Control Systems

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Contents

***Abstract*—This manual is an introduction to control systems in feedback circuits. Links to sample Python codes are available in the text.**

Download python codes using

```
svn co https://github.com/gadepall/school/trunk/
    control/feedback/codes
```

1 Feedback Voltage Amplifier: Series-Shunt

1.1. Fig. 1.1.1 shows a non-inverting op-amp configuration with parameters described in Table 1.1. Draw the equivalent control system.
Solution: See Fig. 1.1.2

1.2. Draw the small signal model for Fig. 1.1.1.
Solution: The equivalent circuit of the amplifier is in Fig. 1.2

1.3. Assuming that the operational amplifier has infinite input resistance and zero output resistance, find the *feedback factor H*.
Solution: From Fig. 1.2,

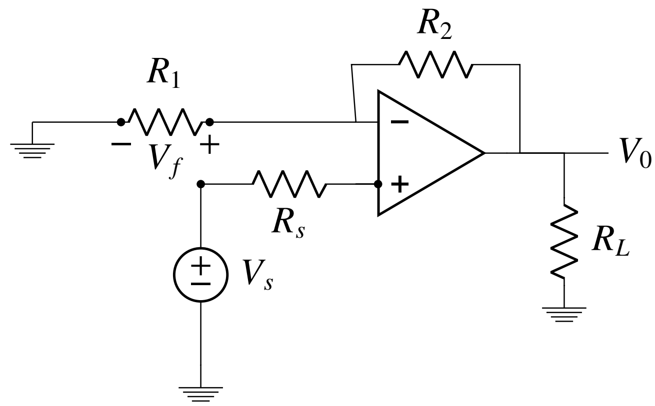

Fig. 1.1.1

Parameter	Value
input resistance	∞
output resistance	**0**
Input voltage	V_s
Output Voltage	V_o
Feeding resistance	R_1
Feedback resistance	R_2
Source resistance	R_s
load resistance	R_L

TABLE 1.1

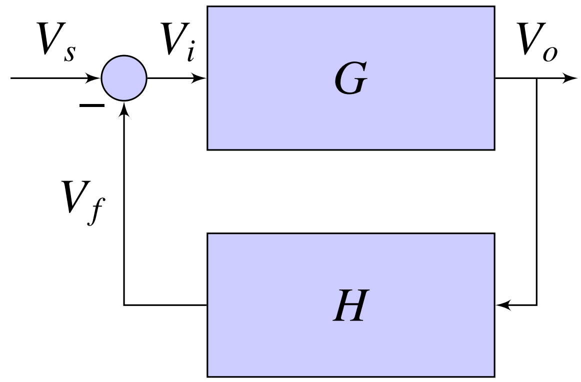

Fig. 1.1.2

$$V_0 = GV_i \tag{1.3.1}$$

$$V_i = V_s - V_f \tag{1.3.2}$$

$$V_f = \frac{R_1}{R_1 + R_2} V_o \tag{1.3.3}$$

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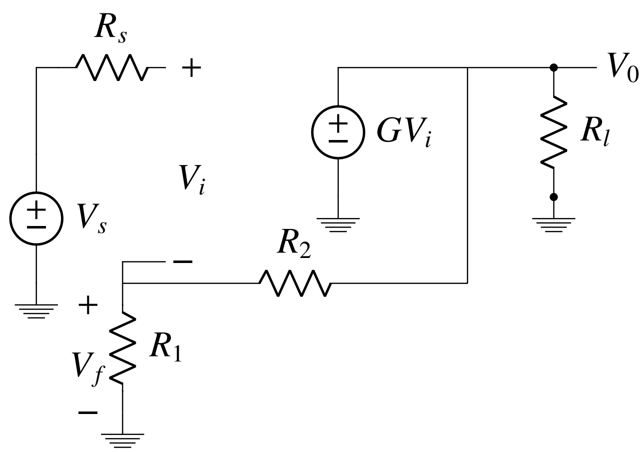

Fig. 1.2

assuming that the current through R_s is very small. Thus,

$$H = \frac{V_f}{V_o} = \frac{R_1}{R_1 + R_2} \tag{1.3.4}$$

1.4. Obtain the closed loop gain T and summarize your results through a Table.
Solution: Table 1.4 provides a summary.

$$T = \frac{V_0}{V_i} = \frac{G}{1 + GH} \tag{1.4.1}$$

$$= \frac{G\left(R_1 + R_2\right)}{\left(R_1 + R_2\right) + GR_1} \tag{1.4.2}$$

Parameters	Definition	For given circuit
Open loop gain	G	G
Feedback factor	H	$\frac{R_1}{R_1+R_2}$
Loop gain	GH	$G\frac{R_1}{R_1+R_2}$
Amount of feedback	1+GH	$1+\frac{GR_1}{R_1+R_2}$
Closed loop gain	$\frac{G}{1+GH}$	$\frac{G(R_1+R_2)}{R_1+R_2+GR_1}$

