Feedback in Electronic Circuits

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INTRODUCTION

Consider the feedback amplifier shown.

\[ XL = A \cdot XE = A (XS - XF) = A (XS - BXL) \]
\[ = A \cdot XS - A \cdot B \cdot XL \text{ or } XL(1+AB)=A \cdot XS \]

\[ Af = XL/XS = A/(1+AB) \]

In this analysis, A is defined as the gain of the amplifier without feedback, known as the open loop gain, B is the gain of the feedback network, T= -AB is known as the loop gain, and Af is the gain of the amplifier with feedback, known as the closed loop gain.
NEGATIVE FEEDBACK: If the loop gain is negative for any circuit then that circuit has negative feedback. For negative feedback the closed loop gain is:

$$Af = \frac{A}{1 + AB}$$

POSITIVE FEEDBACK: If the loop gain is positive for any circuit then that circuit has positive feedback. $Af = A / (1 – AB)$. Note that if $AB = 1$ the gain $Af = $ infinity and the circuit will oscillate. That is no input is needed. Which is useful if you want an oscillator.

We will continue by discussing only negative feedback.
NEGATIVE FEEDBACK DECREASES SENSITIVITY

Decrease in Sensitivity – Suppose A changes by x%. How much would Af change? To answer this question lets compute the sensitivity of Af with respect to A:

\[ \frac{\Delta A_f}{A_f} = \frac{\Delta A}{A} = \frac{\delta A_f}{\delta A} \cdot \frac{A}{1+AB} \]

Divide both sides by Af

\[ \frac{\Delta A_f}{A_f} = \frac{1}{(1+AB)^2} \cdot \frac{\Delta A}{A} \]

So we see that the sensitivity of the gain Af to changes in gain A is less than 1 which is an improvement over an amplifier without feedback.
NEGATIVE FEEDBACK DECREASES SENSITIVITY

Decrease in Sensitivity –

\[ \frac{R_2}{R_1} = -10 \]

10⁴ < A < 10⁵

The gain without feedback, A, is large but not precise (may change from one op amp to the next).

The gain with feedback, A_f, is \(-\frac{R_2}{R_1} = -10\) which is precise (and lower than A)
NEGATIVE FEEDBACK DECREASES DISTORTION

Reduction in Distortion: Suppose an amplifier consists of two stages, A1 and A2 such that \( A = A_1A_2 \) and that distortion is modeled as the addition of an unwanted signal \( X_S' \) as shown in the figure below.

\[
XL = A_2 \cdot X_E' = A_2 \left( X_I + X_S' \right)
\]

\[
XL = A_2 \left( A_1 X_E + X_S' \right) = A_2 \left( A_1 (X_S - X_F) + X_S' \right)
\]

\[
XL = A_2 (A_1 (X_S - B X_L) + X_S')
\]
NEGATIVE FEEDBACK DECREASES DISTORTION

If Xs’ were some unwanted signal, say distortion, we could decrease the effect of Xs’ by introducing it as close as possible to the output of the amplifier. In other words make A, as large as possible, use feedback to achieve the desired gain and also reduce distortion introduced after A1. In many amplifiers distortion is introduced in the output stage, (crossover, etc.)

\[
XL = A2 \cdot XE' = A2 \cdot (XI + XS')
\]

\[
XL = A2(A1XE + XS') = A2 (A1(XS-XF) + XS')
\]

\[
XL = A2(A1(XS-BXL) + XS')
\]

\[
XL = A2A1XS – A2A1BXL + A2XS'
\]

\[
XL = \frac{A1A2}{(1+A1A2B)} \left( \frac{XS + XS'}{A1} \right)
\]
NEGATIVE FEEDBACK DECREASES DISTORTION

Without Feedback
Dashed Line

With Feedback
Solid Line

Crossover Distortion
NEGATIVE FEEDBACK INCREASES BANDWIDTH

Bandwidth is the frequency range where the amplifier gain is flat.

\[ A(j\omega) = \frac{1000}{1 + j \frac{f}{f_1}} \]

Let \( f_1 = 1000 \text{ hz} \)

\[ Af(j\omega) = \frac{A}{1+AB} = \frac{1000}{1+jf/f_1} = \frac{1000}{1+100\frac{f}{f_1}} \]

\[ Af(j\omega) = \frac{1000}{1+jf/(101f_1)} \]

\[ A = 1000 = 60\text{dB} \]

\[ 40\text{dB} \]

\[ A_f = 10 = 20\text{dB} \]

\[ 0\text{dB} \]

\[ A_f = 10 = 20\text{dB} \]

\[ 0\text{dB} \]
SUMMARY OF ADVANTAGES OF NEGATIVE FEEDBACK

Negative feedback reduces the gain of an amplifier compared to the gain without feedback:

However, an amplifier with negative feedback has the following improvements:

1. The gain with feedback is less sensitive to the amplifier gain value itself
2. Feedback can reduce unwanted distortion.
3. Feedback increases the bandwidth
REVIEW OF TWO PORT EQUIVALENT CIRCUITS

\[ I_1 = y_{11} V_1 + y_{12} V_2 \]
\[ I_2 = y_{21} V_1 + y_{22} V_2 \]

\[ V_1 = h_{11} I_1 + h_{12} V_2 \]
\[ I_2 = h_{21} I_1 + h_{22} V_2 \]

\[ I_1 = g_{11} V_1 + g_{12} I_2 \]
\[ V_2 = g_{21} V_1 + g_{22} I_2 \]

\[ V_1 = z_{11} I_1 + z_{12} I_2 \]
\[ V_2 = z_{21} I_1 + z_{22} I_2 \]
A Generalized Approach for the Analysis of Feedback Amplifiers:

The components of a feedback amplifier are:

