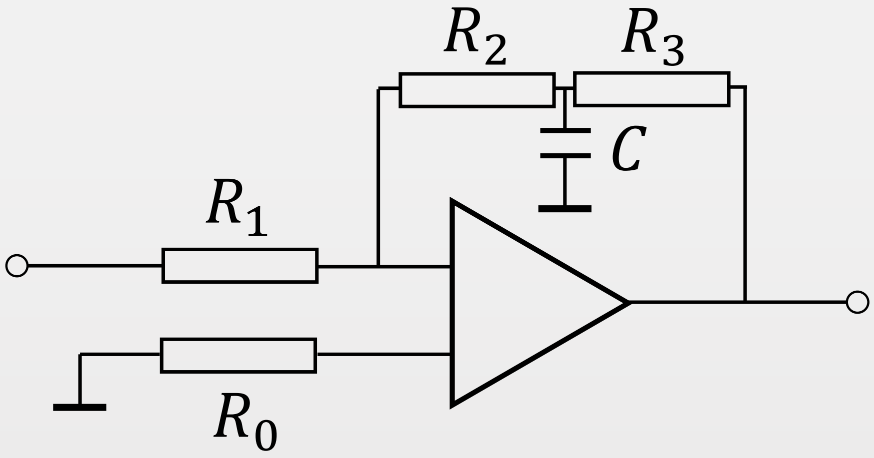
积分(I)



$$G_c(s) = \frac{1}{\tau s}$$

$$\tau = R_1 C$$

比例-微分(PD)

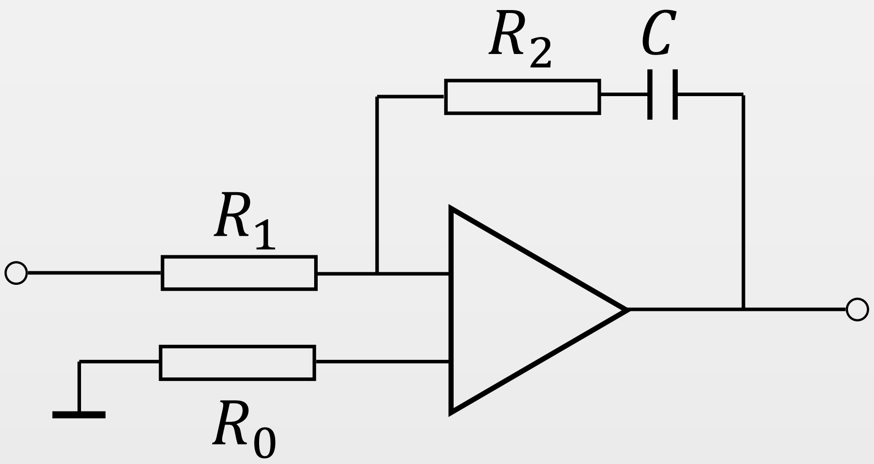


$$G_c(s) = K(\tau s + 1)$$

$$\tau = \frac{R_2 R_3}{R_1 + R_3} C$$

$$K = \frac{R_2 + R_3}{R_1}$$

比例-积分(PI)

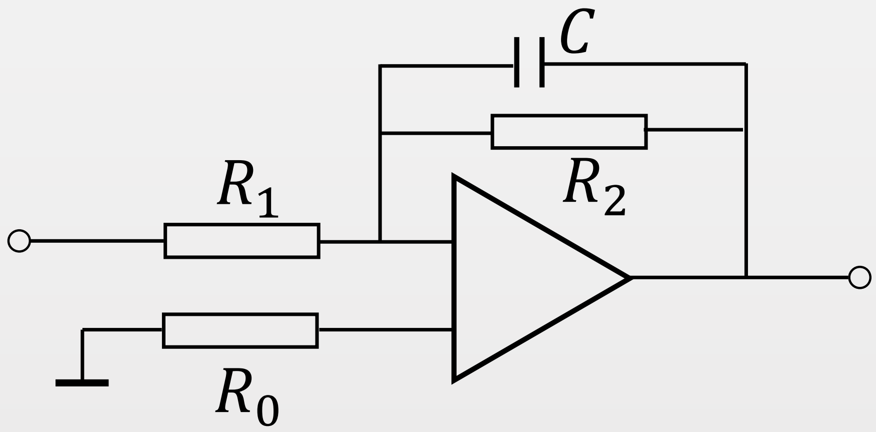


$$G_c(s) = \frac{K(\tau s + 1)}{\tau s}$$

$$\tau = R_2 C$$

$$K = \frac{R_2}{R_1}$$

滤波型调节器（惯性环节）



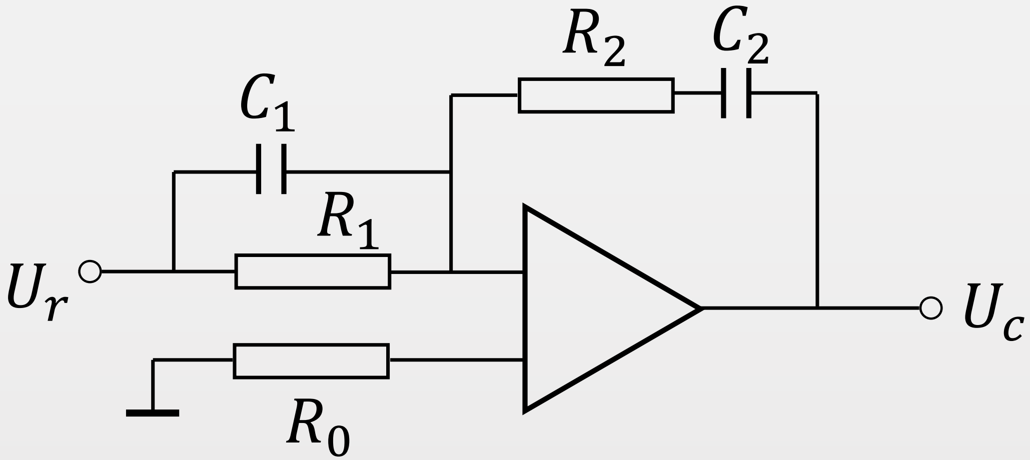
$$G_c(s) = \frac{K}{1 + \tau s}$$

$$\tau = R_2 C$$

$$K = \frac{R_2}{R_1}$$

PID控制器

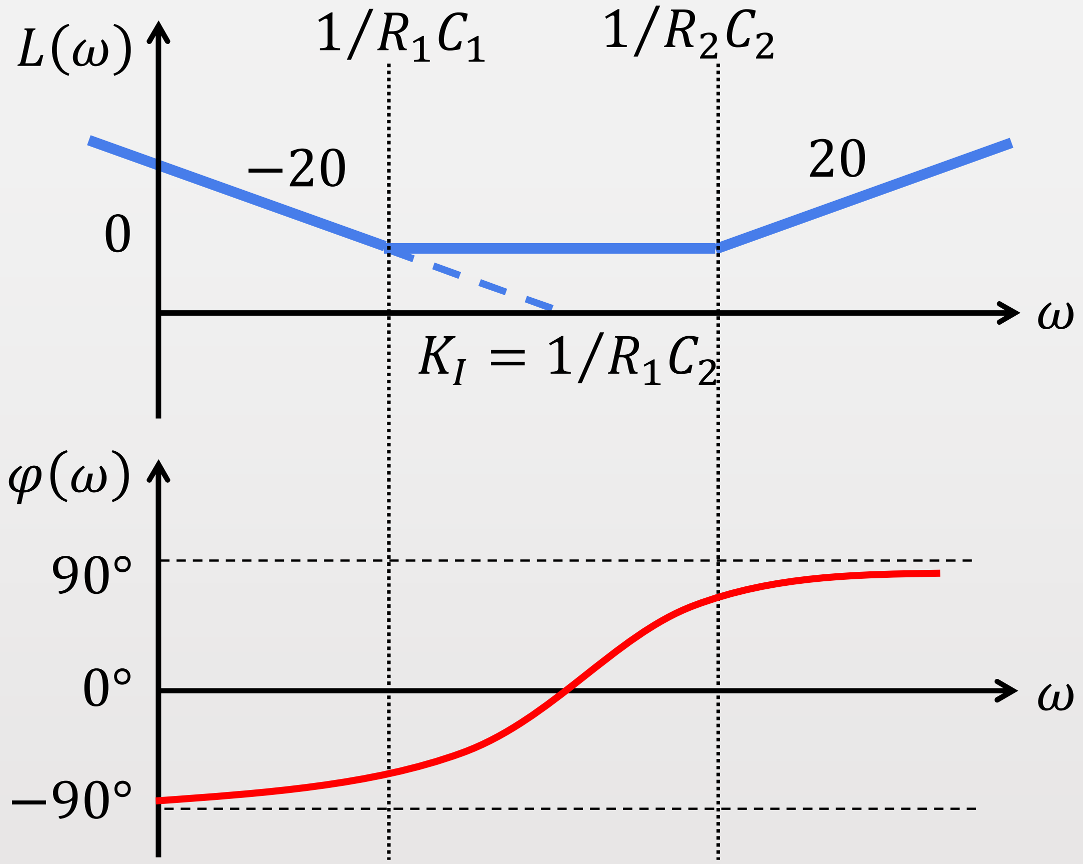
$$\frac{U_r}{\dfrac{1}{\dfrac{1}{R_1}+C_1 s}} = \frac{U_c}{R_2+\dfrac{1}{C_2 s}}$$



$$G_c(s)=\frac{U_c}{U_r}=\boxed{R_2 C_1} s+\boxed{\left(\frac{C_1}{C_2}+\frac{R_2}{R_1}\right)}+\boxed{\frac{1}{R_1 C_2}}\frac{1}{s}=K_D s+K_P+\frac{K_I}{s}$$

