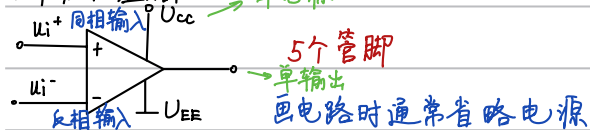


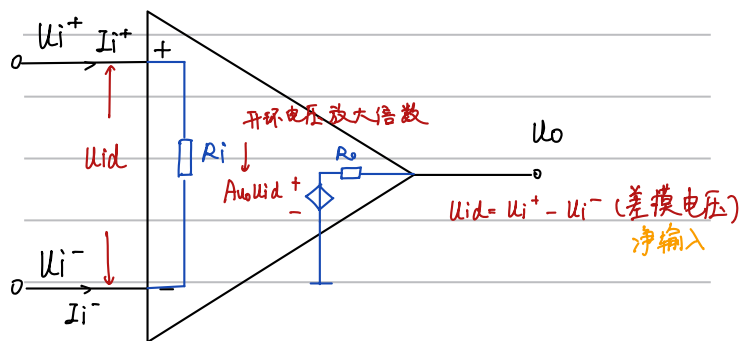


第二章 集成运算放大器的基本应用电路

2.1 应用基础



△模型

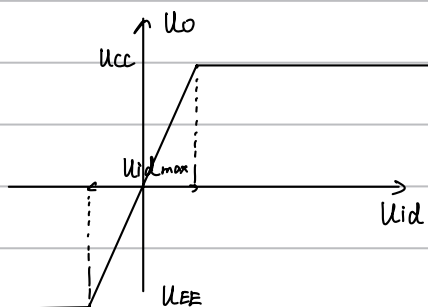


△理想条件

- ① 输入电阻 $R_i \rightarrow \infty$
- ② 输出电阻 $R_o \rightarrow 0$
- ③ 放大倍数 $A_{u0} \rightarrow \infty$
- ④ $I_i^+ = I_i^- \rightarrow 0$
- ⑤ A_{u0} 与频率无关

↓ 关系

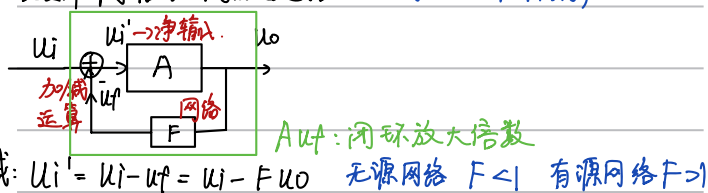
△传输特性



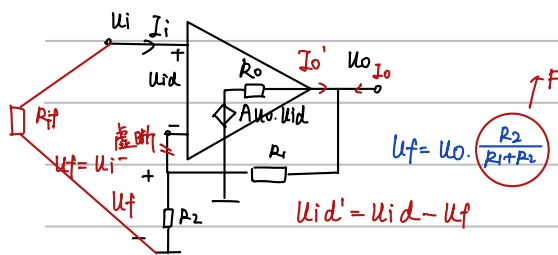
理想情况下, $U_{idmax} \rightarrow 0$ $U_i^+ \approx U_i^-$ 虚短

2.2 引入电阻负反馈

2.2.1 同相比例放大器 (引入到同相输入端)



减: $U_i^- = U_i - U_f = U_i - F U_o$



$$\because \text{虚短} \therefore U_{i+} = U_{i-}$$

$$\therefore U_{i-} = U_o \cdot \frac{R_2}{R_1 + R_2} = U_{i+} = U_i$$

$$A_{uF} = \frac{U_o}{U_i} = \frac{R_1 + R_2}{R_2} = 1 + \frac{R_1}{R_2}$$

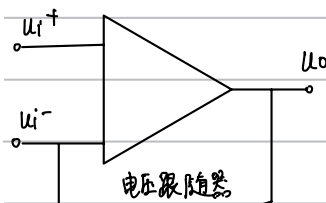
$$\text{输入电阻 } R_{if} = \frac{U_i}{I_i}$$

$$I_i = \frac{U_{id}}{R_i} = \frac{U_{i+} - U_{i-}}{R_i} = 0$$

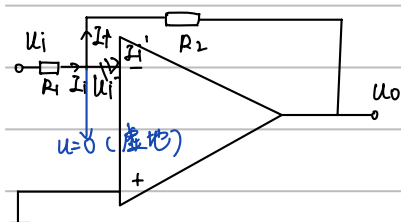
$$R_{if} \rightarrow \infty$$

$$\text{输出电阻 } R_{of} = \frac{U_o}{I_o}$$

$$U_i \rightarrow 0, R_o \rightarrow 0, I_o = I_o' \rightarrow \infty, R_{of} = 0$$



