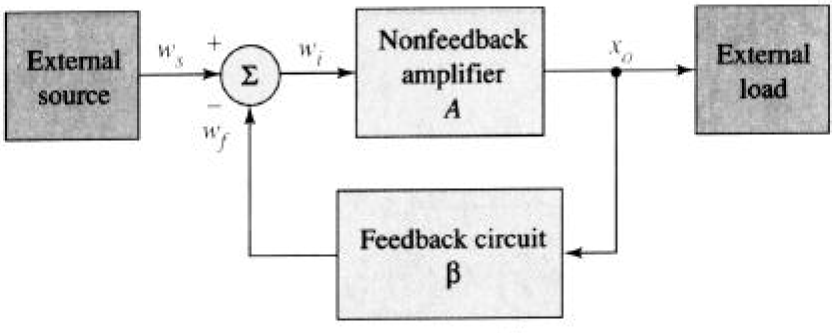
回授概論

Introduction of Feedback Circuits

General Scheme of a feedback circuit



Feedback amplifier structure.

輸出訊號 x_o 及訊號 $w_{s,i,f}$ 可為電流或電壓訊號

$$x_o = Aw_i = A(w_s - w_f) = A(w_s - bx_o)$$

$$A_f = \frac{x_o}{w_s} = \frac{A}{1+Ab}$$

回授訊號為 $w_f = bx_o = \frac{Ab}{1+Ab} w_s$

一般使用時，$Ab>0$，稱為負回授。若 $Ab=-1$，則電路開始振盪。

負回授對放大器的影響

1. **放大率減小。**

2. **降低放大率對電路元件參數的靈敏度。**

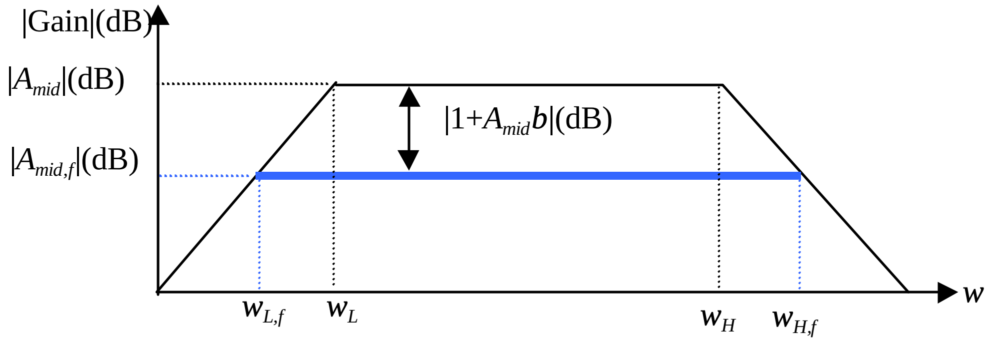
$$S_p^{A_f} = \frac{1}{1+Ab} S_p^A$$

直接由靈敏度定義即可證明。

3. **增加頻寬。**

$$w_H \rightarrow (1+Ab)w_H$$

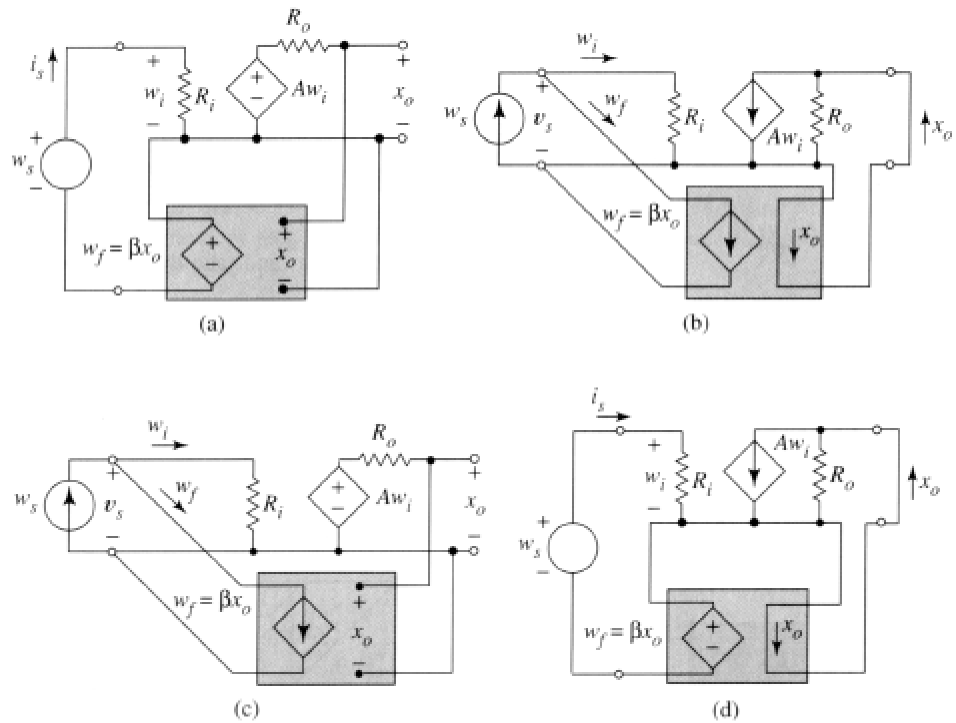
$$w_L \rightarrow \frac{w_L}{(1+Ab)}$$



4. **減小放大器之非線性失真。**

由於放大器的非線性失真在負回授時減掉，或說真正的輸入訊號 w_i **變小。**

5. **改善輸入及輸出阻抗。**



Feedback strategies for different design goals: (a) voltage-series feedback for a voltage amplifier; (b) current-shunt feedback for a current amplifier; (c) voltage-shunt feedback for a transresistance amplifier; (d) current-series feedback for a transconductance amplifier.

Feedback Amplifier Classifications

Design Goal	Feedback Class	Input Resistance	Output Resistance	Ideal Source	Ideal Load	β Circuit Two-Port Model
Voltage amplifier (VCVS)	Voltage series	Increases	Decreases	Voltage	Open circuit	*h*
Transresistance amplifier (CCVS)	Voltage shunt	Decreases	Decreases	Current	Open circuit	*y*
Current amplifier (CCCS)	Current shunt	Decreases	Increases	Current	Short circuit	*g*
Transconductance amplifier (VCCS)	Current series	Increases	Increases	Voltage	Short circuit	*z*