K_D K_P K_I

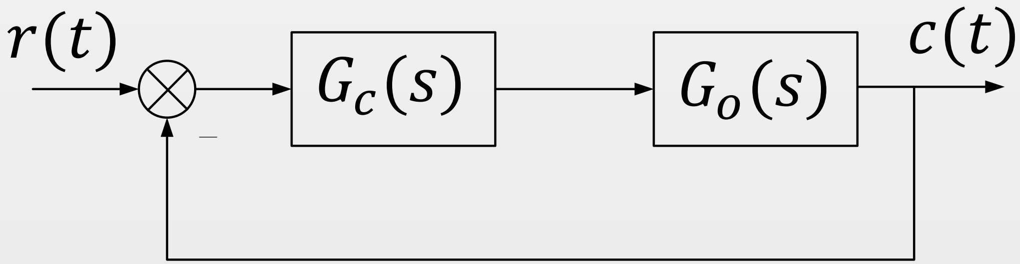
$$G_c(s) = R_2C_1s + \left(\frac{C_1}{C_2} + \frac{R_2}{R_1}\right) + \frac{1}{R_1C_2s}$$
$$= \frac{(R_1C_1s+1)(R_2C_2s+1)}{R_1C_2s}$$

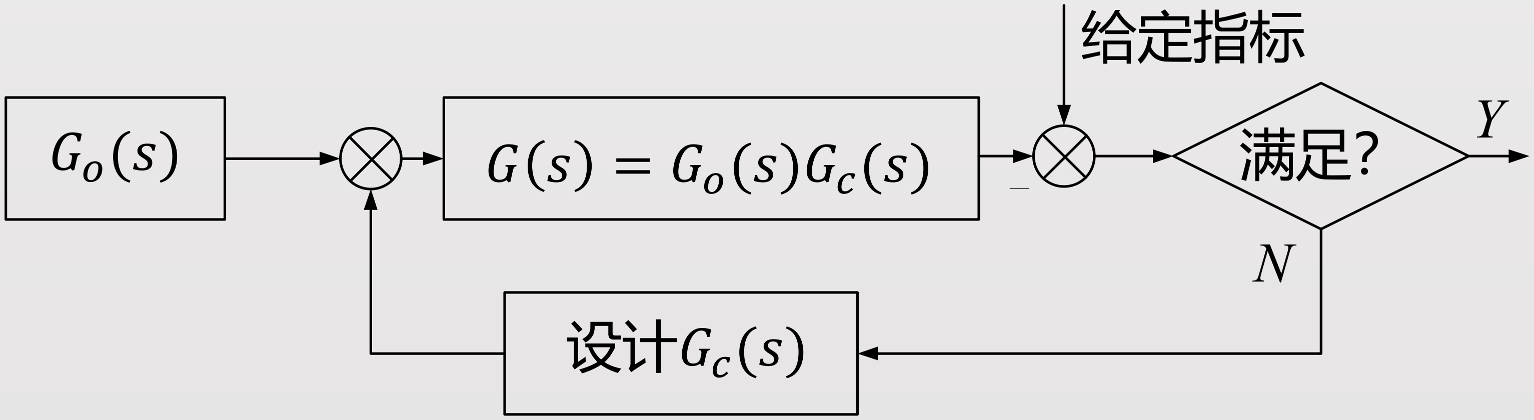


作用：

- 低频段，积分作用，改善稳态性能；
- 中高频段，微分作用，改善动态性能。

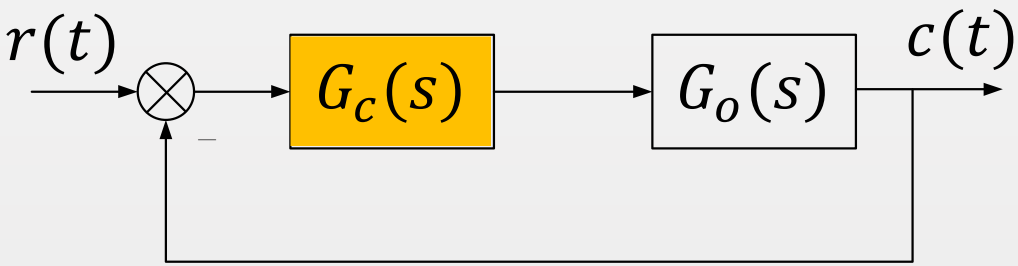
频域法串联校正的设计过程

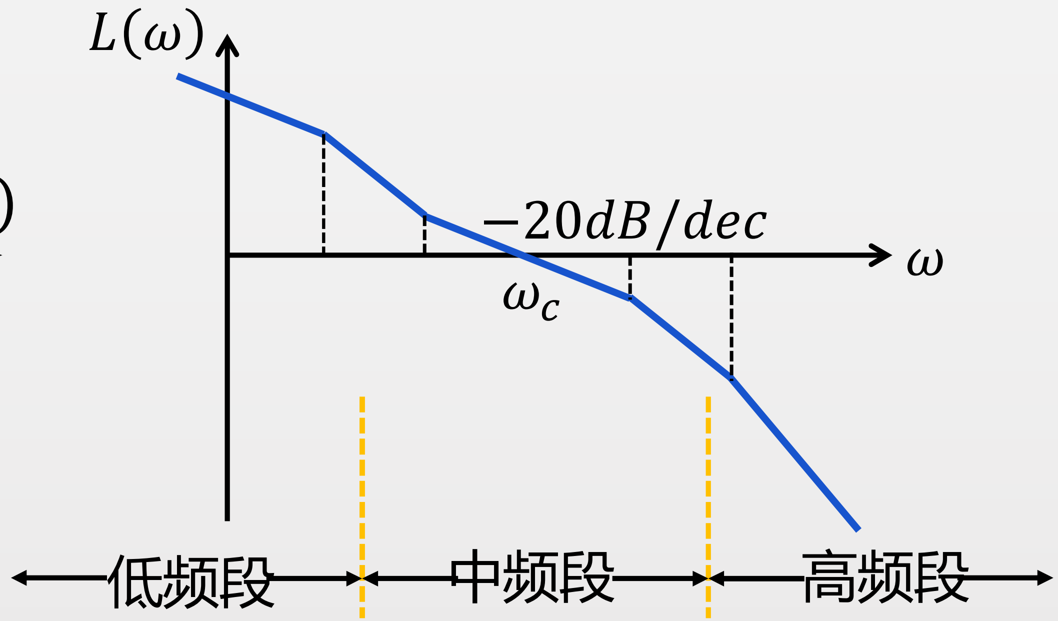




控制系统性能指标

	时域	频域（开环）	频域（闭环）
稳态性能	开环增益K 系统型别υ	(低频段) 开环增益K 系统型别υ	零频值
暂态性能	最大超调量M_p 调节时间t_s	(中频段) 剪切频率ω_c 相角裕度γ	谐振峰值M_r 带宽频率ω_b





- 低频段增益充分大，以保证稳态误差要求；
- 中频段对数幅频特性斜率一般为$-20dB/dec$，并占据充分宽的频带，以保证具备适当的相角裕度；
- 高频段增益尽快减小，以削弱噪声影响。

串联相位超前校正

原理： 利用超前网络相角超前特性增大系统的相角裕度

适用： $\omega_{c0} < \omega_c^*$、$\gamma_0 < \gamma^*$

步骤：

①由 $e_{sr}^* \to K$

②由$G_0(s) \to L_0(\omega) \to \omega_{c0} \to \gamma_0$

③确定$\varphi_m = \gamma^* - \gamma_0 + (5°\sim10°)$，$\alpha = \frac{1-\sin\varphi_m}{1+\sin\varphi_m}$，$-10\lg\alpha$

④作图设计，确定$G_c(s)$

⑤$G(s) = G_c(s)\cdot G_0(s)$，验算$\omega_c$，$\gamma$ 是否满足指标

效果：

①保持低频段　满足稳态精度

②改善中频段　$\omega_c\uparrow$、$\gamma\uparrow$，　ω_c附近斜率减小，动态性能提高

③抬高高频段　抗高频干扰能力降低

例：已知某单位反馈系统的开环传递函数为$G(s)=\frac{K}{s(s+1)}$，要求:$r(t)=t$时，$e_{sr}^* \le 0.1$，$\omega_c^* \ge 5$，$\gamma^* \ge 60°$，试确定串联校正装置的传递函数$G_c(s)$