2.2.2 反相比例放大器



① 电压

$$U_i^+ = U_i^- \text{ (虚短)}$$

$$\text{(叠加定理)} \quad U_i^- = \frac{R_2}{R_1 + R_2} U_i + \frac{R_1}{R_1 + R_2} U_o = 0$$

$$\therefore R_2 U_i + R_1 U_o = 0$$

$$A_{uf} = \frac{U_o}{U_i} = -\frac{R_2}{R_1}$$

② 电流

$$\text{虚断 } I_i' = 0 \Rightarrow I_i - I_f = 0, I_i = I_f$$

$$I_i = \frac{U_i - U_i^-}{R_1}, U_i^- = U_i^+ \text{ (虚短)}, I_i = \frac{U_i}{R_1}$$

$$I_f = \frac{U_i^- - U_o}{R_2} = -\frac{U_o}{R_2}$$

$$\frac{U_i}{R_1} = -\frac{U_o}{R_2} \Rightarrow \frac{U_o}{U_i} = -\frac{R_2}{R_1}$$

③ $R_{if} = \frac{U_i}{I_i}$

$$R_{if} = R_1 + R_2 \parallel R_i$$

$$R_i' = \frac{U_{id}}{I_f}$$

$$I_f = \frac{U_{id} - U_o}{R_2} = \frac{1 - U_{id}}{R_2} \cdot U_{id} = \frac{U_{id}}{R_2} \cdot \frac{1}{1 - A_{uo}} = \frac{U_{id}}{R_2} \cdot \frac{1}{1 + |A_{uo}|}$$

$$R_i' = \frac{R_2}{1 + |A_{uo}|} \rightarrow 0$$

$$R_{if} = R_1$$

④ $R_{of} = \frac{U_o}{I_o} \Big|_{U_i=0} = 0$

$$U_o = A_{uf} \cdot U_i = 0$$

$$U_o = -R_o \cdot I_o' = 0, R_o \rightarrow 0 \Rightarrow I_o' \rightarrow \infty$$

$$U_o - U_i^- = 0 = R_2 (I_o + I_o') \Rightarrow I_o + I_o' = 0$$

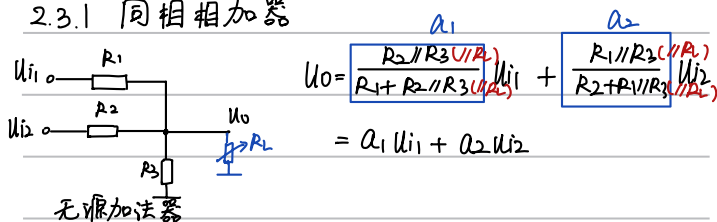
$$\therefore I_o \rightarrow \infty, U_o \rightarrow 0 \Rightarrow R_{of} \rightarrow 0$$

负反馈：反馈都在反相端

△等效解题，无电流流过的电阻，接在地与地之间，可忽略

2.3 相加器

2.3.1 同相相加器

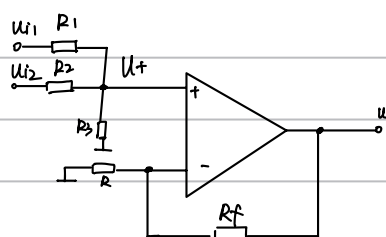


问题：① 只衰减，无放大 ($a_1, a_2 < 1$)

② 若加上变化负载则影响系数

③ 信号源互不独立 (R_1 影响 a_2 , R_2 影响 a_1)