TABLE 1.4

1.5. Find the condition under which closed loop gain T is almost entirely determined by the feedback network.
Solution: If

$$GH \gg 1, \tag{1.5.1}$$

$$T \approx \frac{1}{H} = 1 + \frac{R_2}{R_1} \tag{1.5.2}$$

1.6. If

$$G = 10^4 \tag{1.6.1}$$

$$T = 10, \tag{1.6.2}$$

find H.
Solution: From Table 1.4

$$T = \frac{G}{1 + GH} = 10 \tag{1.6.3}$$

$$\implies H = 0.0999 \tag{1.6.4}$$

1.7. *Gain Desensitivity:* If G decreases by 20%,what is the corresponding decrease in T? Comment.
Solution: From From Table 1.4, Given

$$T = \frac{G}{1 + GH} \tag{1.7.1}$$

$$\implies dT = \frac{dG}{(1 + GH)^2} \tag{1.7.2}$$

$$\implies \frac{dT}{T} = \frac{1}{1 + GH}\frac{dG}{G} \tag{1.7.3}$$

From the information available so far,

$$dG = 20\%, G = 10^4, H = 0.0999 \implies \frac{dT}{T} = 0.025\% \tag{1.7.4}$$

using the following code.

```
codes/ee18btech11005/ee18btech11005.py
```

Thus the closed loop gain is almost invariant to a relatively large (20%) variation in the open loop gain G. This is known as gain desensitivity.

2 Feedback Current Amplifier: Shunt-Series

2.1 Ideal Case

2.1.1. Draw the equivalent control system for the feedback current amplifier shown in 2.1.1.1
Solution: See Fig. 2.1.1.2.

2.1.2. For the feedback current amplifier shown in 2.1.1.1, draw the Small-Signal Model. Neglect the Early effect in Q_1 and Q_2.
Solution: See Fig. 2.1.2.

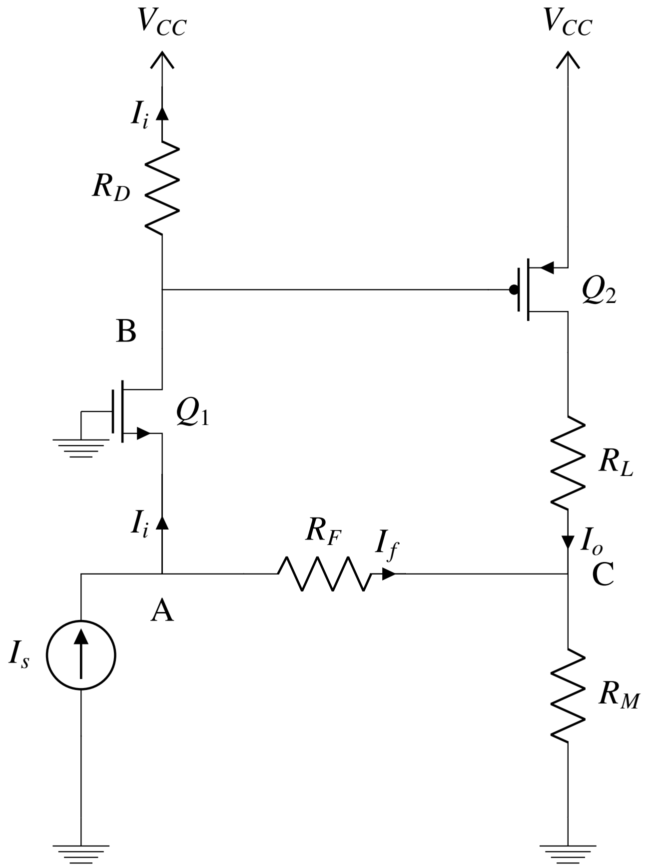

Fig. 2.1.1.1

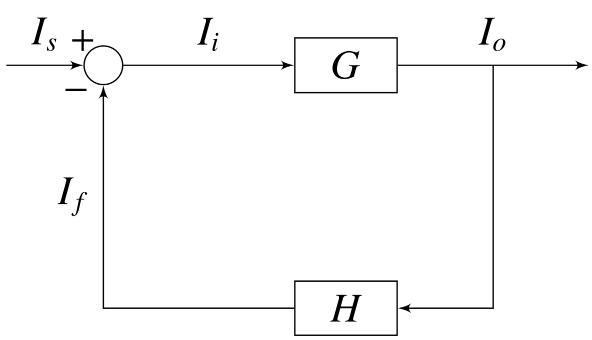

Fig. 2.1.1.2

While drawing a Small-Signal Model, we ground all constant voltage sources and open all constant current sources. All Small-Signal paramters are obtained from DC-Analysis of the circuit. Neglecting Early effect, in Small-Signal Analysis a N-MOSFET is modelled as a Current Source with value of current equal to $g_m v_{gs}$ flowing from Drain to Source. Whereas a P-MOSFET is modelled as a Current Source with value of current equal to $g_m v_{sg}$ flowing from Source to Drain.