1. An Amplifier (y,g,h,z parameter two-port model)
2. A Feedback Network (y,g,h,z parameter two-port model)
3. A Sampling Network (series or parallel connections)
4. A Mixing or Comparing Network (connections)
5. A Load (a resistor)
6. A Source (Thevenin or Norton equivalent)
AMPLIFIER MODELS

\[
\begin{align*}
\text{y-parameter} & : \quad i_e \rightarrow \begin{array}{c}
+ \quad V_e \\
- \quad -i_L \quad y_{11}^A \quad y_{12}^A \quad V_L \\
- \quad y_{21}^A \quad V_e \quad y_{22}^A
\end{array} & \quad \begin{array}{c}
+ \quad h_{11}^A \\
- \quad h_{12}^A \quad V_L \quad h_{22}^A \\
- \quad h_{21}^A \quad i_e \quad h_{22}^A
\end{array} \\
\text{g-parameter} & : \quad i_e \rightarrow \begin{array}{c}
+ \quad V_e \\
- \quad -i_L \quad g_{11}^A \quad g_{12}^A \quad -i_L \\
+ \quad g_{21}^A \quad V_e \quad g_{22}^A
\end{array} & \quad \begin{array}{c}
+ \quad z_{11}^A \\
- \quad z_{12}^A \quad -i_L \quad z_{22}^A \\
- \quad z_{21}^A \quad i_e \quad z_{22}^A
\end{array}
\end{align*}
\]
FEEDBACK NETWORK MODELS

\[
\begin{align*}
\text{ie} & \quad \rightarrow \quad \text{y-parameter} \quad \leftarrow \quad \text{-iL} \\
+ \quad \text{Ve} & \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \ quad
3. The sampling network consists of the wires used to connect the feedback network to the amplifier. Sampling can be done in parallel (voltage sampling) or in series (current sampling) with the load.

4. The mixing network consists of the wires used to connect the feedback network to the amplifier. Mixing can be in parallel (shunt) or series with the source.

5. The load is a resistor connected to the output of the amplifier.

6. The source is represented by its Thevinin or Norton equivalent circuit.

\[ \text{Thevinin: } \frac{V_S}{R_S} \text{ or } I_S R_S \]

\[ \text{Norton: } I_S \text{ or } \frac{V_S}{R_S} \]
FEEDBACK AMPLIFIER CONFIGURATIONS

Since A and B are being considered as two-port networks there are four ways in which these two-port networks can be connected to provide feedback as shown below:

Voltage-Shunt Feedback
(use y parameters)

Voltage-Series Feedback
(use h parameters)

Current-Shunt Feedback
(use g parameters)

Current-Series Feedback
(use z parameters)
Since *voltage – shunt* feedback implies parallel connections for the sampling and mixing networks. We will select, y-parameter two port models and a Norton model for the source. The resulting equivalent circuit can be greatly simplified by combining parallel current sources and parallel conductances.

![Circuit Diagram](image)
VOLTAGE-SHUNT FEEDBACK

Select y-parameters and Norton equivalent circuits for voltage-shunt feedback:
SIMPLIFIED VOLTAGE-SHUNT FEEDBACK

From the previous page we combine current sources in parallel and conductances in parallel. (the equivalent circuit is simplified)

\[
\begin{align*}
y_{11} &= y_{11}^A + y_{11}^B + 1/R_s \\
y_{12} &= y_{12}^A + y_{12}^B \\
y_{21} &= y_{21}^A + y_{21}^B \\
y_{22} &= y_{22}^A + y_{22}^B + 1/RL
\end{align*}
\]
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

KCL gives

\[ IS = y_{11} Ve + y_{12} VL \]
\[ 0 = y_{21} Ve + y_{22} VL \] this eqn gives \( Ve = -\frac{y_{22} VL}{y_{21}} \)

\[ IS = y_{11}(-\frac{y_{22} VL}{y_{21}}) + y_{12} VL = [-\frac{y_{11}y_{22}}{y_{21}} + y_{12}]VL \]

\[ \frac{VL}{IS} = \frac{1}{[y_{12} - y_{11}y_{22}/y_{21}]} \]

\[ \frac{VL}{IS} = \frac{-y_{21}}{y_{11}y_{22}} \quad \frac{y_{12}y_{21}}{1 + \frac{y_{11}y_{22}}{y_{11}y_{22}}} \]

\[ Af = \frac{A}{1 + AB} \]
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

\( A_{Rf} = \frac{V_L}{I_S} \) is the gain with feedback: Notice that the gain with feedback, \( A_f \), for voltage-shunt feedback has units of ohms (Ω). \( A_f \) is not a voltage gain, it is not a current gain, it is a transresistance.

Suppose we wanted a voltage gain instead of transresistance. Recall that \( I_S \) came from the Norton equivalent of the source. Thus \( V_S = I_S R_S \)

\[ A_{Rf} = \frac{V_L}{I_S} \]

\[ A_{Vf} = \frac{V_L}{V_S} = \left( \frac{V_L}{I_S} \right) \frac{1}{R_S} = A_{Rf} \frac{1}{R_S} \]

\[ A_{If} = \frac{I_L}{I_S} = \left( \frac{V_L}{I_S} \right) \frac{1}{R_L} = A_{Rf} \frac{1}{R_L} \]
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

\[ A_R = \frac{-y_{21}}{y_{11}y_{22}} \] is the gain of the feedback amplifier with the feedback disabled. \( A_R \) is not the gain of the feedback amplifier with the feedback disconnected.

\[ A_{Rf} = \frac{-y_{21}}{y_{11}y_{22}} \quad \left| \begin{array}{c}
\frac{-y_{12}y_{21}}{y_{11}y_{22}} \\
1 + \frac{-y_{12}y_{21}}{y_{11}y_{22}}
\end{array} \right| = \frac{-y_{21}}{y_{11}y_{22}} \]

\[ y_{12} = 0 \]
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

B = \( y_{12} \): this quantity is very important for estimating the gain of the amplifier with feedback

\[
A_{Rf} \approx \frac{1}{B} = \frac{1}{y_{12}}
\]

