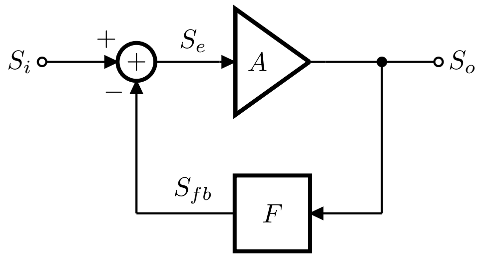

Figure 8.1: The components of a negative feedback amplifier.

8 Feedback Amplifiers

So far, we have studied the "open-loop" behavior of electronic amplifiers. This means that the amplifier output is solely determined by the amplifier input signal, independent of the state of its output. As we have seen, the small signal parameters of these open-loop amplifiers are very dependent on circuit parameters such as β, V_A, or V_{TH}, making it is very hard to get accurate and stable amplifier parameters, such as voltage gain. One way to avoid this problem is to use negative feedback techniques to create "closed-loop" amplifiers, or simply feedback amplifiers.

8.1 Feedback Basics

Consider the block diagram of a basic negative feedback amplifier, in Fig. 8.1, showing the three main components of a feedback network: (1) a forward gain, A, (2) a feedback circuit, with gain F, and (3) a mechanism that can perform subtraction. We represent the signals in Fig. 8.1 using the variable S, since in general, feedback systems and circuits can work with voltages, currents, charge, etc.

The *forward gain*, A is provided by an amplifier, amplifying the *error signal*, S_e. Thus,

$$S_o = A \cdot S_e \tag{8.1}$$

The output, S_o, is then sampled by the feedback circuit, which generates the *feedback signal*, S_{fb}, which is given by

$$S_{fb} = F \cdot S_o \tag{8.2}$$

where F is called the feedback factor. The error signal, S_e, is the difference between the input signal, S_i, and the feedback signal, S_{fb}, and can then be written as

$$S_e = S_i - S_{fb} \tag{8.3}$$

By plugging in Eqs. 8.1 and 8.2 into Eq. 8.3, we get

$$\frac{S_o}{A} = S_i - F \cdot S_o \tag{8.4}$$

We can then compute for the *closed-loop gain*, A_{CL}, as

$$A_{CL} = \frac{S_o}{S_i} = \frac{A}{1 + AF} \tag{8.5}$$

which is the familiar closed-loop gain of a feedback system. We can define the *loop gain*, T, as

$$T = AF \tag{8.6}$$

Thus, the closed-loop gain can be expressed as

$$A_{CL} = \frac{S_o}{S_i} = \frac{1}{F} \cdot \frac{AF}{1 + AF} = \frac{1}{F} \cdot \frac{T}{1 + T} = \frac{1}{F} \cdot \frac{1}{1 + \frac{1}{T}} \tag{8.7}$$

One very interesting consequence of using feedback is that if the forward gain, A, is very large, that is, if $A \to \infty$, then $T \to \infty$, thus

$$A_{CL}|_{A\to\infty} = \frac{1}{F} \tag{8.8}$$

This means that if $A \to \infty$, then closed-loop gain is only dependent on the feedback factor, F. In most applications, the feedback circuit is built using passive devices such as resistors. Therefore, we can create amplifiers whose gain is only dependent on resistor values, and not on transistor parameters!

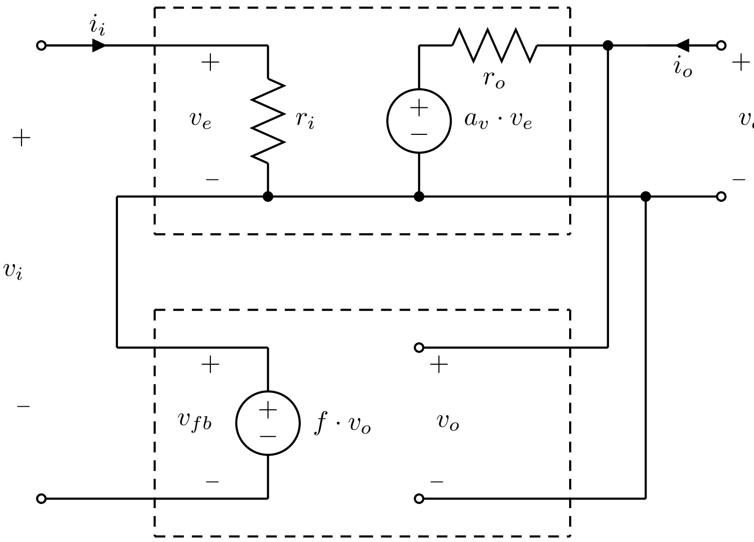

Figure 8.2: The ideal series-shunt feedback amplifier small signal equivalent circuit.