解：①$e_{sr}^* = \frac{1}{K} \le 0.1 \qquad K \ge 10$

②确定原系统的ω_{c0}、γ_0

$\omega_{c0} = \sqrt{10} = 3.16 < \omega_c^*$

$\gamma_0 = 180° - 90° - \arctan 3.16$

$= 17.6° < \gamma^*$

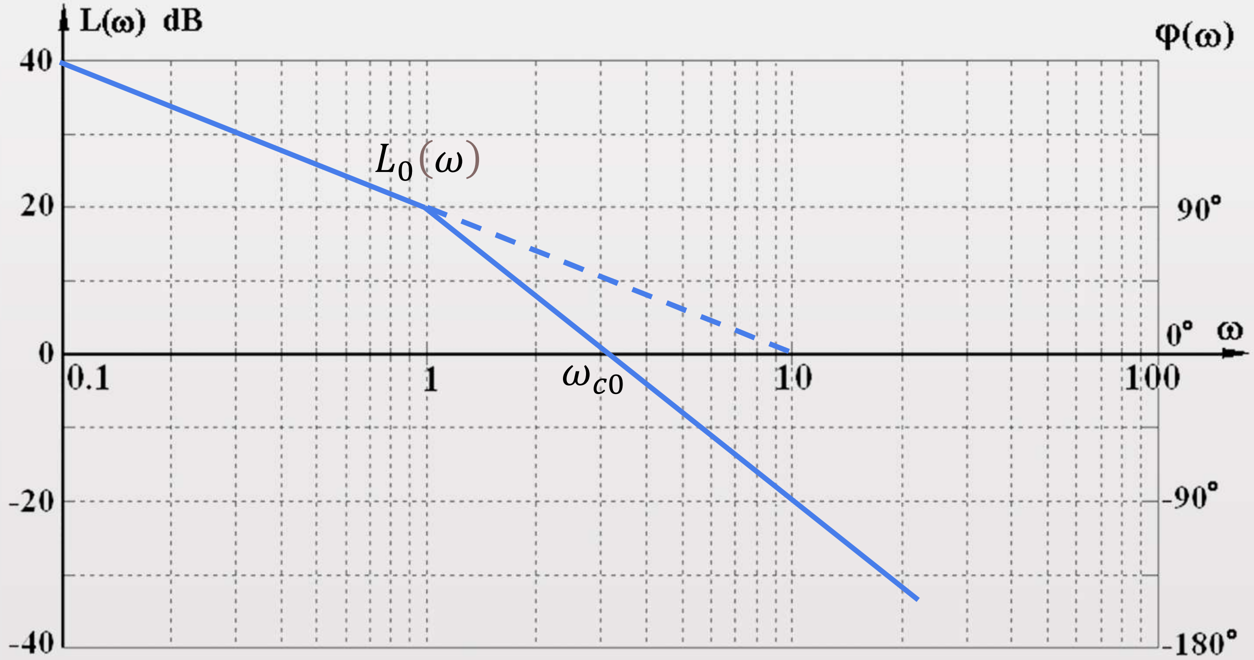
采用串联相位超前校正

③ $\varphi_m = \gamma^* - \gamma_0 + 5°$

$= 60° - 17.6° + 5° = 47.4°$

$$\alpha = \frac{1-\sin 47.4°}{1+\sin 47.4°} \approx \frac{1}{7}$$

$-10\lg\alpha = 8.5\text{dB}$



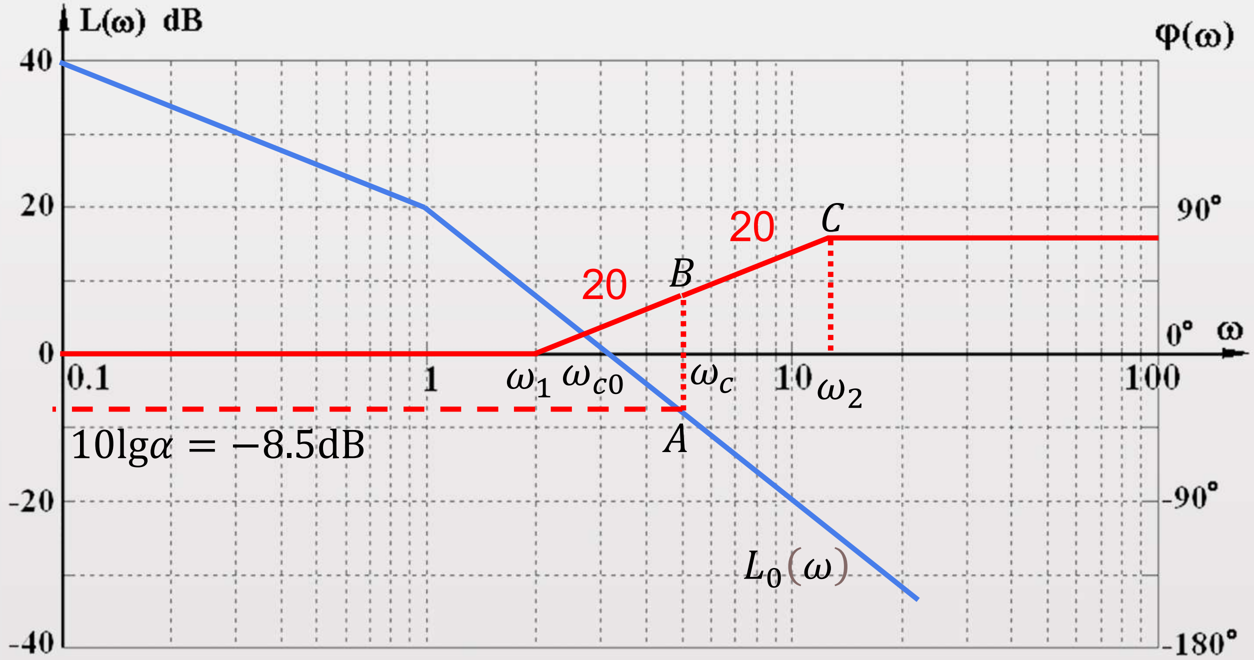
④作图设计

$$8.5 = 40\lg\frac{\omega_c}{\omega_{c0}} \quad \omega_c = 3.16 \times 10^{\frac{8.5}{40}} = 5.16 > \omega_c^*$$

$$\frac{\omega_c}{\omega_1} = \frac{\omega_2}{\omega_c} = \frac{7\omega_1}{\omega_c}$$

$$\omega_1 = 1.94 \qquad \omega_2 = 13.73$$

$$G_c(s) = \frac{\frac{s}{1.94}+1}{\frac{s}{13.73}+1}$$



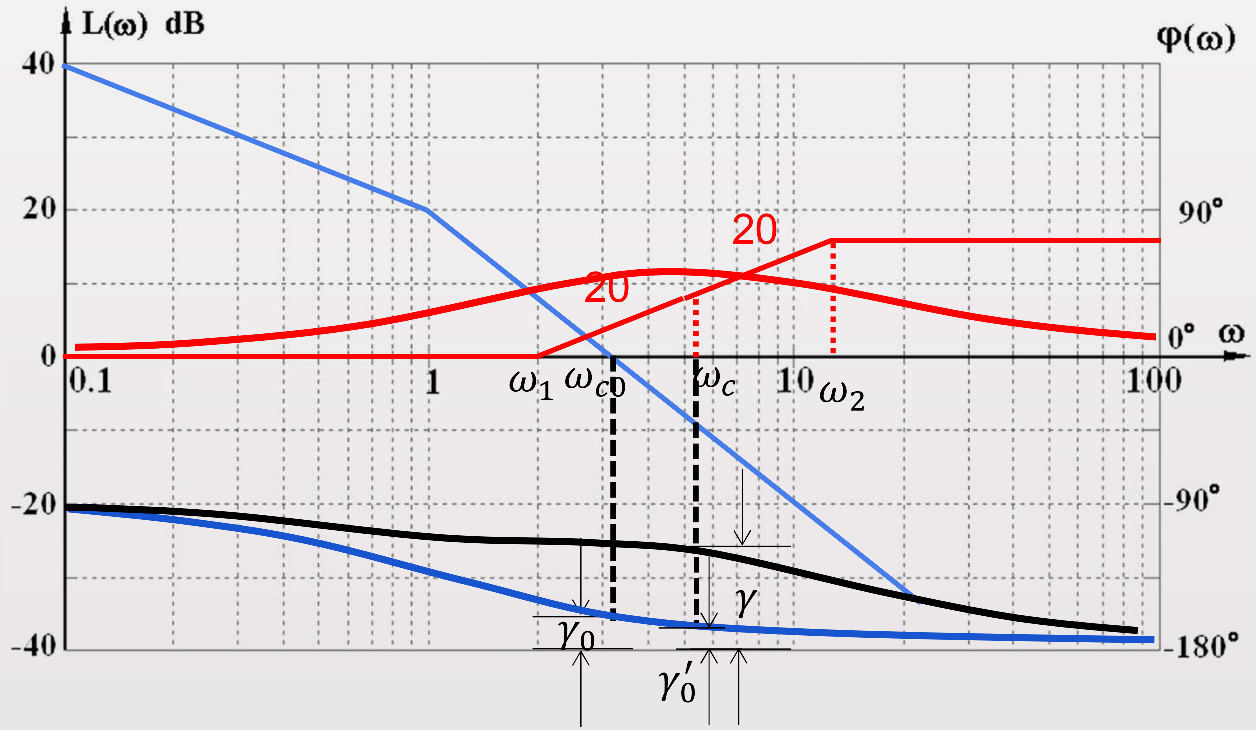
⑤验算

$$G(s) = G_c(s)\cdot G_0(s)$$

$$= \frac{\frac{s}{1.94}+1}{\frac{s}{13.73}+1}\cdot\frac{10}{s(s+1)}$$

$$K = 10 \qquad \omega_c = 5.16 > \omega_c^*$$

$$\gamma = 180° + \arctan\frac{5.16}{1.94} - \arctan\frac{5.16}{13.73} - 90° - \arctan 5.16 = 58.8° < \gamma^*$$