This approximation is good as \( y_{21} \) goes to infinity

\[
A_{Rf} = \frac{-y_{21}}{y_{11}y_{22}} \quad \frac{-y_{12}y_{21}}{y_{11}y_{22}}
\]

Exact gain

\[
T = -BA = \frac{y_{12}y_{21}}{y_{11}y_{22}}
\]

is the loop gain T
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

Input Admittance,  \( Y_{If} = IS/Ve \)

\[
\begin{align*}
IS &= y_{11} Ve + y_{12} VL \\
0 &= y_{21} Ve + y_{22} VL \\
\text{→ } VL &= -\frac{y_{21}}{y_{22}} Ve \\
IS &= y_{11} Ve + y_{12} \left(-\frac{y_{21}}{y_{22}} Ve\right) = y_{11} Ve \left(1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}\right) \\
Y_{If} &= IS/Ve = y_{11} \left(1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}\right) = y_{11} \left(1 - T\right)
\end{align*}
\]
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

Output Admittance, \( Y_{of} = \frac{I_o}{V_o} \) with \( I_s = \) zero

\[
0 = y_{11} V_e + y_{12} V_o
\]

\[
I_o = y_{21} V_e + y_{22} V_o
\]

\[
0 = y_{11} V_e + y_{12} V_o
\]

\[
I_o = y_{21} \left( -\frac{y_{12}}{y_{11}} V_o \right) + y_{22} V_o = y_{22} V_o \left( 1 - \frac{y_{12}y_{21}}{y_{11}y_{22}} \right)
\]

\[
Y_{of} = \frac{I_o}{V_o} = y_{22} \left( 1 - \frac{y_{12}y_{21}}{y_{11}y_{22}} \right) = y_{22} \left( 1 - T \right)
\]
EXAMPLE VOLTAGE-SHUNT FEEDBACK

Example:

Assume DC analysis is good
\[ \beta = 100, \ VA=\text{infinite}, \ r\pi = 1K \]

1. Identify A block, B block mixing network, sampling network, source and load.
EXAMPLE VOLTAGE-SHUNT FEEDBACK

2. Find two port parameters for A block and B block.

\[ I_1 = y_{11} V_1 + y_{12} V_2 \]
\[ I_2 = y_{21} V_1 + y_{22} V_2 \]

\[
\begin{align*}
\text{A block} & : & \begin{cases}
y_{11}^A = 1/1K = 1E-3 \\
y_{12}^A = 0 \text{ (almost always)} \\
y_{21}^A = \text{gm}=B/r\pi=0.1 \\
y_{22}^A = 1/1K = 1E-3
\end{cases} \\
\text{B block} & : & \begin{cases}
y_{11}^B = 1/10K = 1E-4 \\
y_{12}^B = -1/10K = -1E-4 \\
y_{21}^B = -1/10K = -1E-4 \\
y_{22}^B = 1/10K = 1E-4
\end{cases}
\end{align*}
\]
EXAMPLE VOLTAGE-SHUNT FEEDBACK

3. Find the combined parameters

\[ y_{11} = y_{11}^A + y_{11}^B + \frac{1}{RS} = 1e-3 + 1e-4 + 1e-3 = 2.1e-3 \]
\[ y_{12} = y_{12}^A + y_{12}^B = 0 + -1e-4 = -1e-4 \]
\[ y_{21} = y_{21}^A + y_{21}^B = 0.1 -1e-4 = 0.0999=0.1 \]
\[ y_{22} = y_{22}^A + y_{22}^B + \frac{1}{RL} =1e-3 + 1e-4 + 1e-3 = 2.1e-3 \]

4. Compute quantities of interest

4.1 Gain with feedback (transresistance)

\[ A_{Rf} = \frac{-y_{21}}{y_{11}y_{22}} = \frac{-0.1}{(2.1e-3)(2.1e-3)} = -6940 \text{ ohms} \]
\[ 1 + \frac{-y_{12}y_{21}}{y_{11}y_{22}} \]

4.2 Voltage gain with feedback

\[ A_{Vf} = A_{Rf} \frac{1}{RS} = -6940 \left( \frac{1}{1000} \right) = -6.94 \]
4.3 Current Gain with Feedback

\[ A_{If} = A_{Rf} \left( \frac{1}{RL} \right) = -6940 \left( \frac{1}{1000} \right) = -6.94 \]

4.4 Approximate Gain

\[ A_{Rf} \sim = \frac{1}{y_{12}} = -\frac{1}{10^{-4}} = -10000 \text{ ohms} \]
\[ A_{Vf} \sim = -10000 \left( \frac{1}{RS} \right) = -10 \]
\[ A_{If} \sim = -10000 \left( \frac{1}{RL} \right) = -10 \]

4.5 Loop gain = \( T = \frac{-y_{12}y_{21}}{y_{11}y_{22}} = (-1e-4)(0.1)/(2.1e-3)(2.1e-3) = -2.27 \)
4.6 Input admittance  

\[ Y_{If} = y_{11} (1 - T) = y_{11} (1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}) \]

\[ Y_{If} = (2.1e^{-3})(1 - 2.27) = 6.86 \text{ mS} \]

Input impedance  

\[ Z_{If} = \frac{1}{Y_{If}} = 146 \text{ ohms} \]

Note: this \( Z_{If} = 146 \text{ ohms} \) is equal to the 1Kohm \( RS \) in parallel with \( Z_{in}' \) the amplifier input impedance.

So \( 1000//Z_{in}' = 146 \) therefore we can find \( Z_{in}' = 171 \text{ ohms} \)
4.7 Output Impedance \( Z_{of} = \frac{1}{Y_{of}} \)

\[
Y_{of} = y_{22} (1-T) = y_{22} (1 - 2.27) = 6.86 \text{ mS}
\]

\[
Z_{of} = \frac{1}{Y_{of}} = 146 \text{ ohms}
\]

Note: this 146 includes the 1000 ohm RL
so \( Z_{o'} \) (without RL) is = 171 ohms
Since **voltage** – **series** feedback implies parallel connection at the load and series connection at the source, we will select, h-parameter two port models and a Thevenin model for the source. The resulting equivalent circuit can be greatly simplified by combining appropriate components.