Since we cannot really build amplifiers with infinite gain, we want to quantify the effect of this finite forward gain on the closed-loop gain. For finite A, we can calculate the closed-loop gain as

$$A_{CL} = \frac{1}{F} \cdot \frac{1}{1 + \frac{1}{T}} = \frac{1}{F} \cdot \left(1 - \frac{1}{T} + \frac{1}{T^2} - \frac{1}{T^3} + \dots\right) \approx \frac{1}{F} \cdot \left(1 - \frac{1}{T}\right) = \frac{1}{F} \cdot (1 - \epsilon) \tag{8.9}$$

If we have finite forward gain, our loop gain will also be finite, and the closed-loop gain will once again be dependent on the forward gain, and hence the transistor parameters. Thus, the lower the forward gain, A, the larger the closed-loop gain's deviation from $\frac{1}{F}$. This deviation from the ideal closed-loop gain is normally written as the error term ϵ. Note that as we make the forward gain, A, larger, the error term becomes smaller, and the closed-loop gain approaches $\frac{1}{F}$.

Another important result of using feedback in amplifiers is the reduced sensitivity of the closed-loop gain, A_{CL}, on the forward gain, A. Calculating the sensitivity of A_{CL} to A, we get

$$S_A^{A_{CL}} = \frac{\partial A_{CL}}{\partial A} = \frac{(1 + AF) - AF}{(1 + AF)^2} = \frac{1}{(1 + AF)^2} = \frac{1}{(1 + T)^2} \tag{8.10}$$

Thus, as we increase the forward gain, A, the closed-loop gain, A_{CL}, becomes less sensitive to variations in A.

8.2 Feedback Amplifier Topologies

In the context of feedback amplifiers, the signals, S, in Fig. 8.1, can be a voltage or a current. One way to classify feedback amplifiers is by grouping them according to what quantity is sampled at the output, and what is being compared by the subtraction mechanism.

8.2.1 The Ideal Series-Shunt Feedback Amplifier

A feedback amplifier that compares or subtracts voltages, and uses a voltage signal as input to its feedback network, is called a *series-shunt* feedback amplifier. The small signal equivalent circuit of an ideal series-shunt amplifier is shown in Fig. 8.2.

The feedback amplifier is composed of the (1) forward amplifier, with gain a_v, input resistance r_i, and output resistance r_o, and (2) the ideal feedback network, with feedback factor f. The forward gain is then

$$A_v = \frac{v_o}{v_e} = a_v \tag{8.11}$$

and the feedback factor, F, is

$$F = \frac{v_{fb}}{v_o} = \frac{f \cdot v_o}{v_o} = f \tag{8.12}$$

The loop gain, T, becomes

$$T = A_v \cdot F = a_v \cdot f \tag{8.13}$$

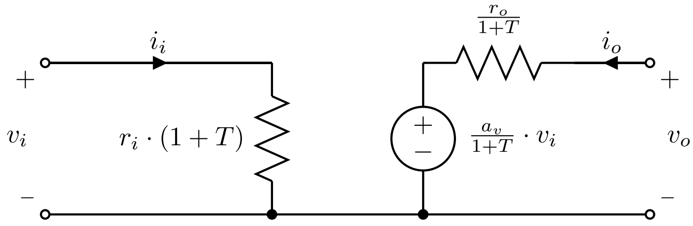

Figure 8.3: The small signal equivalent circuit of the series-shunt amplifier in Fig. 8.2.