$$\gamma_0 - \gamma_0' \approx 5^\circ \sim 10^\circ$$

$$\boxed{\varphi_m = \gamma^* - \gamma_0 + (5^\circ \sim 10^\circ)}$$

重新校正

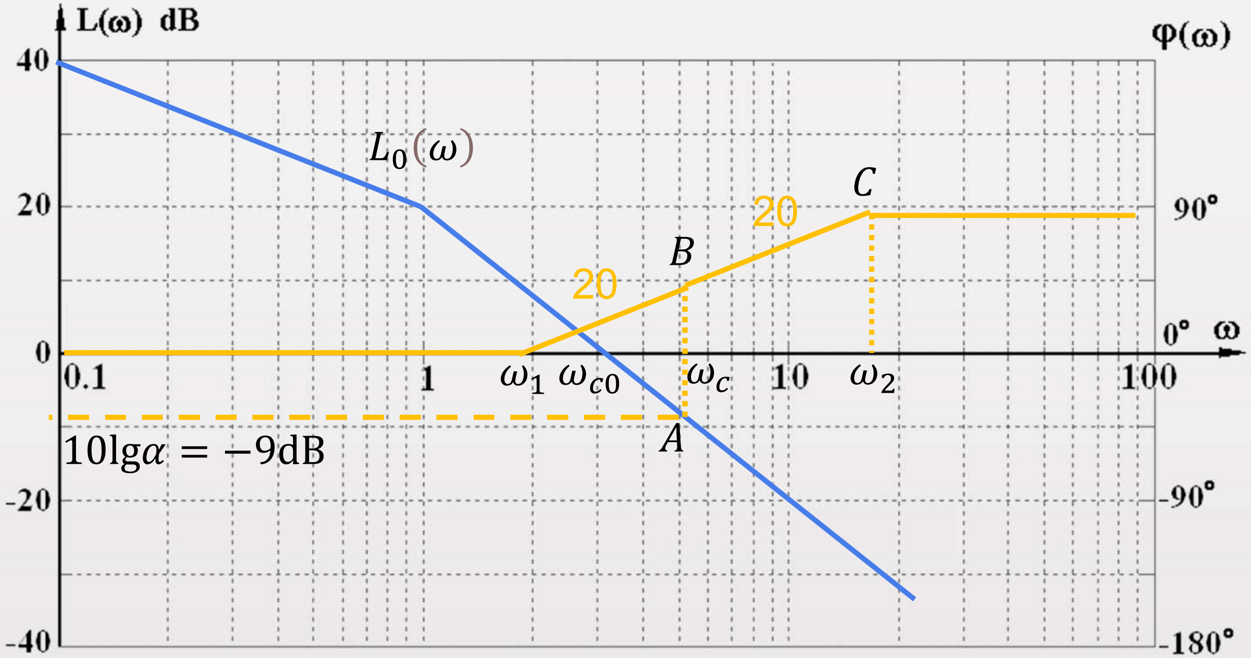
方法①：　令$\alpha = \dfrac{1}{8}$

$$-10\lg\alpha = 9\text{dB}$$

$$\omega_c = 3.16 \times 10^{\frac{9}{40}} = 5.3 > \omega_c^*$$

$$\frac{\omega_c}{\omega_1} = \frac{\omega_2}{\omega_c} = \frac{8\omega_1}{\omega_c}$$

$\omega_1 = 1.87$　　　$\omega_2 = 15$



$$G_c(s) = \frac{\dfrac{s}{1.87} + 1}{\dfrac{s}{15} + 1} \qquad\qquad G(s) = \frac{\dfrac{s}{1.94} + 1}{\dfrac{s}{13.73} + 1} \cdot \frac{10}{s(s+1)}$$

$$\gamma = 180° + \arctan\frac{5.3}{1.87} - \arctan\frac{5.3}{15} - 90° - \arctan 5.3 = 61.8°$$

方法②：

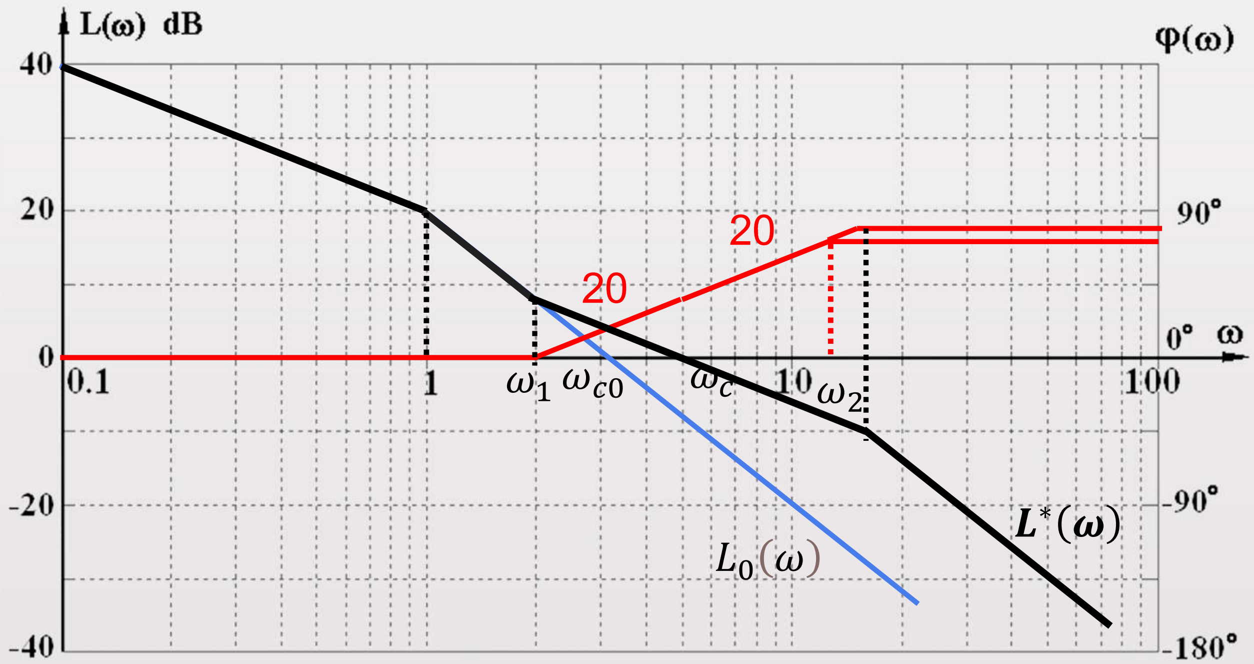
$$令G_{c2}(s)=\frac{\frac{s}{1.94}+1}{\frac{s}{15}+1}$$

$$G(s)=\frac{\frac{s}{1.94}+1}{\frac{s}{15}+1}\cdot\frac{10}{s(s+1)}$$

$$\gamma_2=180°+\arctan\frac{5.16}{1.94}$$

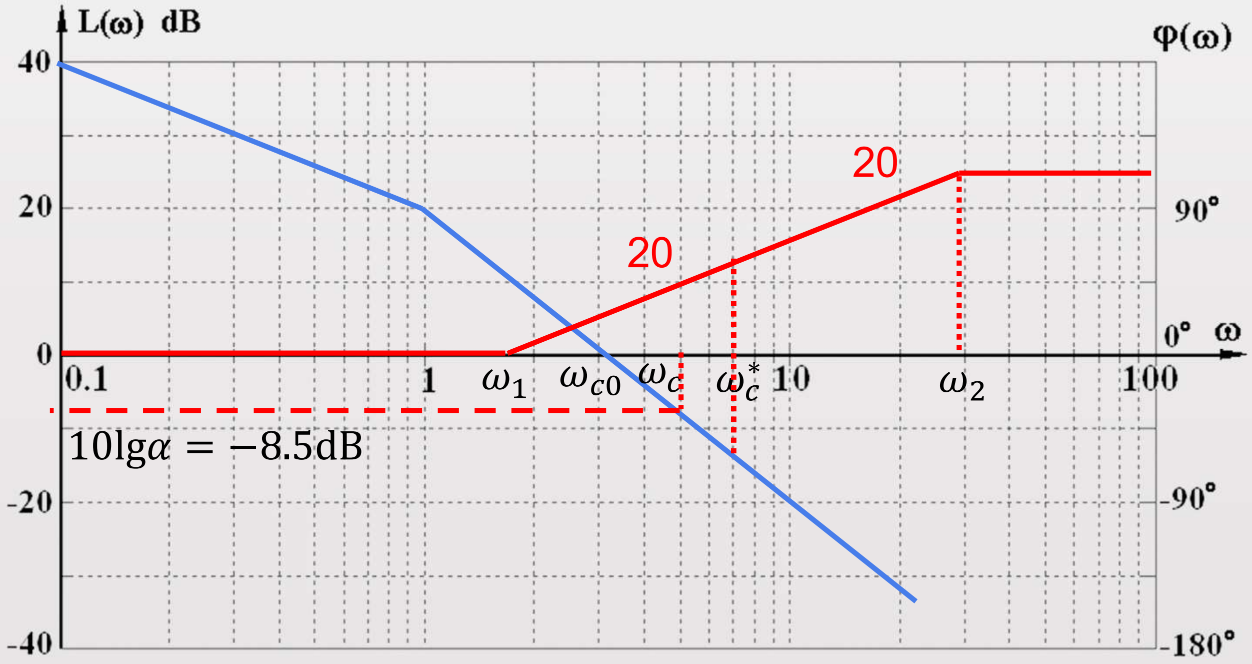
$$-\arctan\frac{5.16}{15}-90°-\arctan 5.16$$

$$=60.4°>\gamma^*$$



还是这个系统：$G(s) = \frac{K}{s(s+1)}$，要求:$r(t)$=t时，$e_{sr}^* \le 0.1$，$\boldsymbol{\omega_c^* \ge 7}$，$\gamma^* \ge 60°$，试确定串联校正装置的传递函数$G_c(s)$

$\omega_c = 5.16 < \omega_c^*$



串联相位滞后校正

原理：利用滞后网络幅值衰减特性，将系统的中频段压低，使校正后系统的剪切频率减小，挖掘系统自身的相角储备

适用： $\omega_{c0} > \omega_c^*$、 $\gamma_0 < \gamma^*$

步骤：

①由 $e_{sr}^* \rightarrow K$

②由$G_0(s) \rightarrow L_0(\omega) \rightarrow \omega_{c0} \rightarrow \gamma_0$

③确定$\gamma_0(\omega_c) = \gamma^* + 6°$， $\Rightarrow \omega_c$

④作图设计，确定$G_c(s)$

⑤$G(s) = G_c(s) \cdot G_0(s)$，验算$\omega_c$，$\gamma$是否满足指标

效果：

①保持低频段　满足稳态精度

②降低中频段　$\omega_c \downarrow$、$\gamma \uparrow$，损失快速性，改善均匀性

③压低高频段　提高抗高频干扰能力

例：已知某单位反馈系统的开环传递函数为$G(s)=\dfrac{K}{s(0.2s+1)(0.1s+1)}$，要求:

$K_v^*=30$，$\omega_c^*\geq 2.3$，$\gamma^*\geq 40°$，试确定串联校正装置的传递函数$G_c(s)$

解：①$K_v^*=\lim_{s\to 0} sG(s)=K$

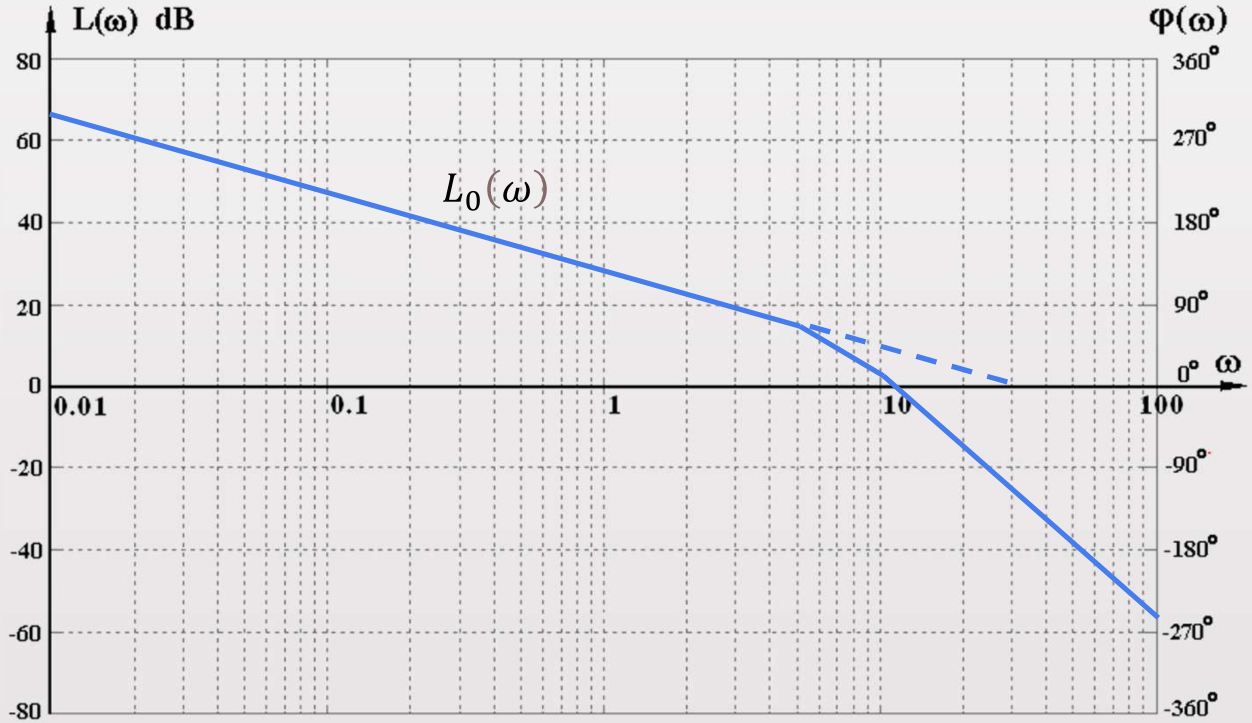
$K=30$

②

$$\frac{30}{\omega_{c0}\cdot\frac{\omega_{c0}}{5}\cdot\frac{\omega_{c0}}{10}}=1$$

$\omega_{c0}=11.45>\omega_c^*$

$$\gamma_0=90°-\arctan\frac{11.45}{5}-\arctan\frac{11.45}{10}$$
$$=-25.28°<\gamma^*$$



若采用串联超前校正:

$\varphi_m=\gamma^*-\gamma_0+10°>60°$，不能一次成功

在$\omega_c^*=2.3$处，$\gamma_0(\omega_c^*)=52.345°>\gamma^*+6°$

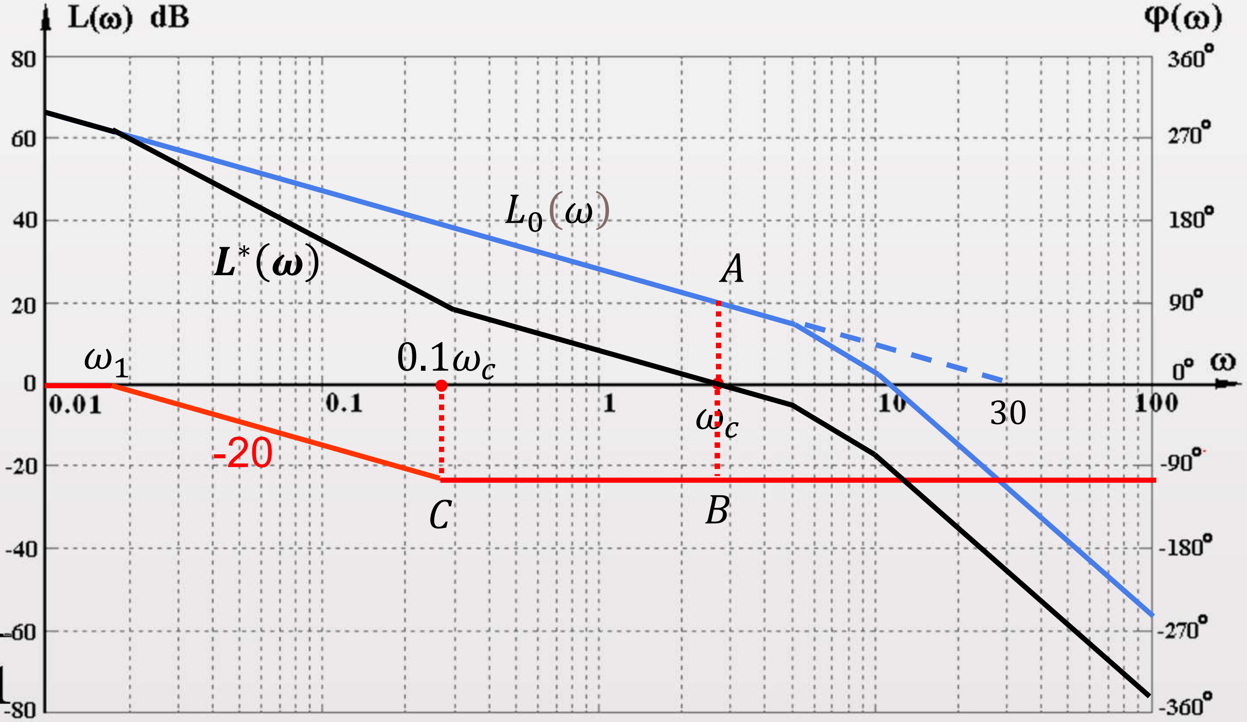
③令$\gamma_0(\omega_c) = \gamma^* + 6° = 46° = 180° + \varphi(\omega_c)$