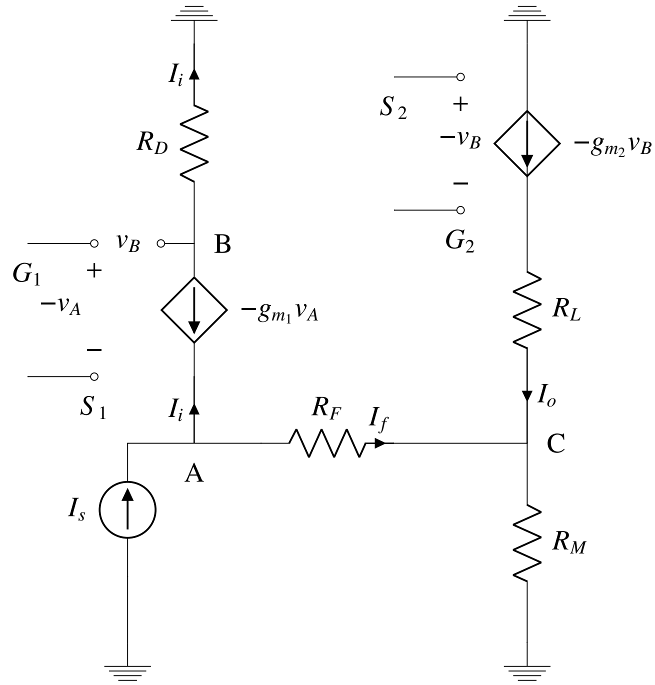

Fig. 2.1.2: Small Signal Model

2.1.3. Write all the node/loop equations using KCL/KVL.

Solution: From Figs. 2.1.1.1 and 2.1.2,

$$I_i = \frac{v_B}{R_D} \tag{2.1.3.1}$$

$$I_o = -g_{m_2} v_B \tag{2.1.3.2}$$

$$v_C - v_A = -I_f R_F \tag{2.1.3.3}$$

$$v_C = \left(I_o + I_f\right) R_M \tag{2.1.3.4}$$

$$I_i = g_{m_1} v_A \tag{2.1.3.5}$$

2.1.4. Find the Expression for the Open-Loop Gain G.

Solution: From (2.1.3.1) and (2.1.3.2),

$$G = \frac{I_o}{I_i} = -g_{m_2} R_D \tag{2.1.4.1}$$

2.1.5. Find the Expression of the Feedback Factor H.

Solution:

$$H = \frac{I_f}{I_o}, \tag{2.1.5.1}$$

From (2.1.3.3) and (2.1.3.4),

$$\left(I_o + I_f\right) R_M - v_A = -I_f R_F \tag{2.1.5.2}$$

$$\implies \left(I_o + I_f\right) R_M + \frac{I_i}{g_{m_1}} = -I_f R_F \tag{2.1.5.3}$$

from (2.1.3.5). Dividing by I_o,

$$\implies (1+H)R_M + \frac{1}{g_{m_1}G} = -HR_F \quad (2.1.5.4)$$

upon substituting from (2.1.4.1) and (2.1.5.1). Simplifying further, we obtain

$$\implies H = \frac{\frac{1}{g_{m_1}g_{m_2}R_D} - R_M}{R_F + R_M} \quad (2.1.5.5)$$

$$\approx -\frac{R_M}{R_F + R_M} \quad (2.1.6)$$

for $R_M \gg \frac{1}{g_{m_1}g_{m_2}R_D}$.

2.1.6. Find the Expression for the Closed-Loop Gain $T = \frac{I_o}{I_s}$.
Solution: From (2.1.4.1) and (2.1.5.6),

$$T = \frac{I_o}{I_s} = \frac{G}{1+GH} \quad (2.1.6.1)$$

$$= -\frac{g_{m_2}R_D}{1 + g_{m_2}R_D/\left(1 + \frac{R_F}{R_M}\right)} \quad (2.1.6.2)$$

2.2 Practical Case

2.2.1. Draw the Block Diagram and Circuit Diagram for H.
Solution: The Block Diagram is available in Fig. 2.2.1.1

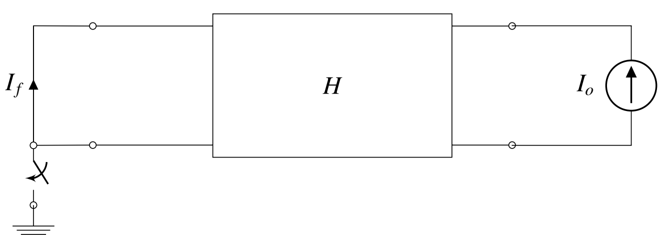

Fig. 2.2.1.1: Feedback Block Diagram

and the corresponding circuit diagram in Fig. 2.2.1.2

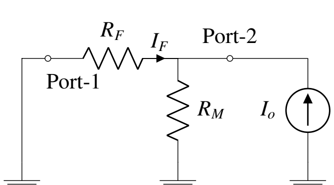

Fig. 2.2.1.2: Feedback Network

2.2.2. Find H from Fig. 2.2.1.2.
Solution: Using current division,

$$\frac{I_f}{I_o} = -\frac{R_M}{R_F + R_M} \quad (2.2.2.1)$$

$$\implies H = -\frac{R_M}{R_F + R_M} \quad (2.2.2.2)$$

2.2.3. Find R_{11} and R_{22} of Feedback Network where R_{11} is input resistance through Port-1 and R_{22} is Input Resistance through Port-2.
Solution: R_{11} is calculated by opening the current source at Port-2. Hence,

$$R_{11} = R_F + R_M \quad (2.2.3.1)$$

While calculating R_{22}, Port-1 should be shorted. Hence,

$$R_{22} = R_F \| R_M \quad (2.2.3.2)$$

$$= \frac{R_F R_M}{R_F + R_M} \quad (2.2.3.3)$$

2.2.4. Draw the block diagram and circuit diagram for calculating G.
Solution: See Figs. 2.2.4.1 and 2.2.4.2

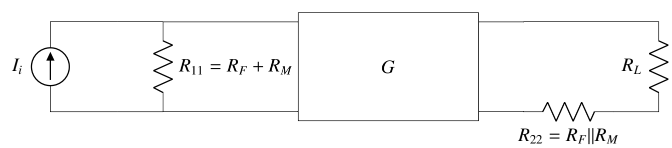

Fig. 2.2.4.1: Open-Loop Block Diagram

2.2.5. Find G.
Solution: The analysis is the same as Problem 2.1.4.

3 Feedback Current Amplifier: Example

3.1. Consider a Feedback Current Amplifier formed by cascading an Inverting Opamp μ with a MOSFET (NMOS). The output current is the Drain Current of the NMOS. Assume that Opamp has an input resistance R_{id}, an Open Circuit Voltage Gain μ, and an output resistance r_{o1}
Identify the type of Feedback Circuit and draw its corresponding Block Diagram Representation
Solution: The Feedback Circuit is a Shunt-Series Feedback Current Amplifier.
See Figs. 3.1.3 and 3.1.2 for the block diagram representation.