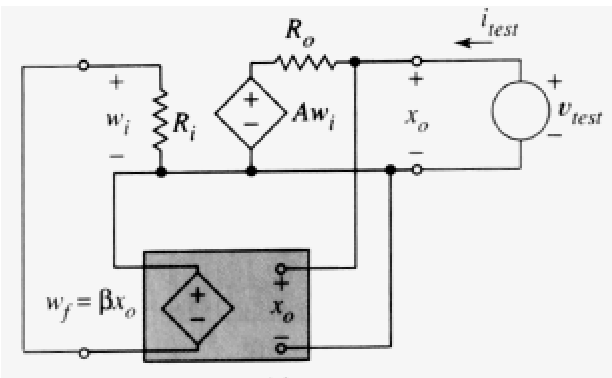
Voltage-Series Feedback

計算輸入阻抗

$$w_s = i_s R_i + b[A(i_s R_i)]$$

$$R_{i,f} = \frac{w_s}{i_s} = R_i(1 + Ab)$$ **不考慮輸出負載**

計算輸出阻抗



$$w_i = -bu_{test}$$

$$u_{test} = R_o i_{test} + Aw_i$$

$$= R_o i_{test} - Abu_{test}$$

$$R_{of} = \frac{u_{test}}{i_{test}}$$

$$= \frac{R_o}{1 + Ab}$$

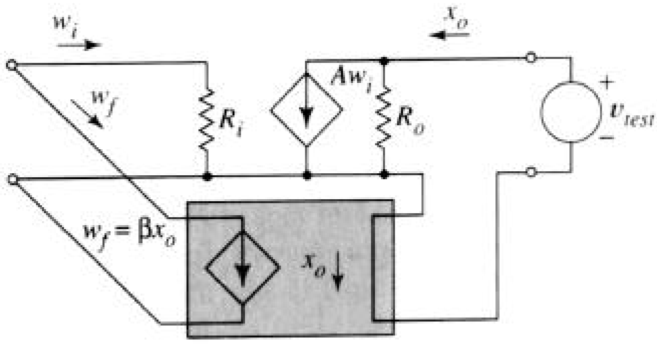
Current-Shunt Feedback

計算輸入阻抗

$$w_s = \frac{u_s}{R_i} + b[A(\frac{u_s}{R_i})]$$

$$R_{i,f} = \frac{u_s}{w_s} = \frac{R_i}{(1 + Ab)}$$ **不考慮輸出負載**

計算輸出阻抗



$$w_i = -bx_o$$

$$x_o = \frac{u_{test}}{R_o} + Aw_i$$

$$= \frac{u_{test}}{R_o} - Abx_o$$

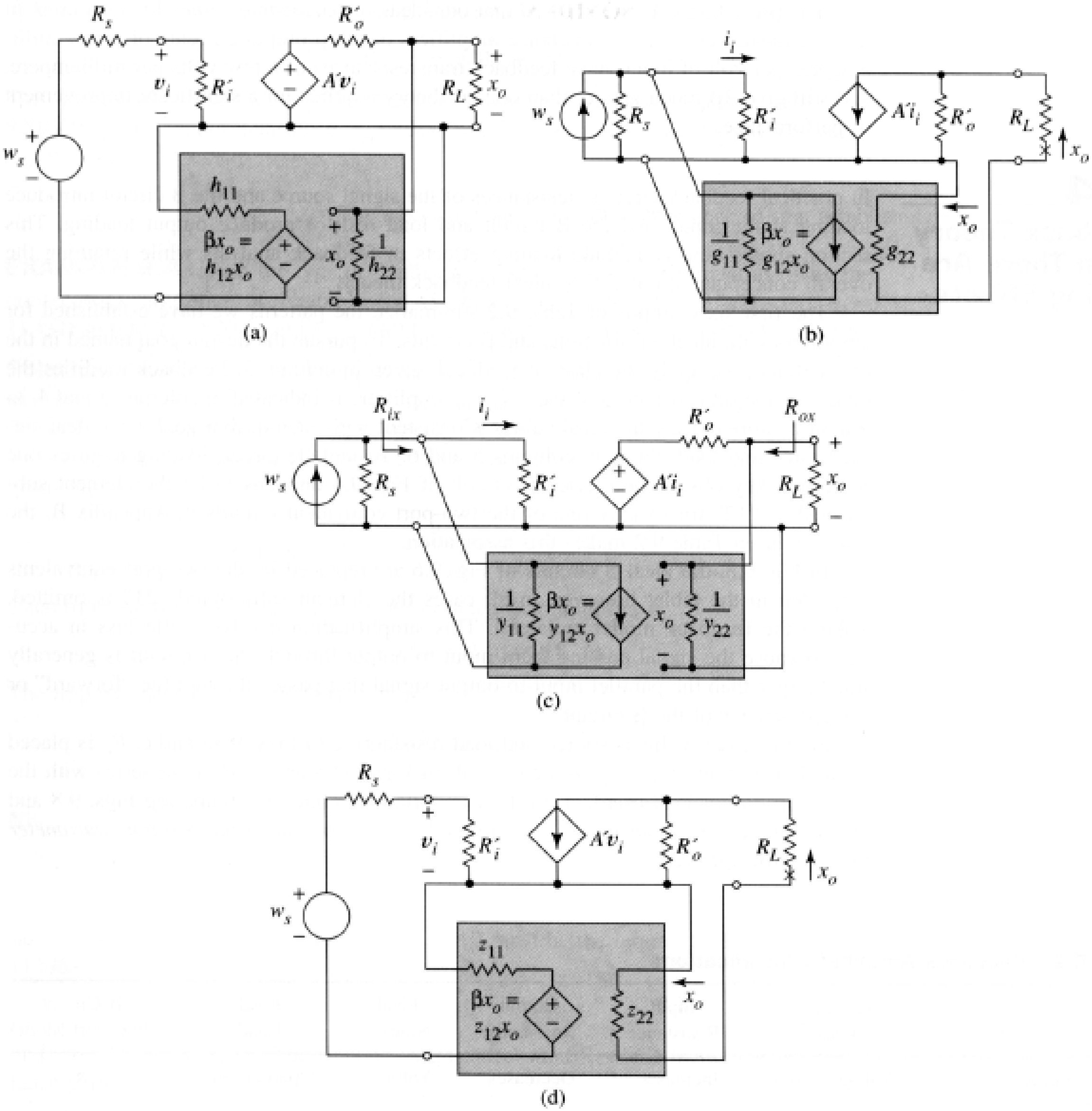
$$R_{of} = \frac{u_{test}}{x_o}$$

$$= R_o(1 + Ab)$$

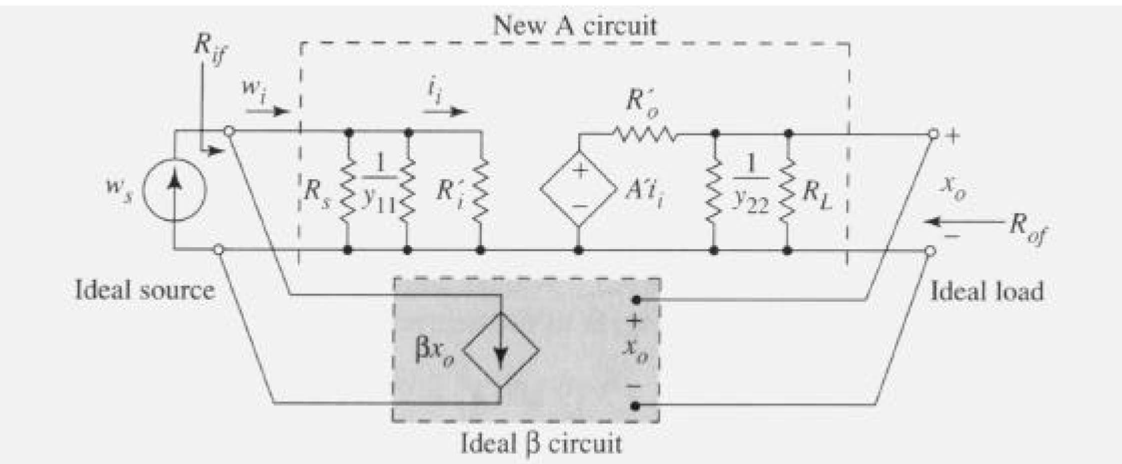
考慮回授電路的負載效應

當回授電路(β network)不是理想的 dependent source 時，他的負載效應必須考慮。處理的方法是將回授電路的輸入及輸出阻抗和主要放大電路合併，回授電路則只剩下理想的 dependent source。分析時則先分析包括回授電路的輸入及輸出阻抗但無回授(b=0)的電路，再考慮回授的影響。

在分析電路之前，回授電路部分必須先找出來，並以線性雙埠模型(linear two-port model)表示，而且以單向(unilateral)電路來做近似，即放大器的輸出訊號可經由回授電路回到輸入，但輸入訊號則無法由回授電路到輸出。



Nonideal feedback circuits: (a) voltage series; (b) current shunt; (c) voltage shunt; (d) current series.