![Circuit Diagram]

**VOLTAGE SERIES FEEDBACK**
From the previous page we combine appropriate components to get the equivalent circuit shown

\[ h_{11} = h_{11}^A + h_{11}^B + R_s \]

\[ h_{12} = h_{12}^A + h_{12}^B \]

\[ h_{22} = h_{22}^A + h_{22}^B + 1/RL \]

\[ h_{21} = h_{21}^A + h_{21}^B \]
ANALYSIS OF VOLTAGE-SERIES FEEDBACK

KVL gives \( VS = h_{11} ie + h_{12} VL \)

KCL gives \( 0 = h_{21} ie + h_{22} VL \) this eqn gives \( ie = -\frac{h_{22} VL}{h_{21}} \)

\( VS = h_{11}(-\frac{h_{22} VL}{h_{21}}) + h_{12} VL = [-\frac{h_{11} h_{22}}{h_{21}} + h_{12}]VL \)

\( \frac{VL}{VS} = \frac{1}{[h_{12} - h_{11} h_{22}/h_{21}]} \)

\[ \frac{VL}{VS} = \frac{-h_{21}}{h_{11} h_{22}} \quad \frac{-h_{12} h_{21}}{1 + \frac{h_{11} h_{22}}{h_{11} h_{22}}} \]

\( Af = \frac{A}{1 + AB} \)
**VOLTAGE SERIES FEEDBACK**

**Gain with Feedback**

\[
A_{Vf} = \frac{-h_{21}}{h_{11}h_{22}} \left(1 + \frac{-h_{12}h_{21}}{h_{11}h_{22}}\right)
\]

This is a voltage gain (other gains can be found)

**Gain with Feedback Disabled**

\[
A_V = \frac{-h_{21}}{h_{11}h_{22}}
\]

**Approximate Gain**

\[
B \approx \frac{1}{h_{12}}
\]

**Loop Gain**

\[
T = \frac{-h_{12}h_{21}}{h_{11}h_{22}}
\]

**Input Impedance**

\[
Z_{If} = h_{11} (1-T)
\]

**Output Admittance**

\[
Y_{of} = h_{22} (1-T)
\]
Assume DC analysis is good
\( \beta = 100, VA=\text{infinite}, r\pi=1K \)

Example:

1. Identify A block, B block mixing network, sampling network, source and load.
2. Find two port parameters for A block and B block.

\[ V_1 = h_{11}^A I_1 + h_{12}^A V_2 \]
\[ I_2 = h_{21}^A I_1 + h_{22}^A V_2 \]

- For A block:
  \[ h_{11}^A = r\pi = 1000 \]
  \[ h_{12}^A = 0 \]
  \[ h_{21}^A = \beta = -100 \]
  \[ h_{22}^A = 1/ro = 0 \]

- For B block:
  \[ h_{11}^B = 0 \]
  \[ h_{12}^B = 1 \]
  \[ h_{21}^B = -1 \]
  \[ h_{22}^B = 1/Re = 1E-3 \]
3. Find the combined parameters

\[ h_{11} = h_{11}^A + h_{11}^B + \frac{RS}{RB} = 1000 + 0 + 1000 = 2000 \]

\[ h_{12} = h_{12}^A + h_{12}^B = 0 + 1 = 1 \]

\[ h_{21} = h_{21}^A + h_{21}^B = -100 -1 = -101 \]

\[ h_{22} = h_{22}^A + h_{22}^B + \frac{1}{RL} = 0 + 1e^{-3} + 1e^{-3} = 2e^{-3} \]

4. Compute quantities of interest

4.1 Gain with feedback (Voltage Gain)

\[ A_{Vf} = \frac{-h_{21}}{h_{11}h_{22}} \]

\[ A_{Vf} = \frac{101}{(2000)(2e^{-3})} = 0.962 \]
4.2 Approximate Voltage Gain

\[ A_{Vf} \approx \frac{1}{h_{12}} = 1 \]

4.3 Loop gain = \( T = \frac{-h_{12}h_{21}}{h_{11}h_{22}} \)

\[ = (-101)(1)/(2000)(2e^{-3}) = -25.3 \]
EXAMPLE VOLTAGE-SERIES FEEDBACK

4.4 Input impedance

\[ Z_{If} = h_{11} (1 - T) = h_{11} (1 - \frac{h_{12} h_{21}}{h_{11} h_{22}}) \]

\[ Z_{If} = (2000)(1 - 25.3) = 52.6\text{Kohm} \]

Note: this \( Z_{If} = 52.6\text{K ohms} \) is equal to the 1Kohm \( RS//RB \) in series with \( Z_{in}' \) the amplifier input impedance.

So \( Z_{in}' = 51.6\text{K ohms} \)

\[ V_{th} = \frac{VS}{RB/(RB+RS)} \]

\[ V_{th} = \frac{1\text{K}}{RS//RB} \]

\[ Z_{in}' = 51.6\text{K ohms} \]
4.5 Output Impedance $Z_{of} = 1/Y_{of}$

$$Y_{of} = h_{22} (1-T) = 2E-3 (1 - 25.3) = 50.6 \text{ mS}$$

$$Z_{of} = 1 / Y_{of} = 19.8 \text{ ohms}$$

Note: this 19.8 includes the 1000 ohm RL
so $Zo'$ (without RL) is $= 20.1 \text{ ohms}$
EXAMPLE RIT OP AMP

Lets use feedback to get the exact voltage gain, approximate voltage gain, input impedance and output impedance for the circuit below. The Op Amp is the one you built in lab with a differential amplifier, level shift stage and output stage. The overall voltage gain was 600 V/V and the differential input resistance was ~2K ohms. The output resistance was ~200 ohms.