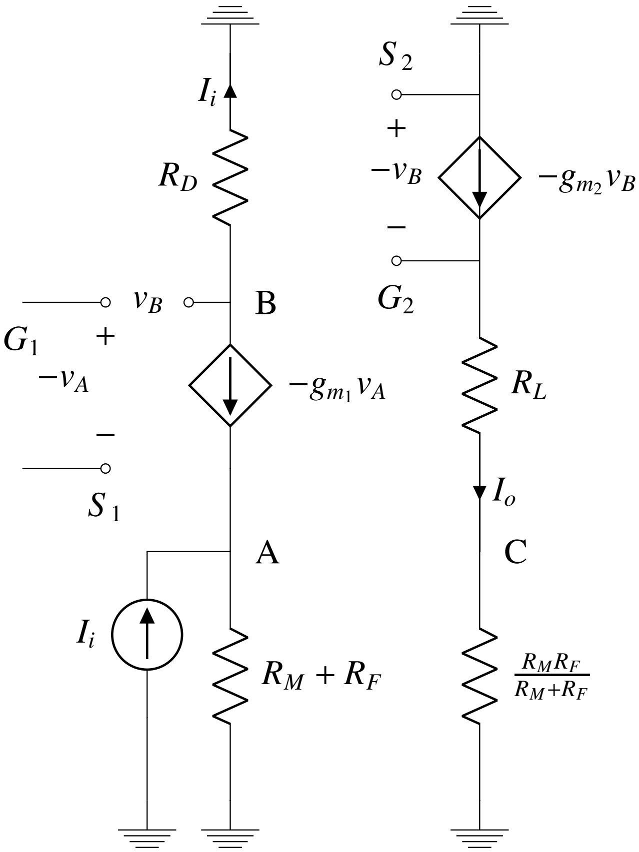

Fig. 2.2.4.2: Open-Loop Network

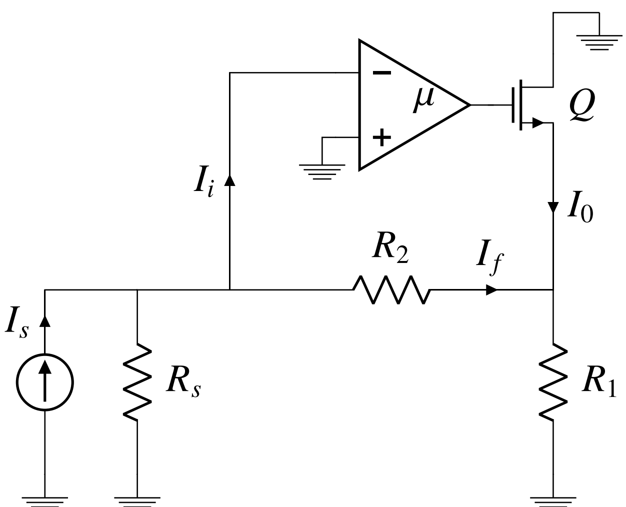

Fig. 3.1.1: Complete Circuit

3.2. Represent the given circuit using a Small Signal Equivalent Model.
Solution: See Fig. 3.2.
To draw Small Signal Equivalent model,
- Replace MOSFET with Current Source and Resistance in parallel with it.
- Replace Opamp with Voltage Source of the input Voltage multiplied by Gain