The feedback network samples the output voltage, v_o, and the output of the feedback network, v_{fb}, is subtracted from the input voltage, v_i. Thus, the error voltage, v_e can be expressed as

$$v_e = \frac{v_o}{a_v} = v_i - v_{fb} = v_i - f \cdot v_o \tag{8.14}$$

Solving for the closed-loop gain, A_{CL}, we get

$$A_{CL} = \frac{v_o}{v_i} = \frac{a_v}{1 + a_v \cdot f} = \frac{a_v}{1+T} = \frac{1}{f} \cdot \frac{T}{1+T} \tag{8.15}$$

Note that the closed-loop gain is reduced by a factor equal to $(1+T)$ relative to the forward amplifier gain. Why would we want lower gains? In order to answer this, let us now examine the other two-port parameters of the feedback amplifier.

In order to calculate the input resistance, we set the output at no-load and apply a test voltage at the input. Since the output is a voltage, the no-load condition is an open circuit, that is, when $i_o = 0$. Thus, the input current, i_i, can be expressed as

$$i_i = \frac{v_e}{r_i} = \frac{v_i - f \cdot v_o}{r_i} = \frac{v_i - f \cdot \frac{1}{f} \cdot \frac{T}{1+T} \cdot v_i}{r_i} = \frac{v_i}{r_i \cdot (1+T)} \tag{8.16}$$

Thus, the input resistance can be calculated as

$$R_i = \frac{v_i}{i_i} = r_i \cdot (1+T) \tag{8.17}$$

Note that the input resistance of the closed-loop (feedback) amplifier is larger than the input resistance of the forward amplifier by a factor of $(1+T)$. If we assume that the closed-loop amplifier is driven by a voltage source, then a larger input resistance would reduce the voltage degradation, due to loading, at the input of the closed-loop amplifier.

Similarly, the output resistance can found by setting the input voltage source to zero, and applying a test voltage at the output. We can then express the output current, i_o, as

$$i_o = \frac{v_o - a_v \cdot v_e}{r_o} = \frac{v_o - a_v \cdot (-f \cdot v_o)}{r_o} = \frac{v_o \cdot (1 + a_v \cdot f)}{r_o} = v_o \cdot \frac{1+T}{r_o} \tag{8.18}$$

Therefore, the output resistance is

$$R_o = \frac{v_o}{i_o} = \frac{r_o}{1+T} \tag{8.19}$$

This closed-loop output resistance is smaller than the outptu resistance of the forward amplifier by a factor of $(1+T)$. Note that if the output is a voltage, then lowering the output resistance will allow the closed-loop amplifier to drive smaller resistive loads, due to less loading effects.

The small signal equivalent circuit of the closed-loop amplifier is shown in Fig. 8.3. We can now see that by using feedback, we can reduce the voltage gain of the closed-loop amplifier, but in exchange, we get better input and output resistances.

8.2.2 The Ideal Shunt-Shunt Feedback Amplifier

A feedback amplifier that compares or subtracts currents, and uses a voltage signal as input to its feedback network, is called a *shunt-shunt* feedback amplifier. The small signal equivalent circuit of an ideal shunt-shunt amplifier is shown in Fig. 8.4.

Once again, the feedback amplifier is composed of the (1) forward amplifier, with gain a_v, input resistance r_i, and output resistance r_o, and (2) the ideal feedback network, with feedback factor f. Since the input to the forward amplifier is a current, and the output is a voltage, the forward amplifier can be thought of as a *transresistance* amplifier. The forward gain is then equal to

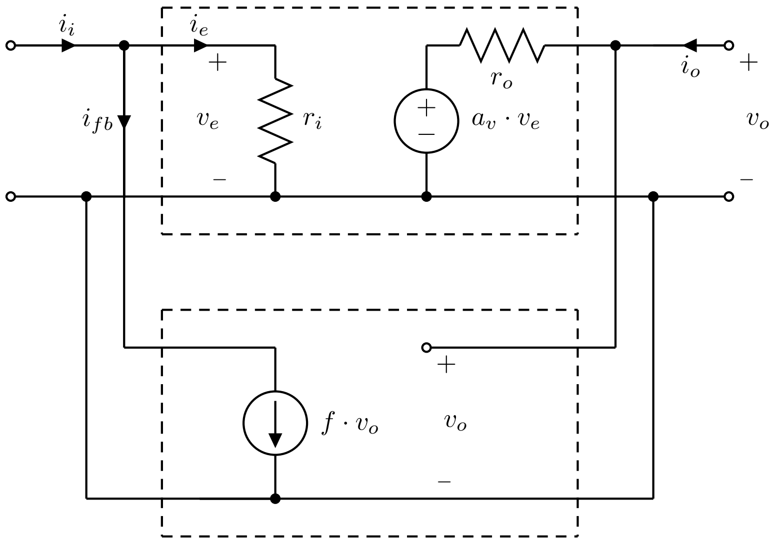

Figure 8.4: The ideal shunt-shunt feedback amplifier small signal equivalent circuit.