$\omega_c = 2.7$

④作图设计，确定$G_c(s)$

$$\frac{30}{\omega_c} = \frac{0.1\omega_c}{\omega_1} \qquad \omega_1 = 0.0243$$

$$G_c(s) = \frac{\frac{s}{0.27}+1}{\frac{s}{0.0243}+1}$$



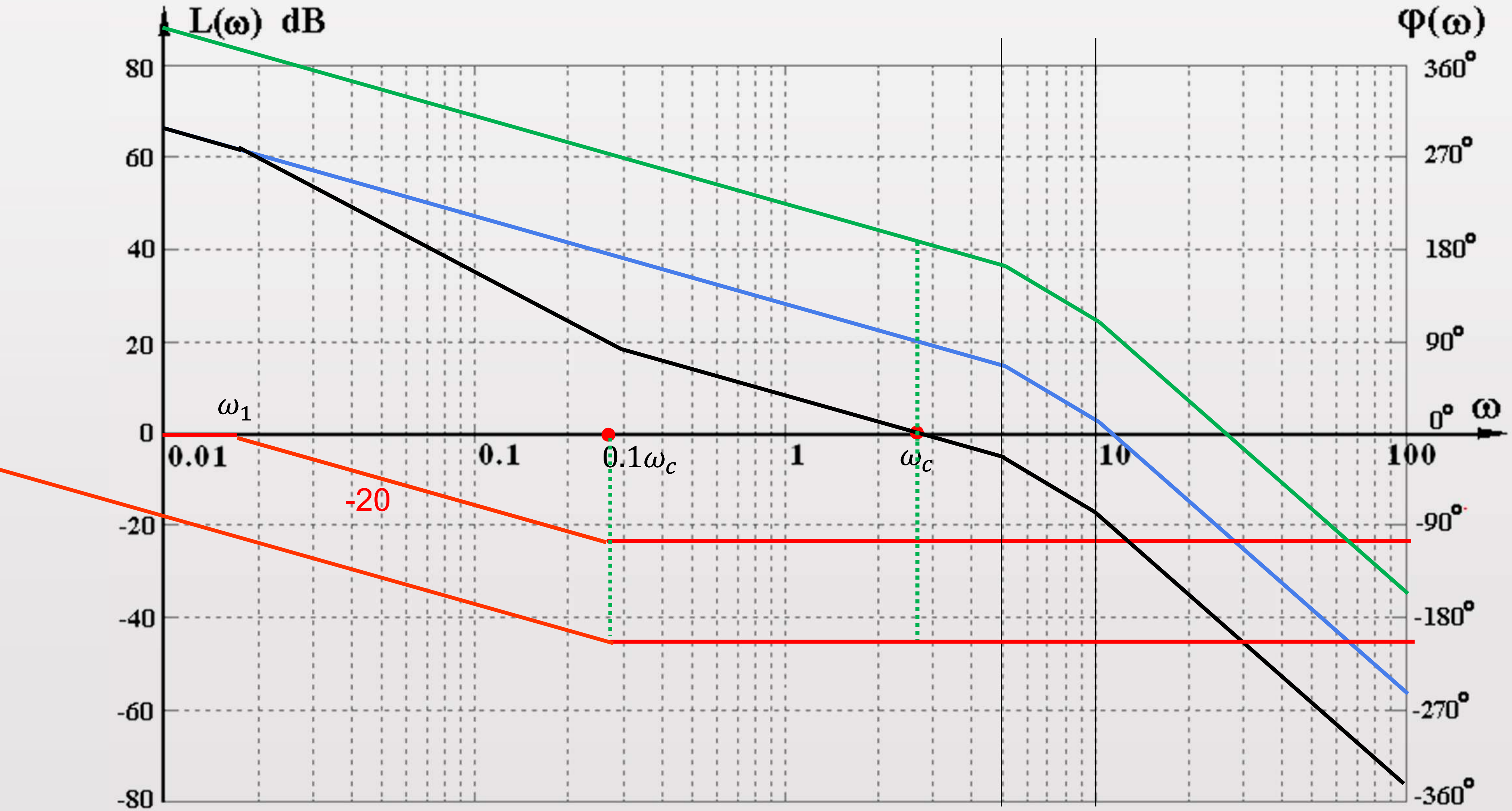
⑤验算

$$G(s) = \frac{30}{s(0.2s+1)(0.1s+1)} \frac{\frac{s}{0.27}+1}{\frac{s}{0.0243}+1}$$

$K = 30 \qquad \omega_c = 2.7$ 符合要求

$$\gamma = 180° + \arctan\frac{2.7}{0.27} - 90° - \arctan(0.2\times 2.7) - \arctan(0.1\times 2.7) - \arctan\frac{2.7}{0.0243}$$

$= 41.3°$ 符合要求



L(ω) dB
φ(ω)
80
60
40
20
0
-20
-40
-60
-80
360°
270°
180°
90°
0°
-90°
-180°
-270°
-360°
ω
ω_1
0.01
0.1
$0.1\omega_c$
1
ω_c
10
100
-20

串联相位滞后-超前校正

原理： 综合利用滞后网络幅值衰减、超前网络相角超前特性。

适用： 超前、滞后均不成功

步骤：

①由 $e_{sr}^{*} \rightarrow K$

②由$G_0(s) \rightarrow L_0(\omega) \rightarrow \omega_{c0} \rightarrow \gamma_0$

③确定$\varphi_m = \gamma^* - \gamma_0(\omega_c^*)\ + 6°$，$\alpha = \dfrac{1-\sin\varphi_m}{1+\sin\varphi_m}$

④作图设计，确定$G_c(s)$

⑤$G(s) = G_c(s) \cdot G_0(s)$，验算$\omega_c$，$\gamma$ 是否满足指标

效果：

①保持低频段　满足稳态精度

②改善中频段　γ显著提高

例：已知某单位反馈系统的开环传递函数为$G(s)=\dfrac{K}{s(\frac{s}{10}+1)(\frac{s}{60}+1)}$，要求:$r(t)=t$时$e_{sr}^*\le\dfrac{1}{126}$，$\gamma^*\ge 35°,\omega_c^*\ge 20\text{rad/s}$，试确定串联校正装置的传递函数$G_c(s)$

解：① $e_{sr}^*=\dfrac{1}{K}\le\dfrac{1}{126}$　　$K\ge 126$

②

$$\omega_{c0}=\sqrt{10\times 126}=35.5$$

$$\gamma_0=90°-\arctan\frac{35.5}{10}-\arctan\frac{35.5}{60}$$

$$=-14.9°\text{（不符合、不稳定）}$$

③若用超前校正

$$\varphi_m=\gamma^*-\gamma_0+10°=59.9°\text{（不行）}$$

若用滞后校正

$$\gamma_0(\omega_c^*)=90°-\arctan\frac{20}{10}-\arctan\frac{20}{60}$$

$$=8.2°<\gamma^*+6°\text{（不行）}$$

决定采用滞后-超前校正

超前部分应该提供的超前角： $\varphi_m = \gamma^* - \gamma_0(20) + 6° = 35° - 8.2° + 6° = 32.8°$

$$\alpha = \frac{1-\sin\varphi_m}{1+\sin\varphi_m} = \frac{1}{3.4}$$

$$\sqrt{\alpha} = \frac{1}{1.85}$$

④作图设计，确定$G_c(s)$

$$\omega_1 = \sqrt{\alpha}\omega_c = 10.81$$

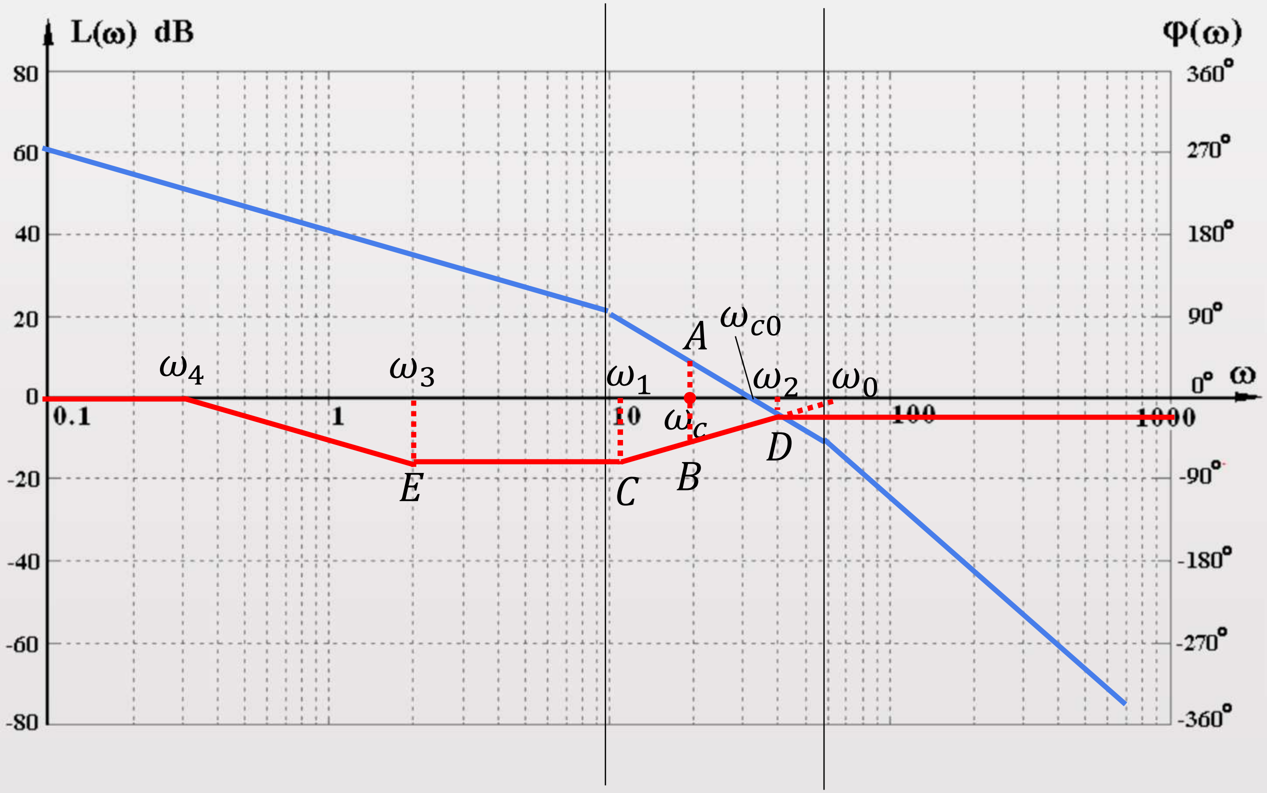
$$\omega_2 = \frac{1}{\sqrt{\alpha}}\omega_c = 37$$

$$\omega_3 = 0.1\omega_c = 2$$

$$\frac{\omega_{c0}}{\omega_c} = \frac{\omega_0}{\omega_{c0}} \qquad \omega_0 = 63$$

$$\frac{\omega_0}{\omega_1} = \frac{\omega_3}{\omega_4} \qquad \omega_4 = 0.343$$

$$G_c(s) = \frac{(\frac{s}{2}+1)(\frac{s}{10.81}+1)}{(\frac{s}{0.343}+1)(\frac{s}{37}+1)}$$



⑤验算

$$G(s)=\frac{126}{s(\frac{s}{10}+1)(\frac{s}{60}+1)}\cdot\frac{\left(\frac{s}{2}+1\right)\left(\frac{s}{10.81}+1\right)}{\left(\frac{s}{0.343}+1\right)\left(\frac{s}{37}+1\right)}$$