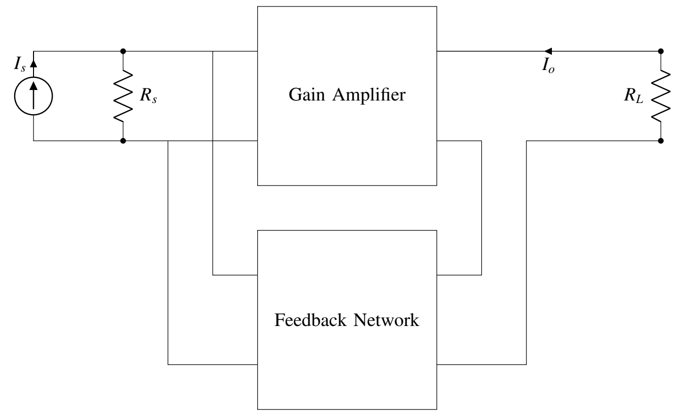

Fig. 3.1.2: Shunt Series Amplifier Block Diagram

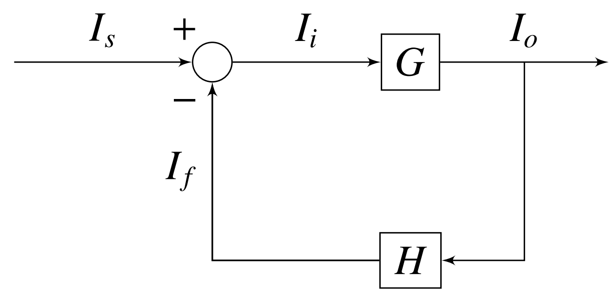

Fig. 3.1.3: Block Diagram

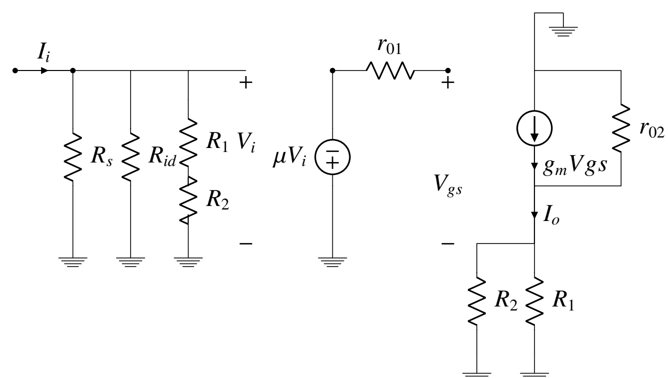

Fig. 3.2: Small Signal Model

3.3. Describe the resistances involved in the circuit
Solution: See Table 3.3
3.4. Draw the Block Diagram for H, with the corresponding Circuit.
Solution: See Figs. 3.4 and 3.4
3.5. Find the Feedback Gain H. **Solution:** In Fig. 3.4, I_f is the current in R_2

$$\implies H = \frac{I_f}{I_o} = -\frac{R_1}{R_1 + R_2} \tag{3.5.1}$$

Resistance	Description
R_i	Total Input Resistance
R_{out}	Total Ouput Resistance
R_{id}	Input resistance of Opamp
r_{o1}	Output resistance of Opamp
r_{o2}	Output resistance of MOSFET
R_i	Input resistance of Open Loop
R_o	Output resistance of Open Loop
R_{if}	Input resistance of Feedback
R_{of}	Output resistance of Feedback
R_s	Resistance of Current Source

TABLE 3.3

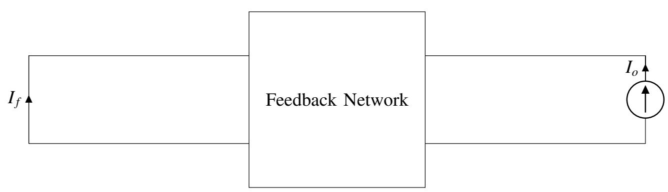

Fig. 3.4: Feedback Block

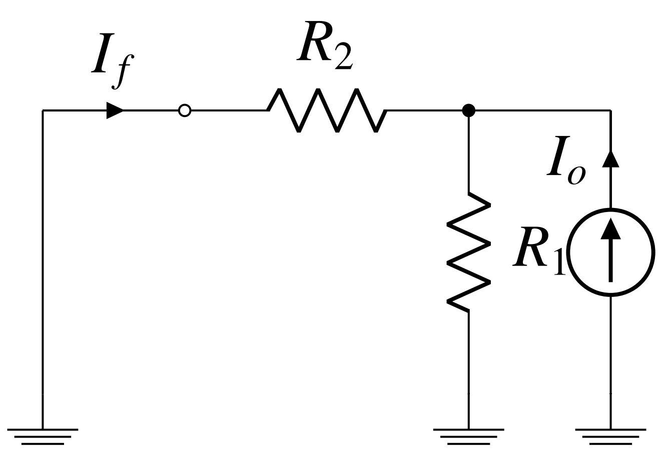

Fig. 3.4: Feedback Circuit

3.6. Find R_{11} and R_{22}.
Solution: From Fig. 3.4,

$$R_{11} = R_1 + R_2 \tag{3.6.1}$$

From Feedback Circuit, R_{22} is resistance obtained by shorting Feedback Network

$$R_{22} = R_1 \parallel R_2 \tag{3.6.2}$$

3.7. Draw the Block Diagram for G, with the corresponding Circuit.

Solution: See Figs. 3.7.1 and 3.7.2

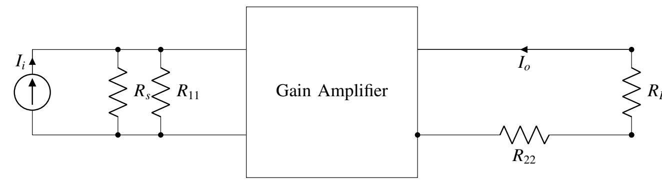

Fig. 3.7.1: Gain Block

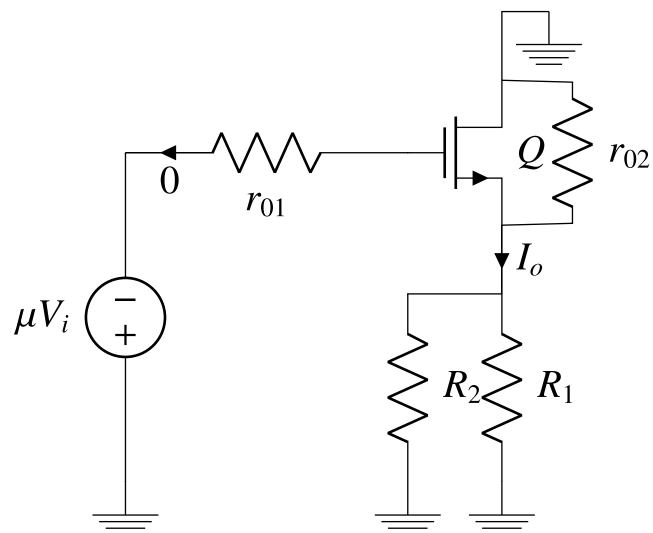

Fig. 3.7.2: Gain Circuit

3.8. Find the Gain G.
Solution: In Fig. 3.7.2,

$$R_i = R_s \parallel R_{id} \parallel (R_1 + R_2) \tag{3.8.1}$$

$$V_i = I_i R_i \tag{3.8.2}$$

$$I_o = -\mu V_i \frac{1}{1/g_m + (R_1 \parallel R_2 \parallel r_{o2})} \frac{r_{o2}}{r_{o2} + (R_1 \parallel R_2)} \tag{3.8.3}$$