Nonideal voltage-shunt feedback circuit with R_s, $1/y_{11}$, $1/y_{22}$, and R_L associated with the A circuit.

線性雙埠模型 (linear two-port model)

$$\begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ i_2 \end{pmatrix}$$

z Parameters

$$\begin{pmatrix} i_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}$$

y Parameters

$$\begin{pmatrix} u_1 \\ i_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \begin{pmatrix} i_1 \\ u_2 \end{pmatrix}$$

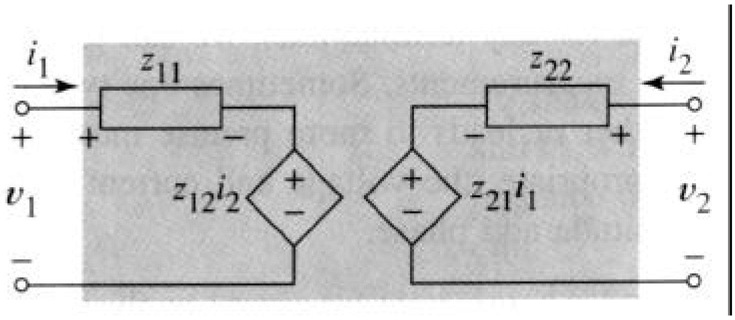
h Parameters

$$\begin{pmatrix} i_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix} \begin{pmatrix} u_1 \\ i_2 \end{pmatrix}$$

g Parameters

等效電路

z Parameters

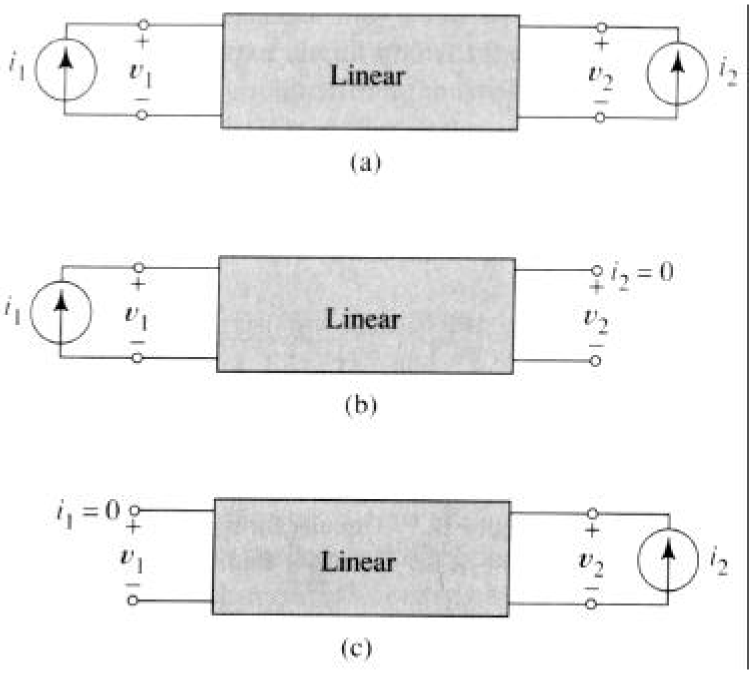


$z_{11} = \frac{u_1}{i_1}\Big|_{i_2=0}$ *open-circuit input impedance*

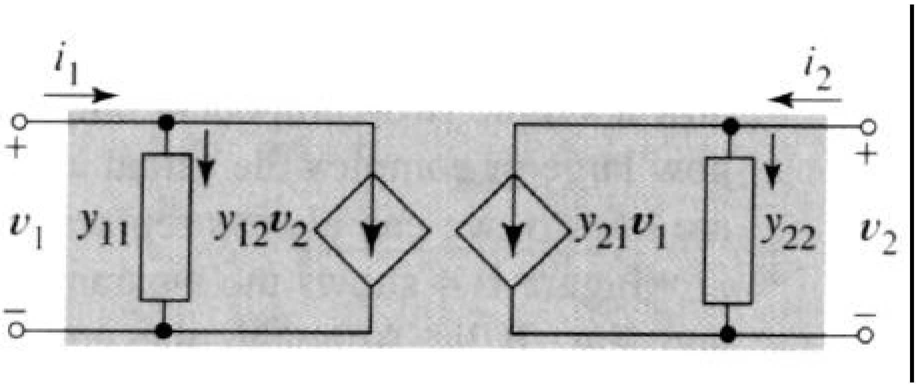
$z_{21} = \frac{u_2}{i_1}\Big|_{i_2=0}$ *open-circuit forward transfer impedance*

$z_{12} = \frac{u_1}{i_2}\Big|_{i_1=0}$ *open-circuit reverse transfer impedance*

$z_{22} = \frac{u_2}{i_2}\Big|_{i_1=0}$ *open-circuit output impedance*



y Parameters

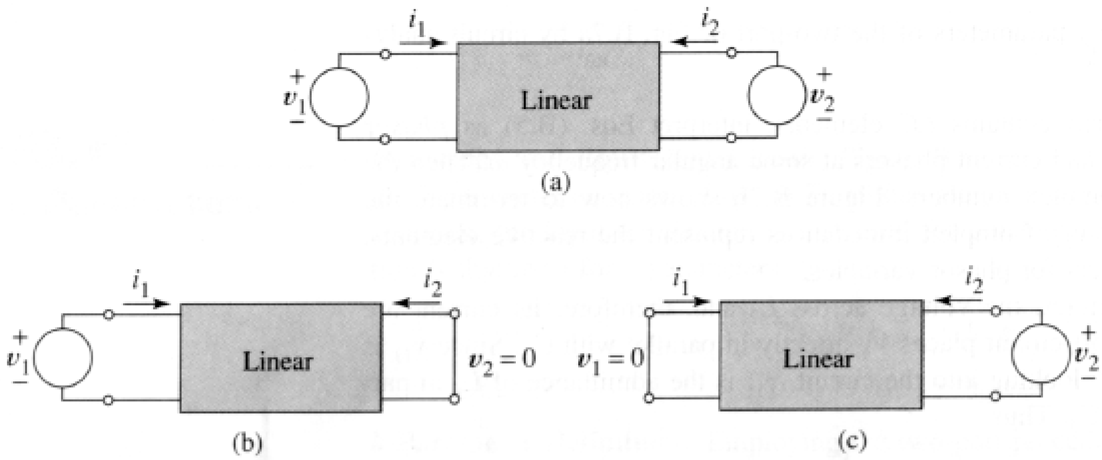


$y_{11} = \frac{i_1}{u_1}\bigg|_{u_2=0}$ *short-circuit input admittance*

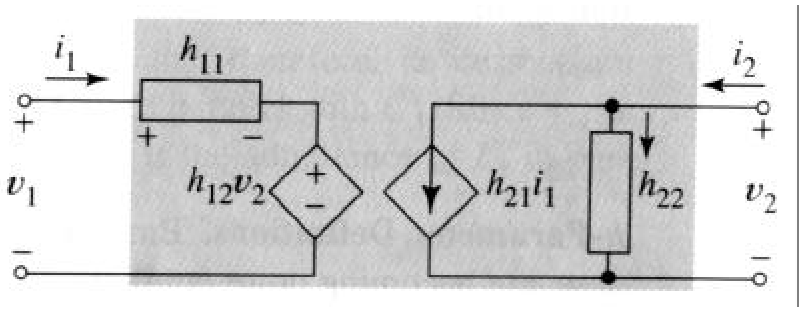
$y_{21} = \frac{i_2}{u_1}\bigg|_{u_2=0}$ *short-circuit forward transfer admittance*