$$R_m = \frac{v_o}{i_e} = a_v \cdot r_i \tag{8.20}$$

and the feedback factor, F, is

$$F = \frac{i_{fb}}{v_o} = \frac{f \cdot v_o}{v_o} = f \tag{8.21}$$

The loop gain, T, can be expressed as

$$T = R_m \cdot F = a_v \cdot r_i \cdot f \tag{8.22}$$

It is very important to note that the loop gain, T, is unit-less. This a convenient way to check if your analysis is correct.

The output voltage can be expressed as

$$v_o = a_v \cdot r_i \cdot (i_i - i_{fb}) = a_v \cdot r_i \cdot (i_i - f \cdot v_o) \tag{8.23}$$

Thus, the closed-loop gain is

$$R_{CL} = \frac{v_o}{i_i} = \frac{a_v \cdot r_i}{1 + a_v \cdot r_i \cdot f} = \frac{R_m}{1+T} = \frac{1}{f} \cdot \frac{T}{1+T} \tag{8.24}$$

Once again, we see that the forward gain is reduced by a factor of $(1+T)$ when the forward amplifier is placed in feedback.

The closed-loop input resistance can be found by applying an input current and calculating the input voltage. The output current is set to zero (an open circuit) to satisfy the no-load condition. The input voltage is then

$$v_i = i_e \cdot r_i = (i_i - f \cdot v_o) \cdot r_i = \left(i_i - f \cdot \frac{a_v \cdot r_i}{1+T} \cdot i_i\right) \cdot r_i \tag{8.25}$$

Thus, the closed-loop input resistance can be expressed as

$$R_i = \frac{r_i}{1+T} \tag{8.26}$$

Note that the input resistance is now smaller than the open-loop input resistance by a factor of $(1+T)$. For current-input amplifiers, this is a big improvement since it reduces the degradation due to loading when being driven by a current source with finite output resistance.

The closed-loop output resistance can be found using the procedure applies to the series-shunt amplifier. However, since the input is a current, zero-input means an open-circuited input. Applying a test voltage, v_o, at the output results in an output current equal to

$$i_o = \frac{v_o - a_v \cdot v_e}{r_o} = \frac{v_o - a_v \cdot r_i \cdot (-f \cdot v_o)}{r_o} = v_o \frac{1+T}{r_o} \tag{8.27}$$

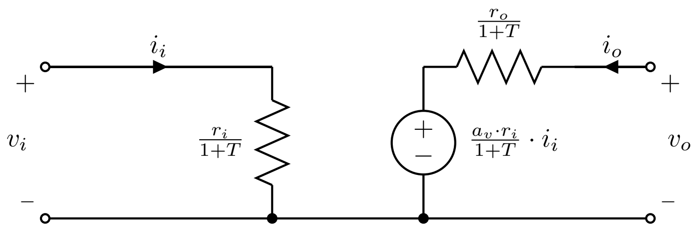

Figure 8.5: The small signal equivalent circuit of the shunt-shunt amplifier in Fig. 8.4.