$$G = \frac{I_o}{I_i} = -\mu \frac{R_i}{1/g_m + (R_1 \parallel R_2 \parallel r_{o2})} \frac{r_{o2}}{r_{o2} + (R_1 \parallel R_2)} \tag{3.8.4}$$

We use the approximation

$$1/g_m \ll (R_1 \parallel R_2 \parallel r_{o2}) \tag{3.8.5}$$

This is because the $\frac{1}{g_m}$ is in order of few Ωs but, R_1, R_2 and r_{o2} are in order of kΩs

$$G = -\mu \frac{R_i}{R_1 \parallel R_2} \tag{3.8.6}$$

3.9. Calculate Loop Gain GH
Solution:

$$GH = \mu \frac{R_i}{\frac{1}{g_m} + (R_1 \parallel R_2 \parallel r_{o2})} \frac{r_{o2}}{r_{o2} + (R_1 \parallel R_2)} \frac{R_1}{R_1 + R_2} \tag{3.9.1}$$

$$\implies GH \simeq \mu \frac{R_i}{R_1 \parallel R_2} \frac{R_1}{R_1 + R_2} = \mu \frac{R_i}{R_2} \tag{3.9.2}$$

3.10. If loop gain is large, find approximate expression for closed loop gain T
Solution: Given,

$$GH \gg 1 \tag{3.10.1}$$

$$T = \frac{G}{1 + GH} \simeq \frac{1}{H} \tag{3.10.2}$$

$$T \simeq \frac{1}{H} = -\left(1 + \frac{R_2}{R_1}\right) \tag{3.10.3}$$

3.11. Give expressions for R_{if}, R_{in}

$$R_{if} = R_i/(1 + GH) \tag{3.11.1}$$

$$\implies \frac{1}{R_{if}} = \frac{1}{R_i} + \frac{\mu}{R_2} \tag{3.11.2}$$

$$\implies R_{if} = R_i \parallel \frac{R_2}{\mu} \tag{3.11.3}$$

Substituting the value of R_i,

$$R_{if} = R_s \parallel R_{id} \parallel (R_1 + R_2) \parallel \frac{R_2}{\mu} \tag{3.11.4}$$

$$R_{if} = R_s \parallel R_{in} \tag{3.11.5}$$

$$\implies R_{in} = R_{id} \parallel (R_1 + R_2) \parallel \frac{R_2}{\mu} \tag{3.11.6}$$

$$R_{in} \simeq \frac{R_2}{\mu} \tag{3.11.7}$$

3.12. Give expressions for R_o, R_{of}, R_{out}
Solution:

$$R_o = r_{o2} + (R_1 \parallel R_2) + (g_m r_{o2})(R_1 \parallel R_2) \tag{3.12.1}$$

$$\implies R_o \simeq g_m r_{o2} (R_1 \parallel R_2) \tag{3.12.2}$$

$$R_{of} = R_o(1 + GH) \simeq GHR_o \tag{3.12.3}$$

$$R_{of} \simeq \mu(\frac{R_i}{R_2})(g_m r_{o2})(R_1 \parallel R_2) \tag{3.12.4}$$

$$R_{out} = R_{of} = \mu \frac{R_i}{R_1 + R_2}(g_m r_{o2})R_1 \tag{3.12.5}$$

3.13. Given the following values

Parameter	Value
μ	1000
R_s	∞
R_{id}	∞
r_{o1}	$1k\Omega$
R_1	$10k\Omega$
R_2	$90k\Omega$
g_m	$5mA/V$
r_{o2}	$20k\Omega$

TABLE 3.13

Find numerical value of R_i and use it to find the value of G
Solution: Using the given numerical values on the previously obtained equations, we obtain:

$$R_i = \infty \parallel \infty \parallel (10 + 90) = 100k\Omega \tag{3.13.1}$$

$$G = -1000 \frac{100}{10 \parallel 90} = -11.11 \times 10^3 \tag{3.13.2}$$

3.14. Check the validity of the approximation that we use to neglect $1/g_m$
Solution:

$$1/g_m = 0.2k\Omega \ll (10 \parallel 90 \parallel 20)k\Omega = 6.2k\Omega \tag{3.14.1}$$