Identify the feedback and make sure it is negative feedback.
The small signal ac equivalent circuit of the feedback amplifier on the previous page is:

\[ RS = 2K \]

\[ RL = 1K \]

\[ R2 = 10K \]

\[ R1 = 1K \]

\[ Rin \]

\[ Rout = 200 \]

\[ Vin - 600Vin \]

Voltage – Series

h - parameters
EXAMPLE VOLTAGE-SERIES FEEDBACK

Find two port parameters for A block and B block.

\[ V_1 = h_{11} I_1 + h_{12} V_2 \]
\[ I_2 = h_{21} I_1 + h_{22} V_2 \]

Inverting Amp

\[ h_{11}^A = 2K \]
\[ h_{12}^A = 0 \]
\[ h_{21}^A = -6000 \]
\[ h_{22}^A = 1/200 = 5E-3 \]

\[ h_{11}^B = 1K//10K = 909 \]
\[ h_{12}^B = 1/11 = 0.0909 \]
\[ h_{21}^B = -0.0909 \]
\[ h_{22}^B = 1/11K = 9.09E-5 \]
EXAMPLE VOLTAGE-SERIES FEEDBACK

Find the combined parameters

\[ h_{11} = h_{11}^A + h_{11}^B + RS = 2000 + 909 + 2000 = 4909 \]
\[ h_{12} = h_{12}^A + h_{12}^B = 0 + 0.0909 = 0.0909 \]
\[ h_{21} = h_{21}^A + h_{21}^B = -6000 \]
\[ h_{22} = h_{22}^A + h_{22}^B + \frac{1}{RL} = \frac{1}{200} + \frac{1}{11K} + \frac{1}{1K} = 6.091E-3 \]

Compute quantities of interest

1. Exact Gain with feedback (Voltage Gain)

\[ A_{Vf} = \frac{-h_{21}}{h_{11}h_{22}} = \frac{-(-6000)}{(4909)(6.091E-3)} = \frac{10.4}{(4909)(6.09E-3)} = 10.4 \]
EXAMPLE VOLTAGE-SERIES FEEDBACK

2. Approximate Voltage Gain

\[ A_{Vf} \sim = \frac{1}{h_{12}} = \frac{1}{0.0909} = 11 \]

which agrees with ideal op amp theory

3. Loop gain = \( T = -\frac{h_{12}h_{21}}{h_{11}h_{22}} = -18.2 \)

4. Input Impedance

\[ Z_{If} = h_{11} \left( 1 - T \right) \]

\[ = \frac{4909 \cdot (1 - -18.2)}{1 - -18.2} = 94.5K \]

but includes RS

\[ = 94.5K - 2K = 92.5K \) without RS

5. Output Impedance

\[ Y_{Of} = h_{22} \left( 1 - T \right) \]

\[ = 6.09E-3 \cdot (1 - -18.2) = 0.117S \]

but includes RL

\[ Z_{out} = \frac{1}{0.117} = 8.53 \text{ ohms} \]

but includes RL

\[ Z_{out} = Z'_{out} \div RL = 8.53 \text{ ohms} \]

\[ Z'_{out} = 8.61 \text{ ohm without RL} \]
### SUMMARY OF FEEDBACK AMPLIFIERS

#### Voltage-Shunt

<table>
<thead>
<tr>
<th>Input Admittance</th>
<th>Loop Gain</th>
<th>Exact Gain</th>
<th>Voltage Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y_{If} = y_{11} (1 - T) )</td>
<td>( T = \frac{y_{12}y_{21}}{y_{11}y_{22}} )</td>
<td>( A_{Rf} = \frac{-y_{21}}{y_{11}y_{22}} )</td>
<td>( A_{If} = A_{Rf} \frac{1}{RS} )</td>
</tr>
<tr>
<td>( Y_{Of} = y_{22} (1 - T) )</td>
<td>( A_{Rf} \approx \frac{1}{y_{12}} )</td>
<td>( T = \frac{-y_{21}}{y_{11}y_{22}} )</td>
<td>( A_{If} = A_{Rf} \frac{1}{RL} )</td>
</tr>
</tbody>
</table>

### Voltage-Series

<table>
<thead>
<tr>
<th>Input Impedance</th>
<th>Loop Gain</th>
<th>Exact Gain</th>
<th>Voltage Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_{If} = h_{11} (1 - T) )</td>
<td>( T = \frac{h_{12}h_{21}}{h_{11}h_{22}} )</td>
<td>( A_{Vf} = \frac{-h_{21}}{h_{11}h_{22}} )</td>
<td>( A_{If} = A_{Vf} )</td>
</tr>
<tr>
<td>( Y_{Of} = h_{22} (1 - T) )</td>
<td>( A_{Vf} \approx \frac{1}{h_{12}} )</td>
<td>( T = \frac{-h_{21}}{h_{11}h_{22}} )</td>
<td>( A_{If} = A_{Vf} \frac{RS}{RL} )</td>
</tr>
</tbody>
</table>

**Transresistance**

\( Z_{If} = h_{11} (1 - T) \)

\( Y_{Of} = h_{22} (1 - T) \)
### SUMMARY OF FEEDBACK AMPLIFIERS

#### Current-Shunt

<table>
<thead>
<tr>
<th>Input Admittance</th>
<th>Loop Gain</th>
<th>Exact Gain</th>
<th>Voltage Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{of} = g_{22}(1-T)$</td>
<td>$T = \frac{g_{12}g_{21}}{g_{11}g_{22}}$</td>
<td>$A_{If} = -\frac{g_{21}}{g_{11}g_{22}}$</td>
<td>$A_{Vf} = A_{If} (-RL/RS)$</td>
</tr>
<tr>
<td>$Z_{If} = g_{11}(1-T)$</td>
<td>$A_{If} \approx \frac{1}{g_{12}}$</td>
<td>$A_{If} = A_{If}$</td>
<td>$A_{If} = A_{If}$</td>
</tr>
</tbody>
</table>