$y_{12} = \frac{i_1}{u_2}\bigg|_{u_1=0}$ *short-circuit reverse transfer admittance*

$y_{22} = \frac{i_2}{u_2}\bigg|_{u_1=0}$ *short-circuit output admittance*



h Parameters

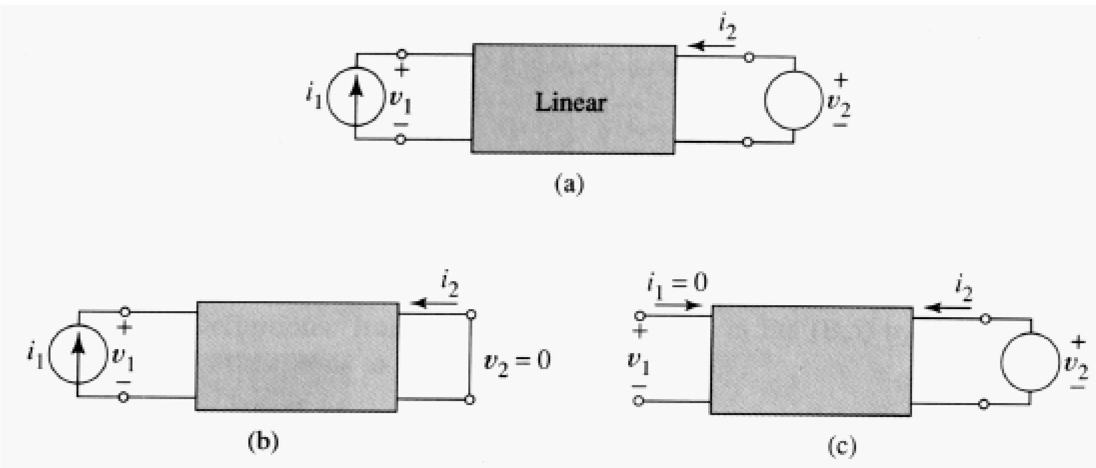


$$h_{11} = \left.\frac{u_1}{i_1}\right|_{u_2 = 0}$$ *short-circuit input impedance*

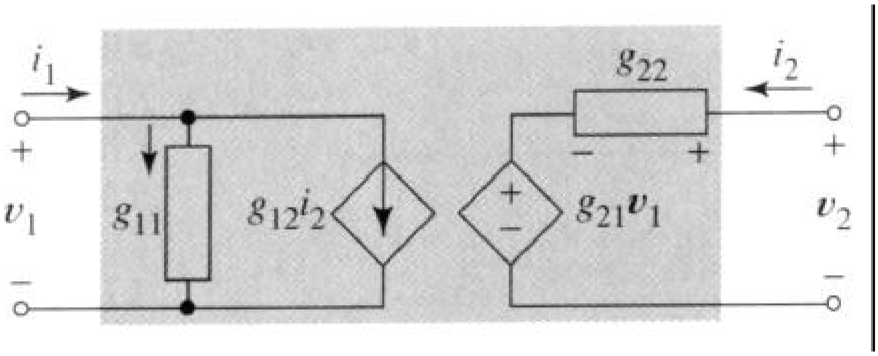
$$h_{21} = \left.\frac{i_2}{i_1}\right|_{u_2 = 0}$$ *short-circuit forward current gain*

$$h_{12} = \left.\frac{u_1}{u_2}\right|_{i_1 = 0}$$ *open-circuit reverse voltage gain*

$$h_{22} = \left.\frac{u_1}{u_2}\right|_{i_1 = 0}$$ *open-circuit output admittance*



g Parameters

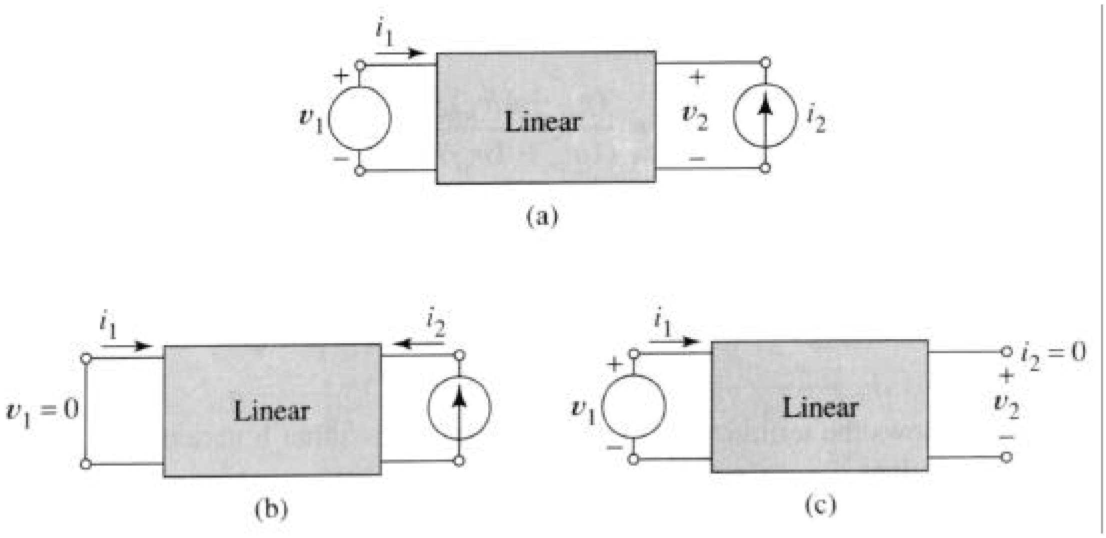


$$g_{11} = \left.\frac{i_1}{u_1}\right|_{i_2 = 0}$$ *open-circuit input admittance*

$$g_{21} = \left.\frac{u_2}{u_1}\right|_{i_2 = 0}$$ *open-circuit forward voltage gain*