Hence, we can see that our approximation is valid

3.15. Find the value of feedback gain H and open loop gain GH

Solution:

$$H = -\frac{R_1}{R_1 + R_2} = -\frac{10}{10+90} = -0.1 \quad (3.15.1)$$

$$GH = 1111 \gg 1 \quad (3.15.2)$$

3.16. Find the approximate value of closed loop gain T
Solution:

$$T \simeq \frac{1}{H} = -\frac{1}{0.1} = -10 \quad (3.16.1)$$

3.17. Find the values of R_{in} and R_{out}
Solution:

$$R_{in} = \frac{R_2}{\mu} = \frac{90k\Omega}{1000} = 90\Omega \quad (3.17.1)$$

$$R_o = g_m r_{o2}(R_1 \parallel R_2) = 5 \times 20(10 \parallel 90) = 900k\Omega \quad (3.17.2)$$

$$R_{out} = (1 + GH)R_o = 1112 \times 900 \simeq 1000M\Omega \quad (3.17.3)$$

Parameter	Value
R_i	$100k\Omega$
$1/g_m$	200Ω
G	-1.11×10^4
H	-0.1
GH	1111
T	-10
R_{in}	90Ω
R_o	$900k\Omega$
R_{out}	$1000M\Omega$

TABLE 3.17

3.18. Verify the above calculations using a Python code.
Solution:

```
codes/ee18btech11021/ee18btech11021_calc.py
```

4 Feedback Transconductance Amplifier: Series-Series

4.1. Part of the circuit of the MC1553 Amplifier is shown in circuit1 in Fig. 4.1.1 with values of various parameters given in Table 4.1. Draw the equivalent block diagrams.

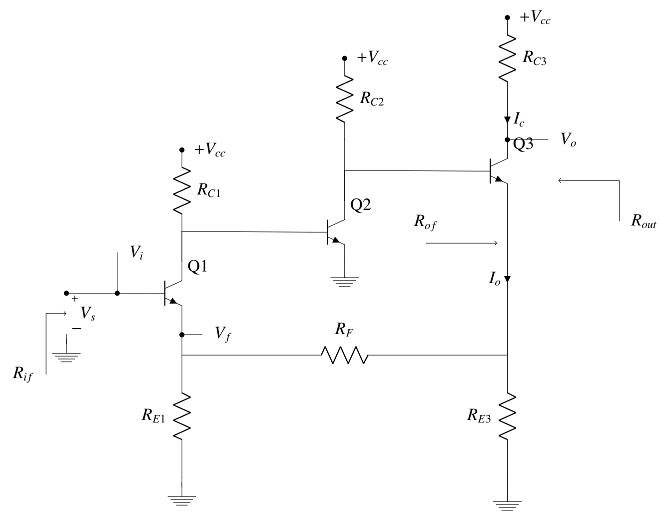

Fig. 4.1.1

Parameter	Value
R_{C1}	$9k\Omega$
R_{E1}	100Ω
R_{C2}	$5k\Omega$
R_F	640Ω
R_{E2}	100Ω
R_{C3}	600Ω
h_{fe}	**100**
r_o	$\infty\Omega$
I_{C1}	**0.6mA**
I_{C2}	**1mA**
I_{C3}	**4mA**
r_{e1}	41.7Ω
$r_{\pi 2}$	$2.5k\Omega$
$\alpha 1$	**0.99**
g_{m2}	**40mA/V**
r_{e3}	6.25Ω
r_{o3}	$25k\Omega$
$r_{\pi 3}$	625Ω

TABLE 4.1: parameters

Solution: The block diagrams are available in Figs. 4.1.2 and 4.1.3.

4.2. Draw the block diagram and equivalent circuit for H for Fig. 4.1.3.

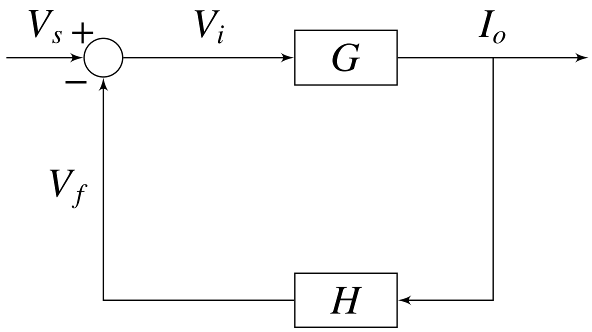

Fig. 4.1.2: block diagram

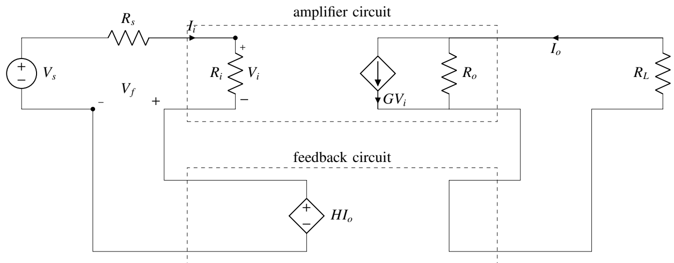

Fig. 4.1.3: Feedback Transconductance Amplifier

Solution: Fig. 4.2.1 gives the required block diagram

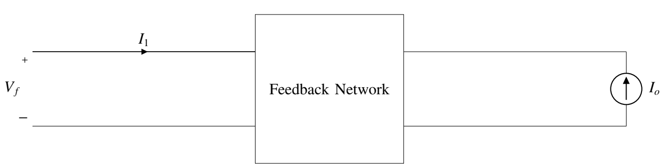

Fig. 4.2.1: Feedback circuit block diagram

$$H = \frac{V_f}{I_o}|_{I_1=0} \tag{4.2.1}$$

and the equivalent H circuit is available in Fig. 4.2.2.