△(有源)同相相加器



$$\text{此时, } U_o = \left(1 + \frac{R_f}{R}\right) U_+$$

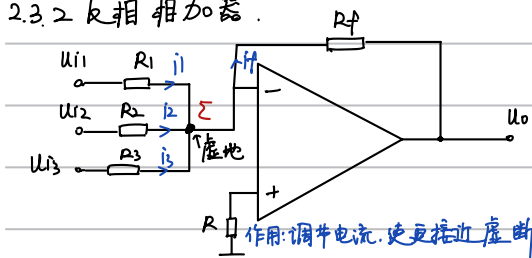
$$= \left(1 + \frac{R_f}{R}\right) \cdot \left(\frac{R_2 \parallel R_3}{R_1 + R_2 \parallel R_3} U_{i1} + \frac{R_1 \parallel R_3}{R_2 + R_1 \parallel R_3} U_{i2} \right)$$

可放大 (系数 > 1), 负载不影响系数

$$\text{若取 } R_1 = R_2, U_o = \left(1 + \frac{R_f}{R}\right) \cdot \frac{R_1 \parallel R_3}{R_1 + R_1 \parallel R_3} \cdot (U_{i1} + U_{i2})$$

$$= k \cdot (U_{i1} + U_{i2})$$

2.3.2 反相相加器



$$\text{应有: } i_1 = \frac{U_{i1}}{R_1}, i_2 = \frac{U_{i2}}{R_2}, i_3 = \frac{U_{i3}}{R_3}$$

$$i_f = i_1 + i_2 + i_3 = \frac{U_{i1}}{R_1} + \frac{U_{i2}}{R_2} + \frac{U_{i3}}{R_3} = -\frac{U_o}{R_f}$$

$$\therefore U_o = -\frac{R_f}{R_1} U_{i1} - \frac{R_f}{R_2} U_{i2} - \frac{R_f}{R_3} U_{i3}$$

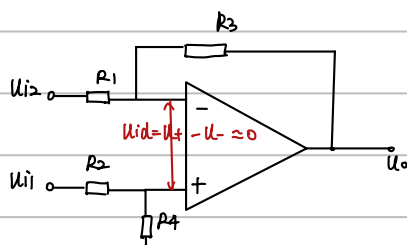
若 $R_1 = R_2 = R_3 = R$

$$\text{则 } U_o = -\frac{R_f}{R} (U_{i1} + U_{i2} + U_{i3}) \quad \text{信号源相互独立}$$

2.4 相减器

2.4.1 基本相减器 (差动放大器)

$$U_o = a_1 U_{i1} - a_2 U_{i2}$$



叠加定理 $U_{i2} = 0$ 同相放大器

$$U_{o1} = U_{i1} \cdot \frac{R_4}{R_2 + R_4} \left(1 + \frac{R_3}{R_1} \right)$$

$U_{i1} = 0$ 反相放大器

$$U_{o2} = U_{i2} \cdot \left(-\frac{R_3}{R_1} \right)$$

$$U_o = U_{o1} + U_{o2} = \frac{R_4}{R_2 + R_4} \left(1 + \frac{R_3}{R_1} \right) U_{i1} - \frac{R_3}{R_1} U_{i2} = a_1 U_{i1} - a_2 U_{i2}$$

$$\text{若 } R_1 = R_2, R_3 = R_4 \text{ 则 } U_o = \frac{R_3}{R_1} (U_{i1} - U_{i2})$$

2.4.2 精密相减器 (仅用放大器)

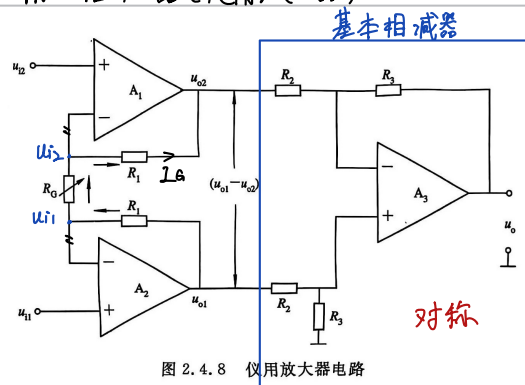


图 2.4.8 仅用放大器电路

$$U_o = \frac{R_3}{R_2} (U_{o1} - U_{o2})$$

$$\therefore \text{虚断} \quad \therefore U_{o1} - U_{o2} = U_{RG} + 2U_{R1}$$

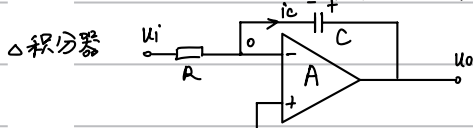
其中 $U_{RG} = U_{i1} - U_{i2}$ (虚短)