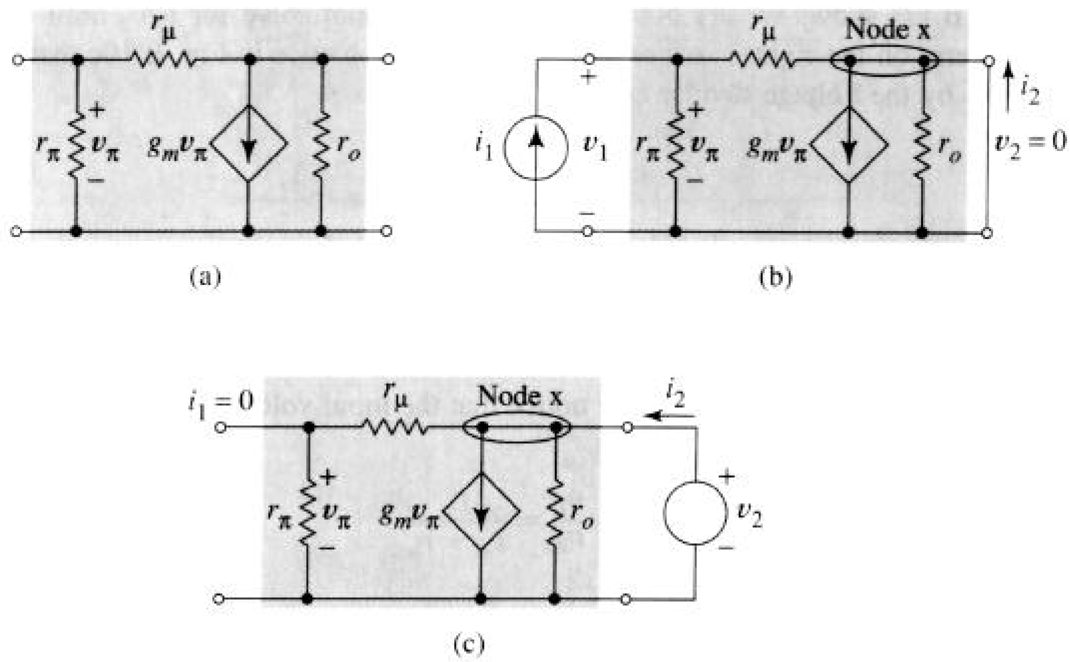
$$g_{12} = \left.\frac{i_1}{i_2}\right|_{u_1 = 0}$$ *short-circuit reverse current gain*

$$g_{22} = \left.\frac{u_2}{i_2}\right|_{u_1 = 0}$$ *short-circuit output impedance*



雙埠等效電路之實例

(1)BJT **的** h parameters



計算 h_{11} 及 h_{21}：將輸出短路

$$h_{11} = \frac{u_1}{i_1} = r_p \,//\, r_m \equiv h_{ie}$$

$$\left[= r_b + \left(r_p \,//\, r_m\right)\right]$$ if we consider the base spreading resistance.

$$i_2 = g_m u_1 - \frac{u_1}{r_m} = \left(g_m - \frac{1}{r_m}\right)\left(r_p \,//\, r_m\right) i_1 = \left(g_m - \frac{1}{r_m}\right) h_{ie} i_1$$

$$h_{21} = \frac{i_2}{i_1} = \left(g_m - \frac{1}{r_m}\right) h_{ie} = \left(g_m - \frac{1}{r_m}\right)\left(r_p \,//\, r_m\right) = \frac{g_m - 1/r_m}{1/r_p + 1/r_m}$$

$$\equiv h_{fe}$$

計算 h_{12} 及 h_{22}：將輸入開路

$$u_p = \frac{r_p}{r_p + r_m} u_2$$

$$i_2 = \frac{u_2}{r_o} + g_m u_p + \frac{u_2}{r_p + r_m} = \left(\frac{1}{r_o} + \frac{g_m r_p}{r_p + r_m} + \frac{1}{r_p + r_m} \right) u_2$$

$$h_{22} = \frac{i_2}{u_2} = \frac{1}{r_o} + \frac{1 + g_m r_p}{r_p + r_m} = \frac{1}{r_o} + \frac{1 + b}{r_p + r_m} \equiv h_{oe}$$

$$h_{12} = \frac{u_1}{u_2} = \frac{r_p}{r_p + r_m} \equiv h_{re}$$

Static *h* Parameters for Common-Emitter BJT

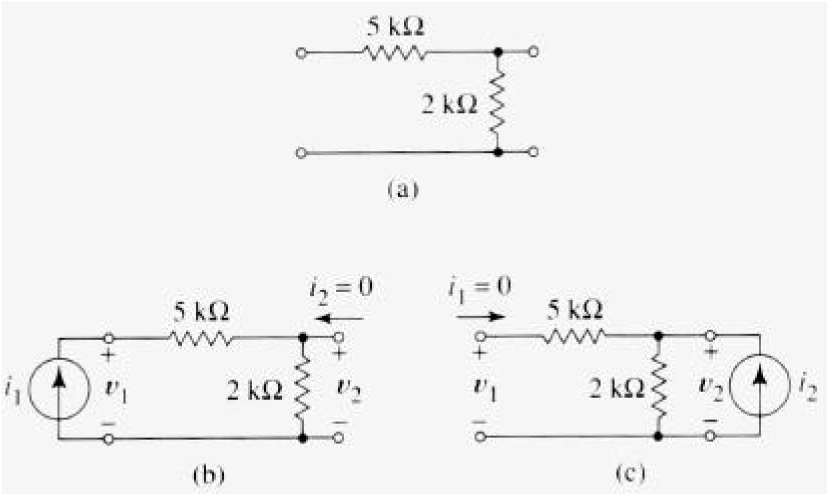
h Parameter	*h* Parameter in Terms of Hybrid Pi Parameters	Approximate Expression for *h* Parameter
h_{ie}	$r_b + (r_\pi \| r_\mu)$	$r_b + r_\pi$
h_{fe}	$\frac{r_\mu g_m r_\pi - r_\pi}{r_\mu + r_\pi}$	β
h_{re}	$\frac{r_\pi}{r_\pi + r_\mu}$	$\frac{r_\pi}{r_\mu}$
h_{oe}	$\frac{1}{r_o} + \frac{\beta + 1}{r_\pi + r_\mu}$	$\frac{1}{r_o} + \frac{\beta}{r_\mu}$

BJT **廠商提供的數據都是** h parameters**，以及** f_t**和** C_m(**或稱** C_{ob}、C_{cb}、C_c、C_{CBO})**，分析前可先換為** hybrid-π model **的參數：**

1. $g_m = \frac{I_C}{V_T}$ 2. $r_p = \frac{h_{fe}}{g_m}$ 3. $r_b = h_{ie} - r_p$

4. $r_m = \frac{r_p}{h_{re}}$ 5. $r_o = \frac{r_m}{r_m h_{oe} - h_{fe}}$ 6. $C_p = \frac{g_m}{2pf_t} - C_m$