**Current Gain**

#### Current-Series

<table>
<thead>
<tr>
<th>Input Impedance</th>
<th>Loop Gain</th>
<th>Exact Gain</th>
<th>Voltage Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{of} = z_{22}(1-T)$</td>
<td>$T = \frac{z_{12}z_{21}}{z_{11}z_{22}}$</td>
<td>$A_{Gf} = -\frac{z_{21}}{z_{11}z_{22}}$</td>
<td>$A_{Vf} = A_{Gf} (-RL)$</td>
</tr>
<tr>
<td>$Z_{If} = z_{11}(1-T)$</td>
<td>$A_{Gf} \approx \frac{1}{z_{12}}$</td>
<td>$A_{Gf} = A_{Gf}$</td>
<td>$A_{If} = A_{Gf}$ (RS)</td>
</tr>
</tbody>
</table>

**Transconductance**
REFERENCES

1. Sedra and Smith, 5.1-5.4
HOMEWORK PROBLEM 1

1. Find all 16 two port parameters for each of the following circuits.

1a) \[ \begin{align*}
    & \text{V1}^+ \\
    & \text{V1}^- \\
    & \text{V2}^+ \\
    & \text{V2}^- \\
    & \text{I1}^- \\
    & \text{I1}^+ \\
    & \text{I2}^+ \\
    & \text{I2}^- \\
    & \text{R1} \\
    & \text{R2} \\
\end{align*} \]

1b) \[ \begin{align*}
    & \text{V1}^+ \\
    & \text{V1}^- \\
    & \text{V2}^+ \\
    & \text{V2}^- \\
    & \text{I1}^- \\
    & \text{I1}^+ \\
    & \text{I2}^+ \\
    & \text{I2}^- \\
    & \text{R} \\
\end{align*} \]

1c) \[ \begin{align*}
    & \text{V1}^+ \\
    & \text{V1}^- \\
    & \text{V2}^+ \\
    & \text{V2}^- \\
    & \text{I1}^- \\
    & \text{I1}^+ \\
    & \text{I2}^+ \\
    & \text{I2}^- \\
    & \text{Vcc} \\
    & \text{RB} \\
    & \text{RC} \\
\end{align*} \]
### HOMEWORK SOLUTION FOR PROBLEM 1

**1a)**

<table>
<thead>
<tr>
<th>Term</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{11}$</td>
<td>$1/(R_1 \parallel R_2)$</td>
</tr>
<tr>
<td>$y_{12}$</td>
<td>$-1/R_1$</td>
</tr>
<tr>
<td>$y_{21}$</td>
<td>$-1/R_1$</td>
</tr>
<tr>
<td>$y_{22}$</td>
<td>$1/R_1$</td>
</tr>
<tr>
<td>$z_{11}$</td>
<td>$R_2$</td>
</tr>
<tr>
<td>$z_{12}$</td>
<td>$R_2$</td>
</tr>
<tr>
<td>$z_{21}$</td>
<td>$R_2$</td>
</tr>
<tr>
<td>$z_{22}$</td>
<td>$R_1 + R_2$</td>
</tr>
<tr>
<td>$h_{11}$</td>
<td>$R_1 \parallel R_2$</td>
</tr>
<tr>
<td>$h_{12}$</td>
<td>$R_2 / (R_1 + R_2)$</td>
</tr>
<tr>
<td>$h_{21}$</td>
<td>$-R_2 / (R_1 + R_2)$</td>
</tr>
<tr>
<td>$h_{22}$</td>
<td>$1 / (R_1 + R_2)$</td>
</tr>
<tr>
<td>$g_{11}$</td>
<td>$1/R_2$</td>
</tr>
<tr>
<td>$g_{12}$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$g_{21}$</td>
<td>$1$</td>
</tr>
<tr>
<td>$g_{22}$</td>
<td>$R_1$</td>
</tr>
</tbody>
</table>

**1b)**

<table>
<thead>
<tr>
<th>Term</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{11}$</td>
<td>$1/R$</td>
</tr>
<tr>
<td>$y_{12}$</td>
<td>$-1/R$</td>
</tr>
<tr>
<td>$y_{21}$</td>
<td>$-1/R$</td>
</tr>
<tr>
<td>$y_{22}$</td>
<td>$1/R$</td>
</tr>
<tr>
<td>$z_{11}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$z_{12}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$z_{21}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$z_{22}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$h_{11}$</td>
<td>$R$</td>
</tr>
<tr>
<td>$h_{12}$</td>
<td>$1$</td>
</tr>
<tr>
<td>$h_{21}$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$h_{22}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$g_{11}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$g_{12}$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$g_{21}$</td>
<td>$1$</td>
</tr>
<tr>
<td>$g_{22}$</td>
<td>$R$</td>
</tr>
</tbody>
</table>

**1c)**

<table>
<thead>
<tr>
<th>Term</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{11}$</td>
<td>$1/(RB \parallel r\pi)$</td>
</tr>
<tr>
<td>$y_{12}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$y_{21}$</td>
<td>$gm$</td>
</tr>
<tr>
<td>$y_{22}$</td>
<td>$1/RC$</td>
</tr>
<tr>
<td>$z_{11}$</td>
<td>$RB \parallel r\pi$</td>
</tr>
<tr>
<td>$z_{12}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$z_{21}$</td>
<td>$-\beta \cdot RC$</td>
</tr>
<tr>
<td>$z_{22}$</td>
<td>$RC$</td>
</tr>
<tr>
<td>$h_{11}$</td>
<td>$(RB \parallel r\pi)$</td>
</tr>
<tr>
<td>$h_{12}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$h_{21}$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>$h_{22}$</td>
<td>$1/RC$</td>
</tr>
<tr>
<td>$g_{11}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$g_{12}$</td>
<td>$-gm \cdot RC$</td>
</tr>
<tr>
<td>$g_{21}$</td>
<td>$RC$</td>
</tr>
<tr>
<td>$g_{22}$</td>
<td>$RC$</td>
</tr>
</tbody>
</table>
2 a) Find \( \sum_{A} Af \)  If A changes by 20% how much does Af change.

b) Redesign the feedback amplifier in a) so that \( \sum_{A} Af \) is reduced by a factor of 100.