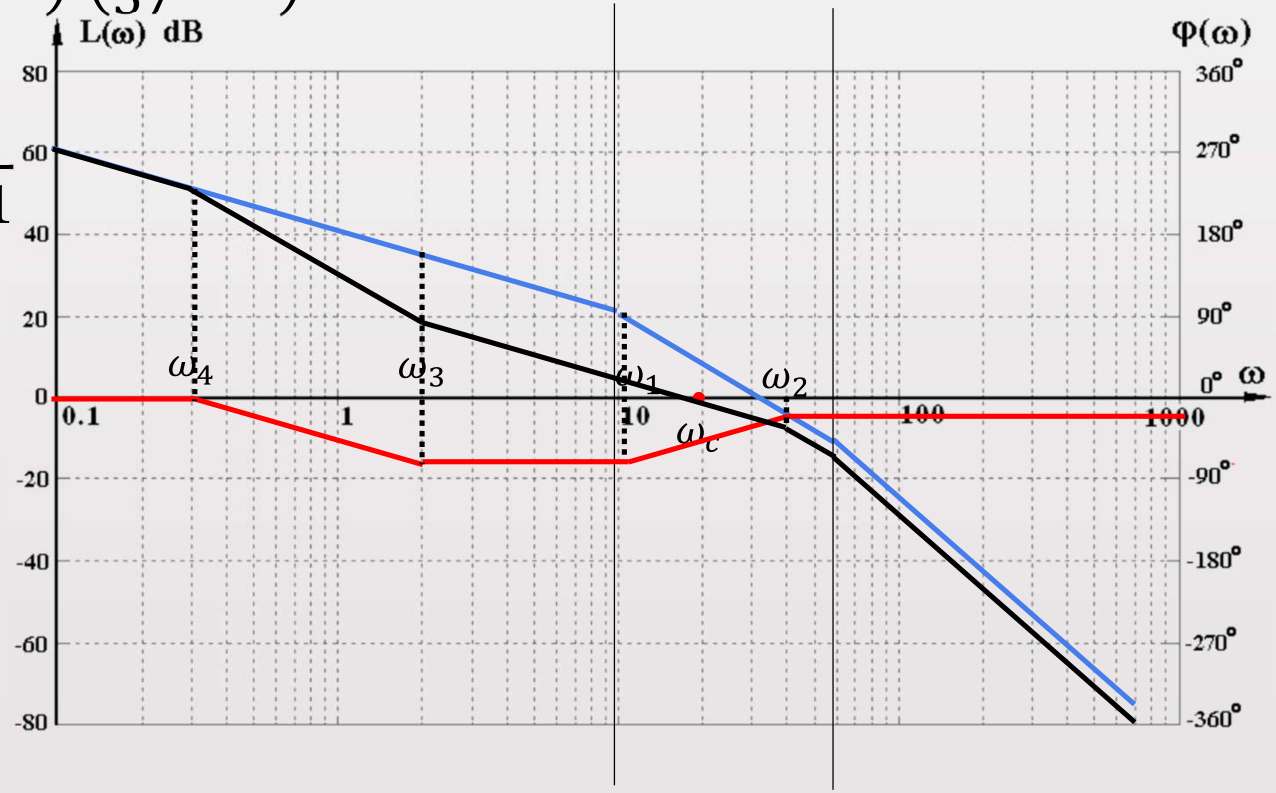
$$\omega_c=20\mathrm{rad/s}$$

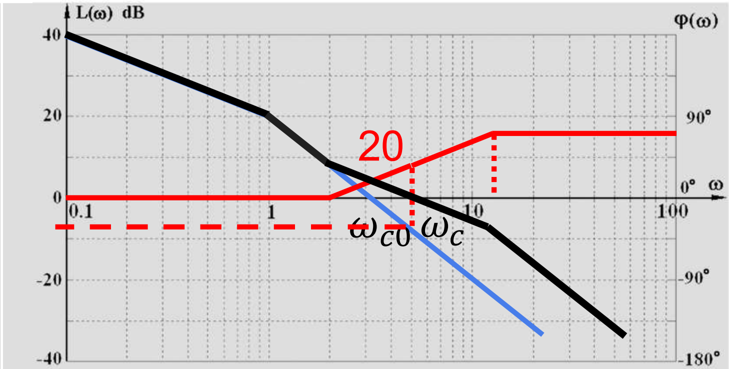
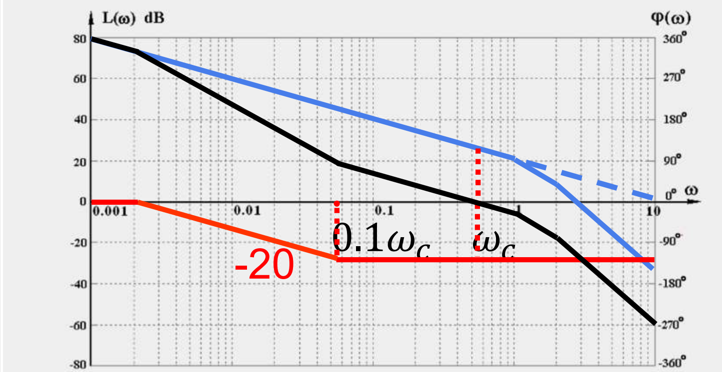
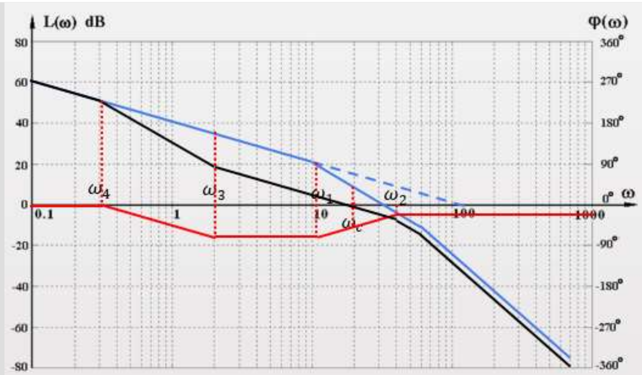
$$\gamma=180°+\arctan\frac{20}{2}+\arctan\frac{20}{10.81}$$

$$-90°-\arctan\frac{20}{10}-\arctan\frac{20}{60}$$

$$-\arctan\frac{20}{0.343}-\arctan\frac{20}{37}$$

$$=36.6°>35°$$



校正方法	网络特点	应用场合	效果	
超前校正 （微分）	**相角超前** 幅值增加	$\omega_{c0} < \omega_c^*$ $\gamma_0 < \gamma^*$	$\boldsymbol{\omega_c}$ ↑ 、$\boldsymbol{\gamma}$ ↑ 抗高频干扰能力↓	
滞后校正 （积分）	**幅值衰减** 相角滞后	$\omega_{c0} > \omega_c^*$ $\gamma_0 < \gamma^*$ $\boldsymbol{\gamma_0(\omega_c^*)}$ $\boldsymbol{> \gamma^* + 6°}$	ω_c ↓ 、$\boldsymbol{\gamma}$ ↑ **抗高频干扰能力↑** **可增大K改善稳态性能**	
滞后-超 前校正	**幅值衰减** **相角超前**	超前、滞 后均不成 功	$\boldsymbol{\gamma}$ ↑↑	

例：已知某单位反馈系统的开环传递函数为$G(s)=\dfrac{K}{(s+1)(\frac{s}{5}+1)(\frac{s}{30}+1)}$，试设计PID控制器，使系统稳态速度误差 $e_{sr}^* \le 0.1$，$\omega_c^* \ge 15$，$\gamma^* \ge 65°$

解：①$r(t)=t$时，

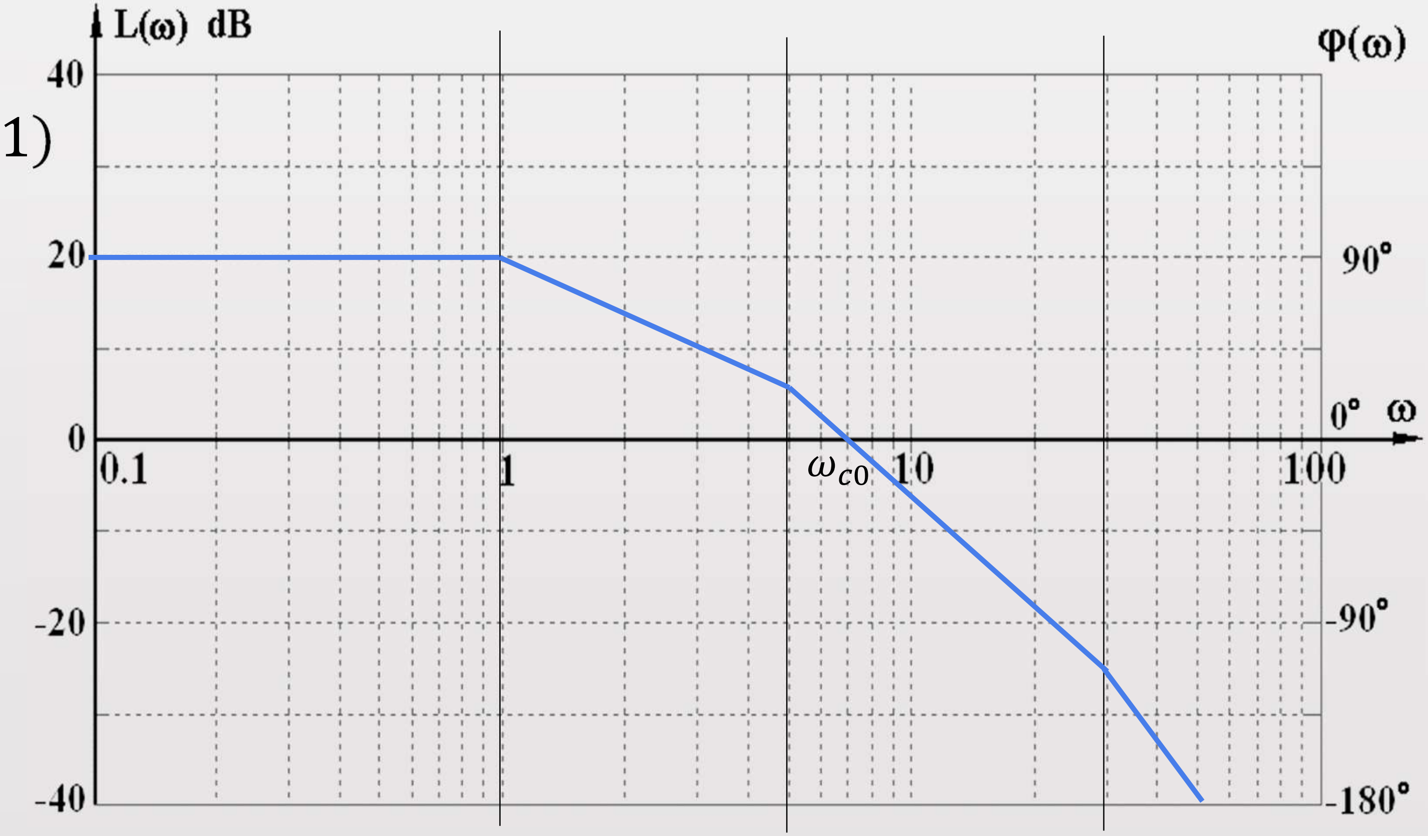
$$e_{sr}^*=\frac{1}{K}\le 0.1 \qquad K=10(\nu=1)$$