(2)**電阻分壓電路之** z parameters



計算 z_{11} **及** z_{21}**：將輸出開路，輸入加一電流源。**

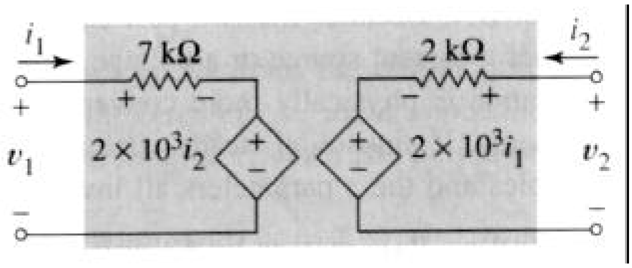
$$z_{11} = \frac{u_1}{i_1} = (5+2)\ \mathbf{k\Omega} = 7\ \mathbf{k\Omega}$$

$$z_{21} = \frac{u_2}{i_1} = 2\ \mathbf{k\Omega} = 2\times 10^3\ \mathbf{V/A}$$

計算 z_{22} **及** z_{12}**：將輸入開路，輸出加一電流源。**

$$z_{22} = \frac{u_2}{i_2} = 2\ \mathbf{k\Omega}$$

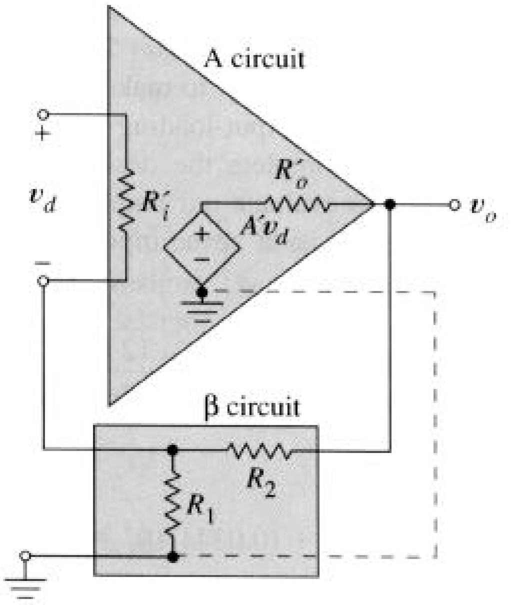
$$z_{12} = \frac{u_1}{i_2} = 2\ \mathbf{k\Omega} = 2\times 10^3\ \mathbf{V/A}$$



回授差動放大器

Difference amplifier topology---voltage-series feedback

簡單的例子：



Noninverting amplifier as a feedback circuit.

右圖為一實際的電路，

先求回授網路的

h parameters

$h_{11} = 1//9\,\mathbf{k\Omega}$

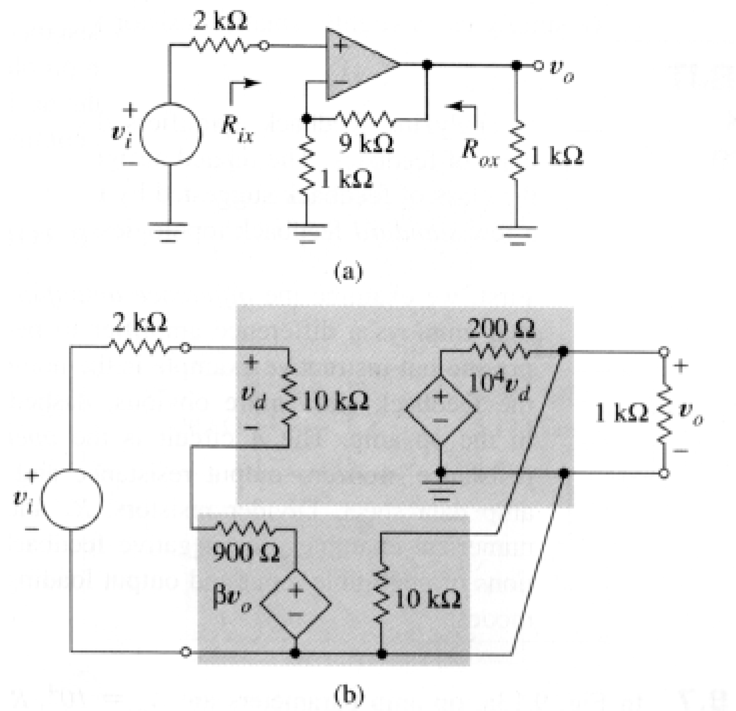
$= 900\,\Omega$

$h_{22} = 1/[(1+9)\,\mathbf{k\Omega}]$

$1/[1\mathbf{0}\,\mathbf{k\Omega}]$

$h_{12} = b = 1/(1+9)$

$= 0.1$



$h_{21} = 0.1$ (short-circuit current gain) **由於是** voltage feedback**，輸入阻抗大大地增加，也就是輸入電流變得很小，**$h_{12}i_{in}$**對輸出電路影響很小，故** h_{12} **對應的** CCCS **忽略。**

將回授關掉---令b=0**，求包含回授電路負載效應的放大器參數（開路參數）。**

$$R_i = (2+10+0.9)\,\mathbf{k}\Omega = 12.9\,\mathbf{k}\Omega$$

$$R_o = (1 // 10 // 0.2)\,\mathbf{k}\Omega = 164\,\Omega$$

$$A = \frac{u_0}{u_i} = \frac{10\,\mathbf{k}}{10\,\mathbf{k}+2\,\mathbf{k}+900} 10^4 \frac{(1//10)\,\mathbf{k}}{(1//10)\,\mathbf{k}+200} = 6354$$

改善因子(improving factor) $1+bA = 1+6354\times 0.1 = 636$

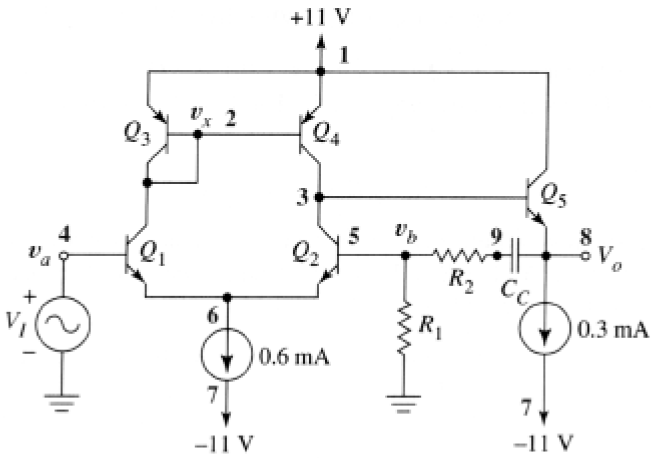
$$A_f = \frac{A}{1+bA} = \frac{6354}{636} = 9.99 \approx \frac{1}{b}$$

$$R_{if} = 12.9\times 636\,\mathbf{k}\Omega = 8.2\,\mathbf{M}\Omega$$

$$R_{of} = 164/636\,\Omega = 0.258\,\Omega$$

一個更實際的電路設計

先將 R_1,R_2 **移去計算無回授電路的特性，計算時** b **端接地。**

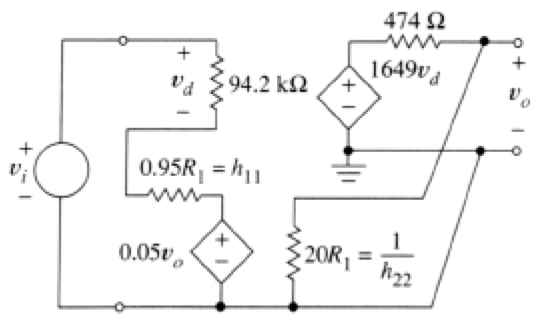


(a)

如果我們想設計一個增益為 20 **的電壓放大器，即**

$$A_f = 20 \approx \frac{1}{b} = \frac{1}{h_{12}}$$

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



(b)

$$R_2 = 19R_1$$
$$h_{11} = R_1 // R_2 = 0.95R_1$$
$$1/h_{22} = R_1 + R_2 = 20R_1$$

為避免輸入及輸出之負載效應，選擇

$$h_{11} = 0.95R_1 << 94.2\,\mathbf{k}\Omega$$
$$1/h_{22} = 20R_1 >> 474\,\Omega$$