Solution:

2 a) \( \sum_{A} Af = \frac{1}{1 + AB} = 1/101 = .0099 \)

If A changes by 20% then Af changes by 20% x 0.0099 = 0.198% ~0.2%

b) If we want the sensitivity to be 1/10001 instead of 1/101 then we increase the gain of the amplifier A to 10,000 giving Af = A/(1+AB) = 1 (same as before) and sensitivity = 1/(1+AB) = 0.0001 thus a 20% change in A is 0.002% change in gain with feedback
HOMEWORK PROBLEM 3 AND SOLUTION

3. \[ X_S + \sum \rightarrow A = A(j\omega) \rightarrow XL \]

\[ B = 0.1 \]

Let \( f_1 = 1000 \) hz

Draw a Bode plot of the amplitude part of the gain function for \( A(j\omega) \) and \( Af(j\omega) \)

**Solution:**

```
<table>
<thead>
<tr>
<th>dB</th>
<th>60</th>
<th>40</th>
<th>20</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hz</td>
<td>1K</td>
<td>10K</td>
<td>100K</td>
<td></td>
</tr>
</tbody>
</table>
```

\[
A(j\omega) = \frac{1000}{1 + j f/f_1}
\]

\[
Af = \frac{A}{1 + AB} = \frac{1000}{1 + j f/1000} = \frac{1000}{1 + j f/101000}
\]

\[
= \frac{1000}{1 + j f/101000 + 100}
\]

\[
= \frac{1000}{101} \frac{1}{1 + j f/101000}
\]
HOMEWORK PROBLEM 4

4) Refer to the feedback amplifiers shown below. For each identify the type of feedback and determine if the feedback is negative or positive.

4a)

4b)
HOMEWORK PROBLEM 4 (CONTINUED)

4c)\[ V_{cc} \quad V_{o} \quad RS \quad Re \quad v_s \]

4d)\[ V_{cc} \quad V_{o} \quad v_s \quad Re \]
HOMEWORK PROBLEM 4 (CONTINUED)

4e)

[Diagram of a circuit with labels Vcc, Vo, Vs]
HOMEWORK PROBLEM 4 SOLUTION

4. All are negative feedback
   a. Voltage Shunt
   b. Voltage Shunt
   c. Voltage Series
   d. Voltage Shunt
   e. Voltage Series
5) For each of the circuits shown in problems 7, 8, and 9, estimate the gain with feedback. \( A_{xf} \approx 1 / B \) and \( B = X_{12} \), where \( X_{12} \) is the appropriate combined two port parameters.

Identify the type of gain, transconductance, transresistance, current or voltage.

Convert \( A_{xf} \) to voltage gain with feedback, \( A_{vf} \).
5a) for the amplifier in problem 6 we have voltage shunt feedback which uses y parameter two port equivalent circuits for the analysis.

\[ y_{12} = y_{12}^A + y_{12}^B = 0 - 1/10K \]

\[ A_{Rf} \approx 1/y_{12} = -10K \text{ ohms} \]

\[ A_{Vf} = A_{Rf} \frac{1}{RS} = -10K/600 = -16.7 \]

5b) for the amplifier in problem 7 we have current shunt feedback which uses g parameter two port equivalent circuits for the analysis.

\[ g_{12} = g_{12}^A + g_{12}^B = 0 -200/(200+10k) = -0.0196 \]

\[ A_{If} \approx 1/g_{12} = -1/0.0196 = -51 \]

\[ A_{Vf} = A_{If} \frac{(-RL)}{RS} = -51 (-2K/1K) = 102 \]

5c) for the amplifier in problem 8 we have voltage series feedback which uses h parameter two port equivalent circuits for the analysis.

\[ h_{12} = h_{12}^A + h_{12}^B = 0 +100/(100+10k) = 0.0099 \]

\[ A_{Vf} \approx 1/h_{12} = 1/0.0099 = -101 \]
HOMEWORK PROBLEM 6

6) Find the exact gain with feedback for each of the circuit shown below.

\[ \beta = 100 \]
\[ r\pi = 1k \]
\[ VA = \text{infinite} \]

\[ Vm = \frac{Ic}{VT} = \frac{\beta}{r\pi} = \frac{100}{1k} = 100\text{mS} \]

Find the two port parameters for the A and B networks and compute \( AV_f \) (exactly)
**HOMEWORK PROBLEM 6 SOLUTION**

\[ y_{11A} = \frac{1}{300K//1K} = 0.001003 \quad y_{12A} = 0 \quad y_{22A} = \frac{1}{1K} = 0.001 \]

\[ y_{21A} = -gm_3(-gm_2(1K//300K//1K))(-gm_1(1K//300K//1K)) = -250 \]

\[ y_{11B} = \frac{1}{10K} = 0.0001 \quad y_{12B} = -\frac{1}{10K} \quad y_{21B} = -\frac{1}{10K} \quad y_{22A} = \frac{1}{10K} \]
HOMEWORK PROBLEM 6 SOLUTION

Exact Gain

\[ A_{Rf} = \frac{-y_{21}}{y_{11}y_{22}} \]

Transresistance

\[ A_r = \frac{250/(.00277)(.0016)}{1+(-0.0001)(250)/(.00277)(.0016)} = -9998\text{ohms} \]

Note: \( A_r \sim 1/y_{12} = -10000 \text{ ohms} \)

\[ A_v = A_r \frac{1}{RS} = -9998/600 = -16.7 \]

\[ y_{11} = y_{11A} + y_{11B} + 1/RS = 0.001 + 0.0001 + 0.00167 = 0.00277 \]

\[ y_{12} = y_{12A} + y_{12B} = -0.0001 - 0 = -0.0001 \]

\[ y_{21} = y_{21A} + y_{21B} = -0.0001 - 250 = -250 \]

\[ y_{22} = y_{22A} + y_{22B} + 1/RL = 0.0001 + 0.001 + 0.0005 = 0.0016 \]
7) Find the exact gain with feedback for the circuit shown below.

\[ r_p = 2K \]
\[ B = 100 \]
\[ r_o = 30K \]
7 cont.) Find the exact gain with feedback for the circuit shown below. The ac equivalent circuit below is useful in separating the B block of the feedback amplifier.