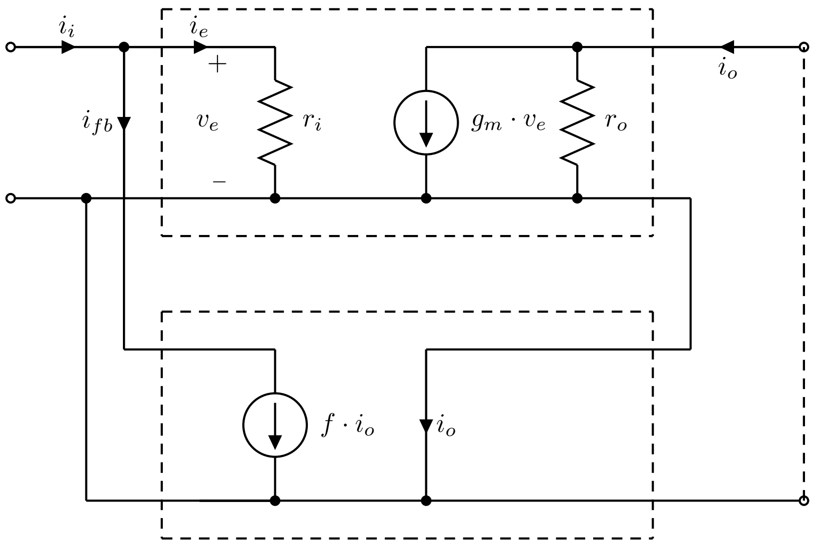

Figure 8.6: The ideal shunt-series feedback amplifier small signal equivalent circuit.

Hence, the output resistance of the closed-loop amplifier is equal to

$$R_o = \frac{r_o}{1+T} \tag{8.28}$$

Again, we see that feedback reduces the output resistance of a voltage-output amplifier, resulting in less degradation when driving resistive loads. The small signal equivalent circuit of the closed-loop amplifier is shown in Fig. 8.5.

8.2.3 The Ideal Shunt-Series Feedback Amplifier

A feedback amplifier that compares or subtracts currents, and samples an output current, which is then used as input to its feedback network, is called a *shunt-series* feedback amplifier. The small signal equivalent circuit of an ideal shunt-shunt amplifier is shown in Fig. 8.6

The forward current gain, A_i, is equal to

$$A_i = \frac{i_o}{i_e} = g_m \cdot r_i \tag{8.29}$$

and the feedback factor is

$$F = \frac{i_{fb}}{i_o} = \frac{f \cdot i_o}{i_o} = f \tag{8.30}$$

Therefore the loop gain, T, can be expressed as

$$T = A_i \cdot F = g_m \cdot r_i \cdot f \tag{8.31}$$

The output current can be expressed as

$$i_o = g_m \cdot r_i \cdot (i_i - f \cdot i_o) \tag{8.32}$$

leading to a closed-loop current gain that is equal to

$$A_{CL} = \frac{i_o}{i_i} = \frac{g_m \cdot r_i}{1 + g_m \cdot r_i \cdot f} = \frac{A_i}{1+T} = \frac{1}{f} \cdot \frac{T}{1+T} \tag{8.33}$$

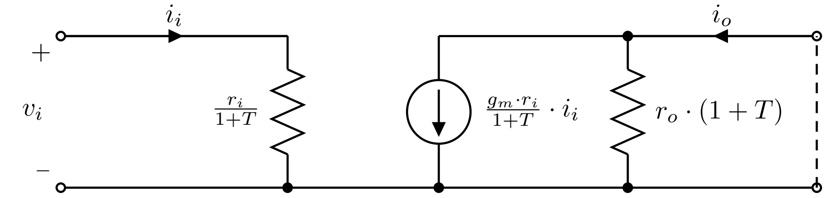

Figure 8.7: The small signal equivalent circuit of the shunt-series amplifier in Fig. 8.6.