$$I_G = \frac{U_{i1} - U_{i2}}{R_g}, \quad U_{R1} = \frac{R_1}{R_g} (U_{i1} - U_{i2})$$

$$\therefore U_{o1} - U_{o2} = \left(1 + \frac{2R_1}{R_g} \right) (U_{i1} - U_{i2})$$

$$\therefore U_o = \frac{R_3}{R_2} \left(1 + \frac{2R_1}{R_g} \right) (U_{i1} - U_{i2}) \quad \text{只需调节一个电阻}$$

2.5 电容负反馈 (积分器、微分器)



$$U_o(t) = -\frac{1}{C} \cdot \int i_C(t) dt$$

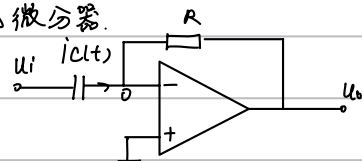
$$= -\frac{1}{C} \int \frac{U_i(t)}{R} dt$$

$$= -\frac{1}{RC} \int U_i(t) dt$$

$$= -\frac{1}{j\omega RC} \int U_i(t) dt, \quad |A_{uj\omega}| = \frac{1}{\omega RC}, \quad \phi(j\omega) = -90^\circ$$

(相对于标准反相而言)
180° - 90° = 90°

微分器



$$U_o = U_i \cdot \left(-\frac{R}{j\omega C} \right) = -j\omega RC \cdot U_i$$

$$|A_{uj\omega}| = \omega RC$$

$$\phi(j\omega) = 90^\circ$$

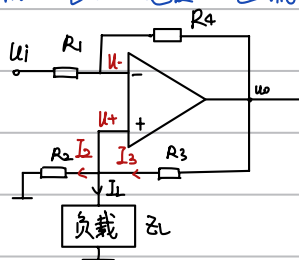
$$i_C(t) = C \cdot \frac{dU_i(t)}{dt}$$

$$U_O(t) = -RC \cdot \frac{dU_i(t)}{dt}$$

(I/V)

2.6 V/I 变换器

电流 → 电压 与 电压 → 电流



$$I_2 + I_L = I_3 \quad (\text{求 } I_2, I_3)$$

$$I_3 = \frac{U_O - U_i}{R_3}, \quad I_2 = \frac{U_i}{R_2}$$

$$\frac{U_i - U_-}{R_1} = \frac{U_- - U_O}{R_4}$$

(叠加定理)

$$U_- - U_O = \frac{R_4}{R_1} (U_i - U_-) \Rightarrow U_- = \frac{R_4}{R_1 + R_4} U_i + \frac{R_1}{R_1 + R_4} U_O$$

$$\therefore U_i = \frac{R_4}{R_1 + R_4} U_i + \frac{R_1}{R_1 + R_4} U_O = I_2 R_2$$

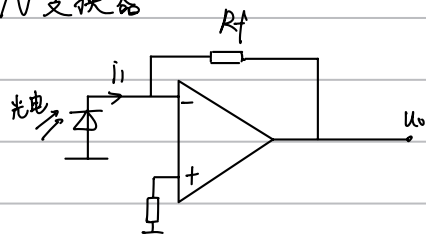
$$I_3 = \frac{U_O - U_i}{R_3} = \frac{R_4 (U_O - U_i)}{(R_1 + R_4) \cdot R_3}$$

$$I_2 = \frac{R_4}{(R_1 + R_4) R_2} U_i + \frac{R_1}{(R_1 + R_4) R_2} U_O$$

$$I_L = I_3 - I_2 = \frac{R_2 R_4 - R_1 R_3}{(R_1 + R_4) \cdot R_2 R_3} U_O - \frac{R_2 R_4 + R_1 R_3}{(R_1 + R_4) R_2 R_3} U_i$$

$$\text{令 } R_1 R_3 = R_2 R_4, \text{ 得 } I_L = -U_i \cdot \frac{1}{R_2}$$

I/V 变换器



$$U_O = -I_i R_f$$