![Circuit Diagram](image-url)
7 cont.)

\[
g_{11A} = 0.5e^{-3}, \quad g_{12A} = 0, \quad g_{21A} = 13.7E^{-3} (30K) = 3020, \quad g_{22A} = 30K \\
g_{11B} = 0.098e^{-3}, \quad g_{12B} = -0.0196, \quad g_{21B} = 0.0196, \quad g_{22B} = 193 \\
\]

\[
1/RS = 1E^{-3}, \quad RL = 2K 
\]

\[
g_{11} = g_{11A} + g_{11B} + 1/RS = 1.598E^{-3} \\
g_{12} = g_{12A} + g_{12B} = -0.0196 \\
g_{21} = g_{21A} + g_{21B} = 3120 \\
g_{22} = g_{22A} + g_{22B} + RL = 32.19K 
\]

Exact Gain (current gain)

\[
A_{If} = \frac{-g_{21}}{g_{11}g_{22}} \left(1 + \frac{-g_{12}g_{21}}{g_{11}g_{22}}\right) = -27.3 
\]

Note: \(A_{if} \approx 1/g_{12} = -51\)

\[
Avf = A_{if} (-RL)/RS = -27.3 \times (-2K/1K) = 54.6 
\]
8) Find the exact gain with feedback for the circuit shown below.

\[ r_T = 2\,\text{K} \]
\[ B = 100 \]
\[ r_o = \text{infinite} \]
\[ R_b >> 1\,\text{K} \]
\[ R_z >> 8\,\text{K} \]
Note: the “A” block and “B” block are not completely separate, with proper mixing and sampling networks. The following equivalent circuit can be used.
First consider the 10K and 100 ohm as the “B” block

We can not just take the 100 ohm out of the emitter of the first transistor because the transistor will not work correctly in the “A” block,

Note: \( h_{21A} >> h_{21B} \) so neglect \( h_{21B} \)
In the emitter of the first transistor put the left hand part of the “B” block 2 port equivalent circuit.

Note: the right $h_{12}V_o$ is in series with a current source and can be eliminated. Note: left $h_{12}V_o$ is in a series loop to left of the two X’s (next page) and can be moved anywhere in that loop.
HOMEWORK PROBLEM 8 SOLUTION

\[ \text{Vin1} + \text{Vin2} + \text{Vin3} \]

\[ r_\pi = 1K \]

\[ g_m \text{Vin1} \]

\[ \text{BIb1 or} \]

\[ 1K \]

\[ r_\pi = 1K \]

\[ g_m \text{Vin2} \]

\[ \text{BIb2 or} \]

\[ 1K \]

\[ r_\pi = 1K \]

\[ g_m \text{Vin3} \]

\[ \text{BIb3 or} \]

\[ RL \]

\[ 10K / 100 \]

\[ 8K \]

\[ 100 \]

\[ 4K \]

\[ 2K \]

\[ h_{12B} \times Vo \]

\[ + \]

\[ - \]

\[ + \]

\[ - \]

\[ Vo \]
Finally we have an ac equivalent circuit where the “A” block and “B” block are separate and proper mixing and sampling networks exist.

\[ h_{11A} = r\pi + (B+1)10K//100 = 12K \]
\[ h_{12A} = 0 \]
\[ h_{22A} = 1/(2K/(r\pi+4K)/(B+1)) = 0.0173 \]
\[ h_{21A} = 268000 \]

\[ h_{21A} = I_2/I_1 \text{ with } V_2 = 0 \]
\[ I_2 = -(B+1)I_{b3} \text{ so } I_2/I_{b3} = -(B+1) = -101 \]
\[ I_{b3} = -BI_{b2} (4K/(4K+rp)) \text{ so } I_{b3}/I_{b2} = -66.7 \]
\[ I_{b2} = BI_{b1} (8K/(8K+(rp+(B+1)100)) \text{ so } I_{b2}/I_{b1} = -39.8 \]
\[ h_{12A} = I_2/I_1 = I_2/I_{b3} \times I_{b3}/I_{b2} \times I_{b2}/I_{b1} = 268000 \]
HOMEWORK PROBLEM 8 SOLUTION

h11 = h11A + h11B = 13K  
RS = 1K

h12 = h12A + h12B = 0 + 0.0099

h21 = h21A + h21B = -268000

RL = infinite, included in “A” block

h22 = h22A + h22B = 0.0174

\[
\text{Exact Gain} = \frac{-h_{21}}{h_{11}h_{22}} = -\frac{-268000}{(13K)(0.0099)} = 93
\]

\[
= \frac{-h_{12}h_{21}}{1 + \frac{-h_{12}h_{21}}{h_{11}h_{22}}} = \frac{-268000(0.0099)}{(13K)(0.0099)}
\]
Pro 2.

Beta = 150

Find Exact Gain With Feedback, Approximate Gain with Feedback, Voltage Gain, Current Gain, Input Resistance
OLD EXAM QUESTION

Pro 2.

Assume \( \beta = 150 \)
\( V_A = 100 \)

Calculate \( \text{gm}, \text{r}_p \) and \( \text{ro} \) for T1 and T2

Calculate dc value of IC for T1 and T2

Calculate \( \text{vo}/\text{vs} \)

Pro 3.

For the circuit in problem 2 use a single resistor to provide voltage shunt feedback to stabilize the gain with feedback at \(~40\ \text{V/V}\). What value of feedback resistor should be used and show how you would connect it by adding it to the schematic of problem 2.