取 R_1=270 Ω, R_2=5.1 kΩ**。**

將回授關掉---令b=0**，求包含回授電路負載效應的放大器參數（開路參數）。**

$$R_i = 94.2\,\mathbf{k} + 0.95 \times 270 = 94.5\,\mathbf{k}$$

$$R_o = 474 // (20 \times 270) = 436\,\Omega$$

$$A = \frac{u_0}{u_i} = \frac{94.2\,\mathbf{k}}{94.2\,\mathbf{k} + 0.95 \times 270} 1649 \frac{20 \times 270}{20 \times 270 + 474} = 1512$$

$$1 + bA = 1 + 1512 \times 0.0503 = 77.1$$

$$R_{if} = 94.5 \times 77.1\,\mathbf{k}\Omega = 7.29\,\mathbf{M}\Omega$$

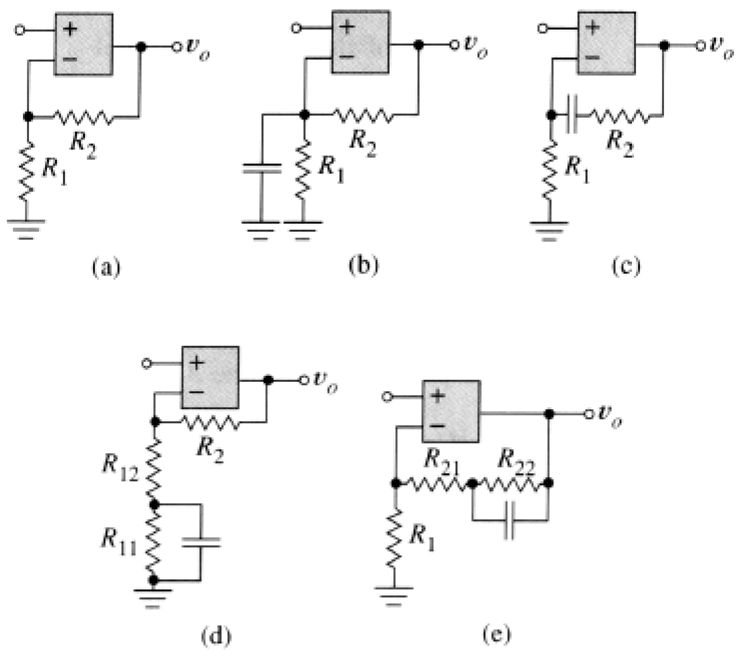
$$R_{of} = 436 / 77.1\ \Omega = 5.66\,\Omega$$

$$A_f = \frac{A}{1 + Ab} = 19.6$$

C_C**決定回授的低頻截止頻率。**

注意，這樣的接法，直流無回授，直流增益遠大於交流增益，必須注意直流偏壓的穩定性。

dc, ac, and mixed feedback

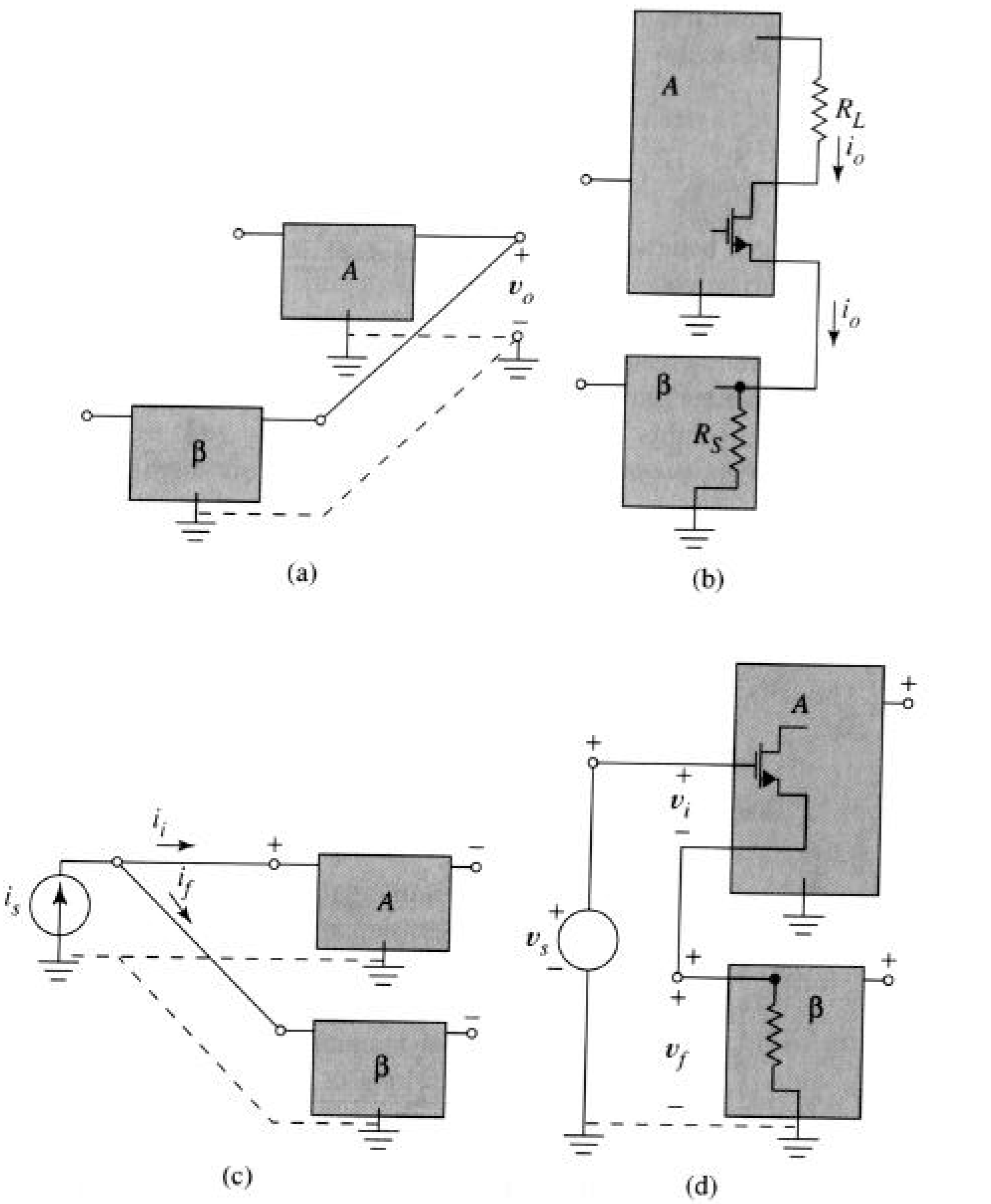


Combinations of dc and ac feedback: (a) dc and ac feedback in equal amounts; (b) dc but no ac feedback; (c) ac but no dc feedback; (d) dc feedback greater than ac feedback; (e) ac feedback greater than dc feedback.