②确定原系统的ω_{c0}、γ_0

$$\omega_{c0}=\sqrt{5\times 10}=7.07<\omega_c^*$$

$$\gamma_0=180°-\arctan 7.07-\arctan\frac{7.07}{5}-\arctan\frac{7.07}{30}=30°<\gamma^*$$

$$\gamma_0(\omega_c^*)=180°-\arctan 15-\arctan\frac{15}{5}-\arctan\frac{15}{30}=-4.3°$$



超前校正、滞后校正、滞后-超前校正均不能成功得到预计动态性能

选择PID校正

令$\omega_c = 15\mathrm{rad/s}$

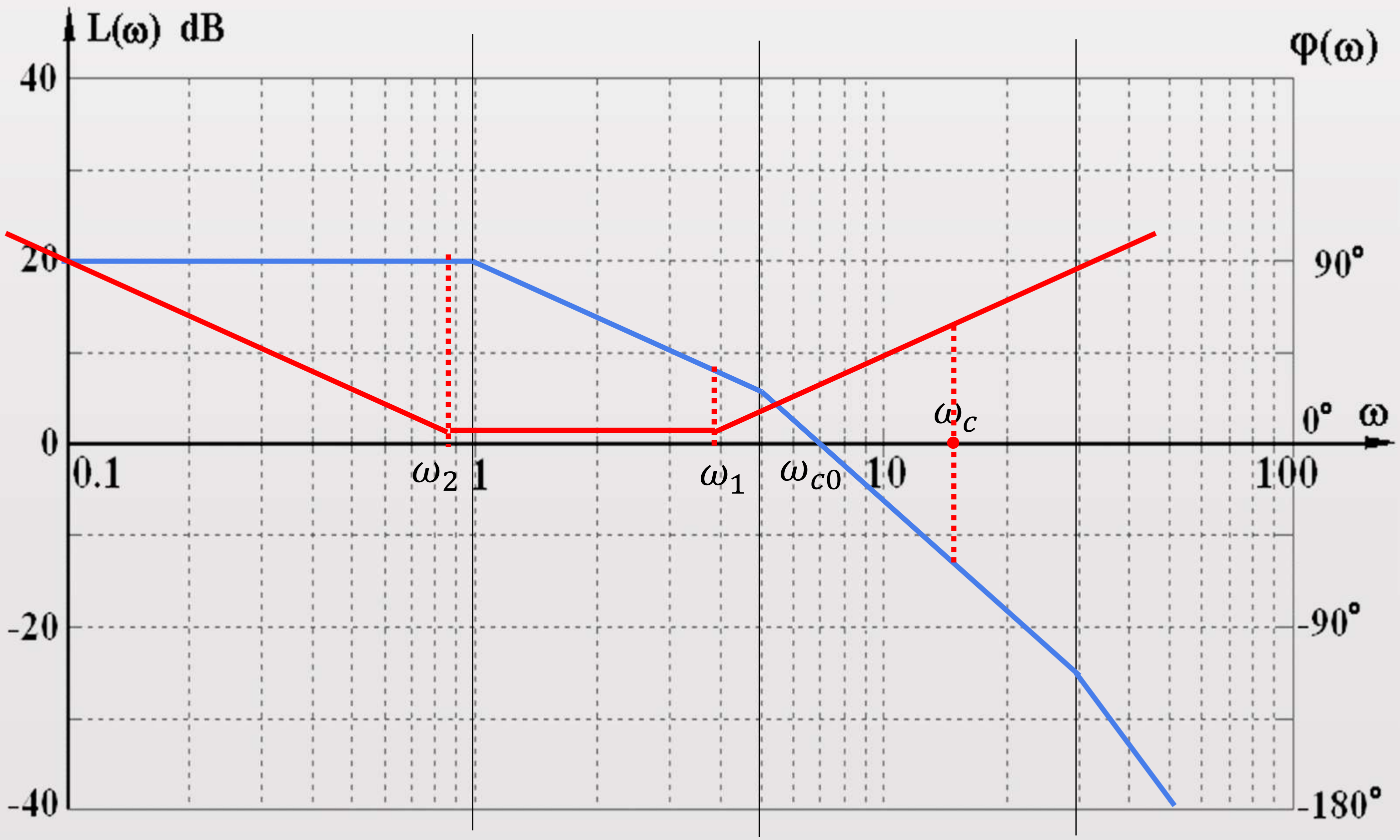
④作图设计，确定$G_c(s)$

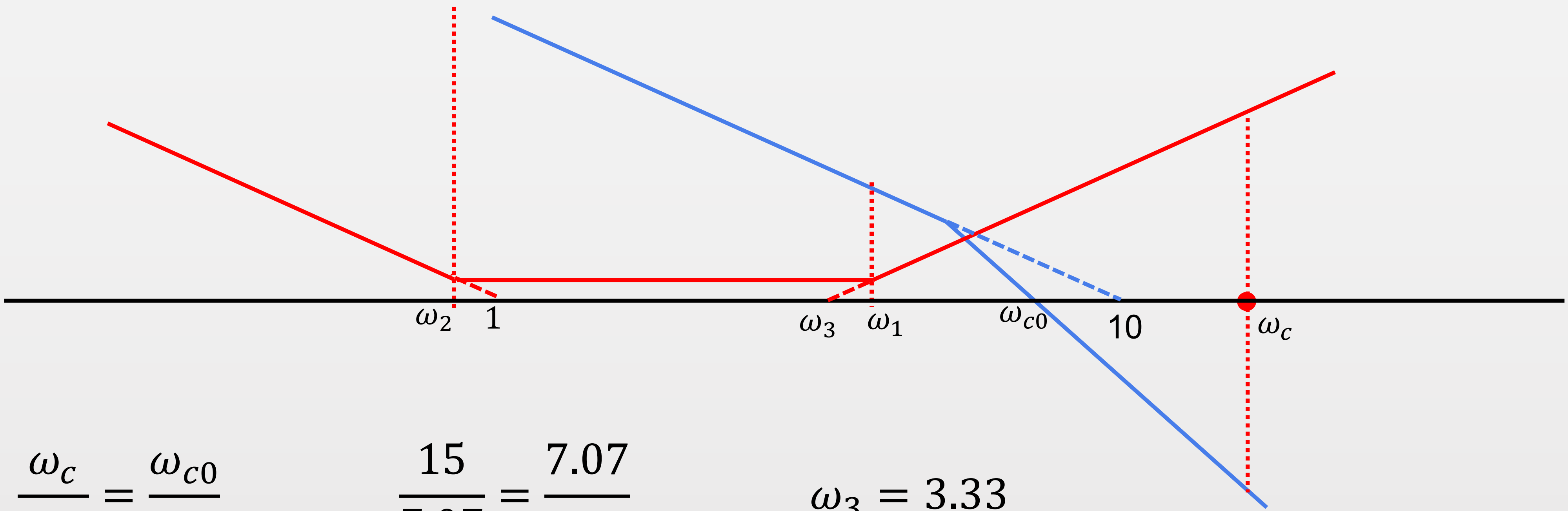
$$\varphi_m = \gamma^* - \gamma_0(\omega_c) + 6° = 65° - (-4.3°) + 6° = 75.3°$$

$$\angle(1+\frac{s}{\omega_1})\Big|_{\omega=15} = \arctan\frac{15}{\omega_1}$$

$$\arctan\frac{15}{\omega_1} = 75.3° \qquad \omega_1 = 3.9$$

PID增益为1





$$\frac{\omega_c}{\omega_{c0}} = \frac{\omega_{c0}}{\omega_3} \qquad \frac{15}{7.07} = \frac{7.07}{\omega_3} \qquad \omega_3 = 3.33$$

$$\frac{1}{\omega_2} = \frac{\omega_1}{\omega_3} \qquad \frac{1}{\omega_2} = \frac{3.9}{3.33} \qquad \omega_2 = 0.854$$

$$G_c(s) = \frac{(\frac{s}{0.854} + 1)(\frac{s}{3.9} + 1)}{s} = \frac{0.3s^2 + 1.426s + 1}{s} = K_D s + K_P + {K_I}/{s}$$

⑤验算

$$G(s) = G_c(s) \cdot G_0(s) = \frac{(\frac{s}{0.854}+1)(\frac{s}{3.9}+1)}{s} \cdot \frac{10}{(s+1)(\frac{s}{5}+1)(\frac{s}{30}+1)}$$

$$\gamma = 180° + \arctan\frac{15}{0.854} + \arctan\frac{15}{3.9} - 90° - \arctan 15 - \arctan\frac{15}{5} - \arctan\frac{15}{30}$$
$$= 67.85° > \gamma^*$$