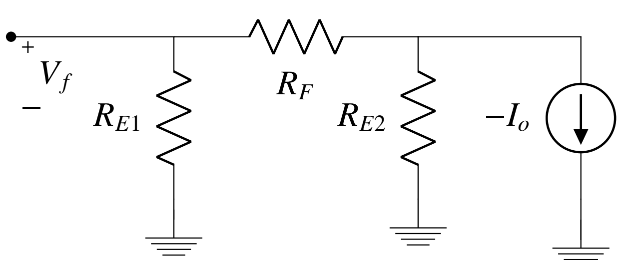

Fig. 4.2.2: H circuit

4.3. Find the feedback Factor H

Solution: From Fig. 4.2.2,

$$H = \frac{V_f}{I_0} = \frac{R_{E1}R_{E2}}{R_{E2}+R_F+R_{E1}} \tag{4.3.1}$$

4.4. Find R_{11} and R_{22} from Figs. 4.4 and 4.2.2

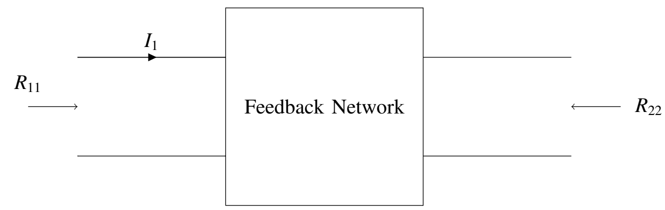

Fig. 4.4: feedback network

Solution:

$$R_{11} = R_{E1}||(R_F+R_{E2}) \tag{4.4.1}$$

$$R_{22} = R_{E2}||(R_F+R_{E1}) \tag{4.4.2}$$

4.5. Draw the block diagram and equivalent circuit for G.
Solution: The required block diagram is available in Fig. 4.5 and the equivalent circuit in

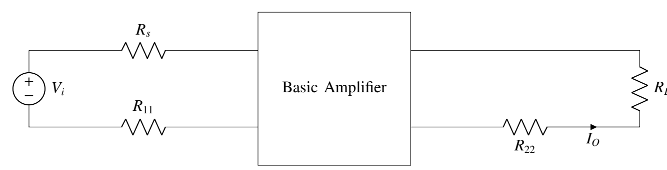

Fig. 4.5: Amplifier circuit block diagram

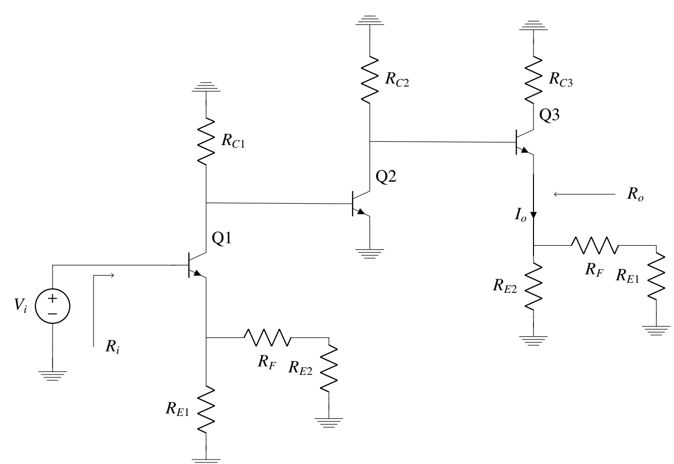

Fig. 4.5: G circuit

4.6. Find G

Solution: To find $G = \frac{I_0}{V_i}$ we determine the gain of first stage,this is written by inspection as-

$$\frac{V_{c1}}{V_i} = \frac{-\alpha(R_{c1}||r_{\pi 2})}{r_{e1} + (R_{E1}||(R_F + R_{E2}))} \tag{4.6.1}$$

Next, we determine the gain of the second stage,which can be written by inspection(noting that $V_{b2} = V_{c1}$)as

$$\frac{V_{c2}}{V_{c1}} = -g_{m2}R_{c2}||(h_{fe} + 1)[r_{e3} + (R_{E2}||(R_F + R_{E1}))] \tag{4.6.2}$$

Finally,for the third stage we can write by inspection

$$\frac{I_0}{V_{c2}} = \frac{I_{e3}}{V_{b3}} = \frac{1}{r_{e3} + (R_{E2}||(R_F + R_{E1}))} \tag{4.6.3}$$

4.7. Find closed loop gain T and Voltage Gain V_0/V_snumerically.

Solution:

$$T = \frac{I_0}{V_s} = \frac{G}{1 + GH} = \frac{20.7}{1 + 20.7 \times 11.9} = 83.7mA/V \tag{4.7.1}$$

4.8. Now assume Loop gain is large and find approximate expression for closed loop gain $T = \frac{I_o}{V_s}$

Solution: When GH $\gg$1,

$$T \approx \frac{I_0}{V_s} \approx \frac{1}{H} \tag{4.8.1}$$

$$= \frac{1}{11.9} = 84mA/V \tag{4.8.2}$$

$$\frac{I_c}{V_s} \approx \frac{I_0}{V_s} = 84mA/V \tag{4.8.3}$$

which we note is very close to the approximate value found in (4.7.1)

4.9. Tabulate all your results.

Solution: See Table 4.9.

4.10. Write a code for doing calculations and verify the values obtained in 4.9

Solution: The following code does all the calculations of above equations to give parameters in 4.9

```
codes/ee18btech11007/circuit_calc.py
```

Parameter	**Value**
G	**20.7A/V**
H	11.9Ω
T	**83.7mA/V**
V_o/V_s	**-50.2V/V**
R_{in}	$3.38M\Omega$
R_{out}	$2.19M\Omega$
R_{of}	$35.6k\Omega$

TABLE 4.9: calculated parameters