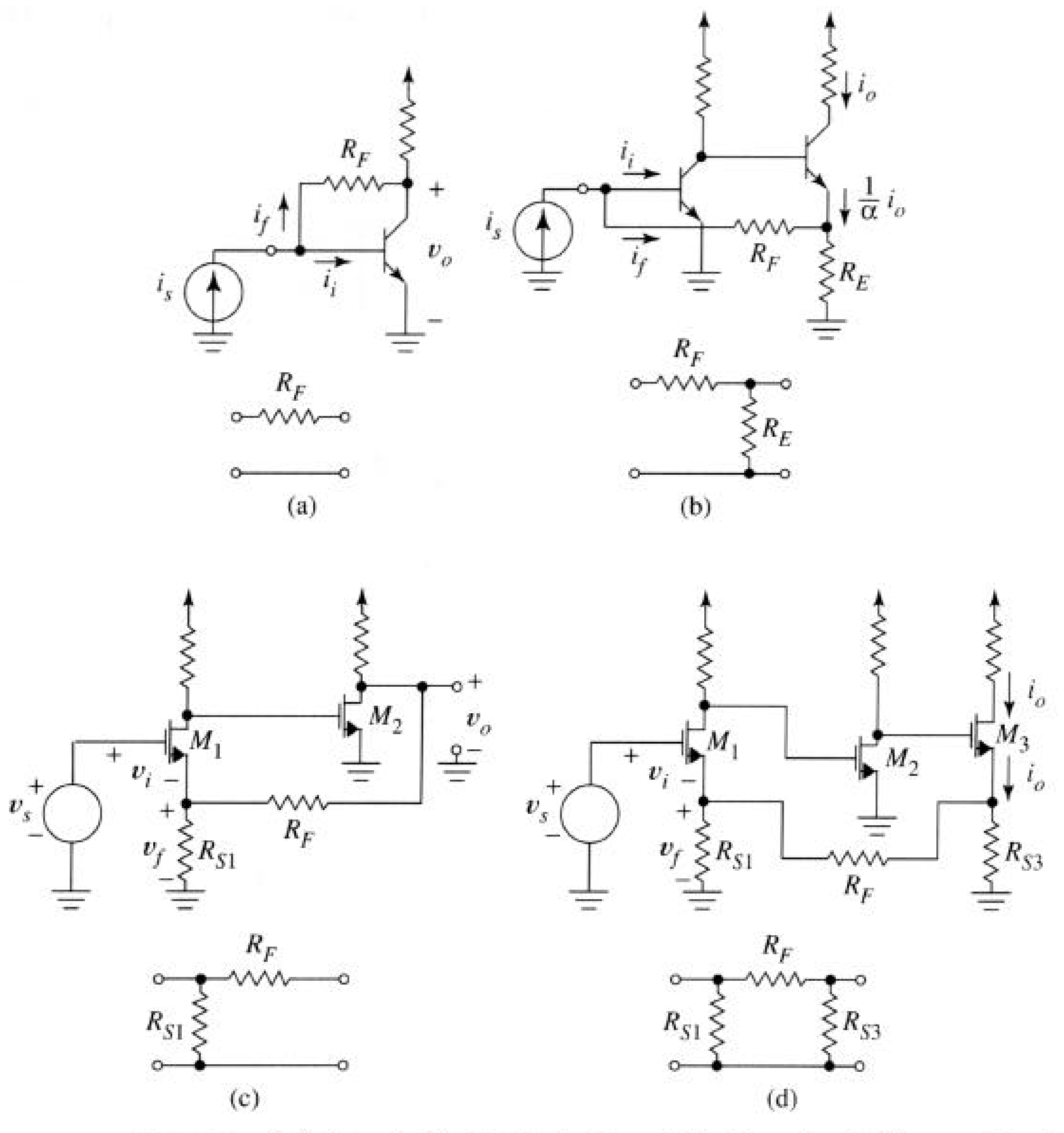
單端放大器的回授

分析最重要的(也是最困難的)步驟是判定回授的種類。

判斷的依據包括：(1)**回授訊號的來源，**(2)**回授訊號的目的地，**(3)**相位(必須是負回授)。**

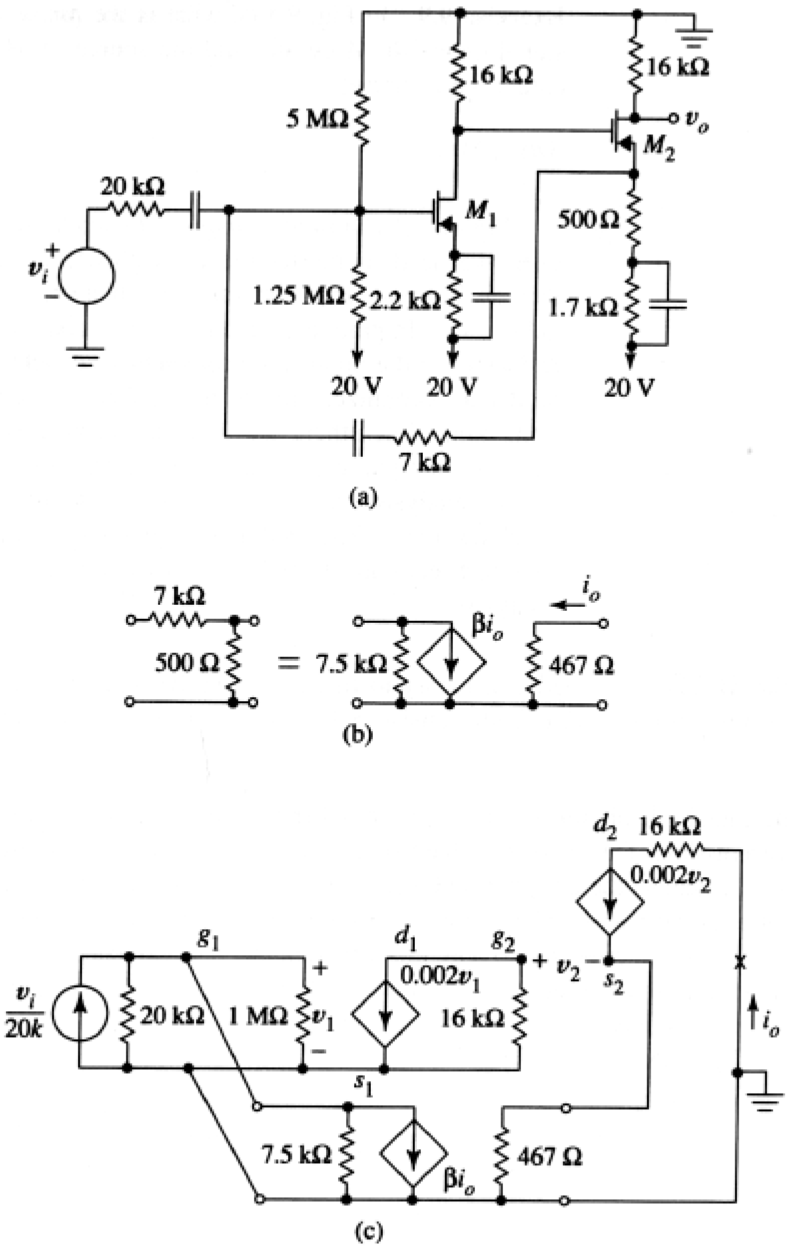


Connections for feedback in single-ended amplifiers: (a) voltage feedback; (b) current feedback; (c) shunt feedback; (d) series feedback.



Examples of single-ended feedback structures: (a) voltage shunt; (b) current shunt; (c) voltage series; (d) current series.

實例



FET current-shunt feedback amplifier: (a) circuit schematic; (b) feedback network and two-port equivalent; (c) midrange circuit for applying feedback theory.

其他注意事項：

(1) R_{if}與 R_{of}的頻率響應

(2) **穩定度**：*Nyquist stability criterion*

放大器不穩定的充要條件為存在一頻率w_o，其迴路增益

$$L(w_o) = A(w_o)b = M\angle 180^\circ, \qquad \textbf{and } M \geq 1$$