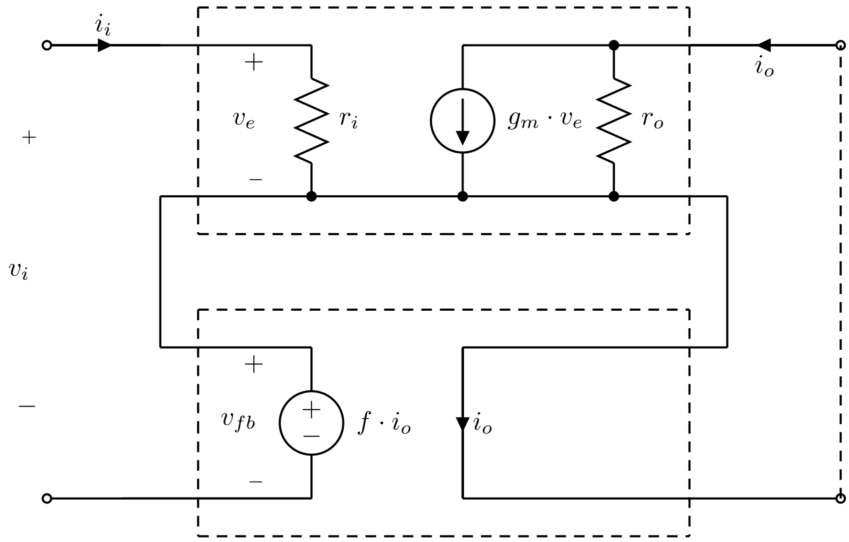

Figure 8.8: The ideal series-series feedback amplifier small signal equivalent circuit.

Once again, we see that the forward gain is reduced by a factor of $(1 + T)$ when the forward amplifier is placed in feedback.

The closed-loop input resistance can be found by applying an input current, i_i, and calculating the input voltage, v_i. The output voltage is set to zero, the no-load condition of the current output amplifier. The output voltage is then equal to

$$v_i = i_e \cdot r_i = (i_i - f \cdot i_o) \cdot r_i = \left(i_i - f \cdot \frac{g_m \cdot r_i}{1+T} \right) \cdot r_i = i_i \cdot \frac{r_i}{1+T} \tag{8.34}$$

Thus, the closed-loop input resistance can be expressed as

$$R_i = \frac{r_i}{1+T} \tag{8.35}$$

Note that the input resistance is reduced by a factor of $(1 + T)$, again, an improvement for current-input amplifiers.

8.2.4 The Ideal Series-Series Feedback Amplifier

A feedback amplifier that compares or subtracts voltages, and samples an output current, which is then used as input to its feedback network, is called a *series-series* feedback amplifier. The small signal equivalent circuit of an ideal shunt-shunt amplifier is shown in Fig. 8.8

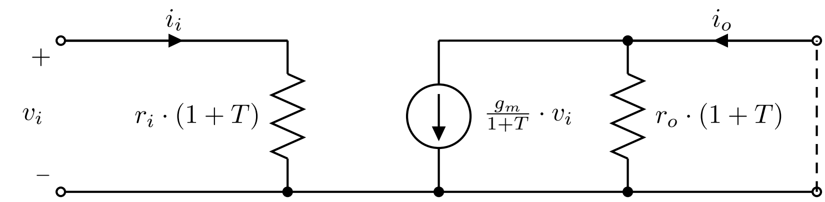

Figure 8.9: The small signal equivalent circuit of the series-series amplifier in Fig. 8.8.

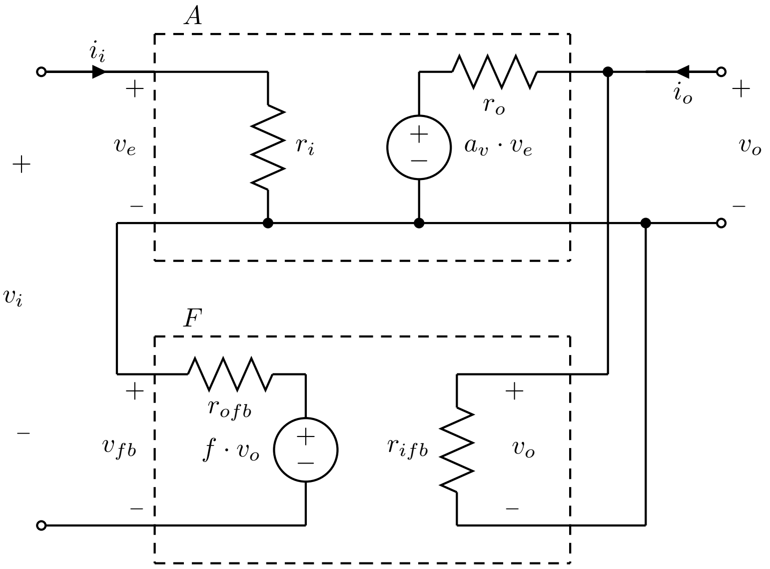

Figure 8.10: The series-shunt feedback amplifier small signal equivalent circuit with a non-ideal feedback network.

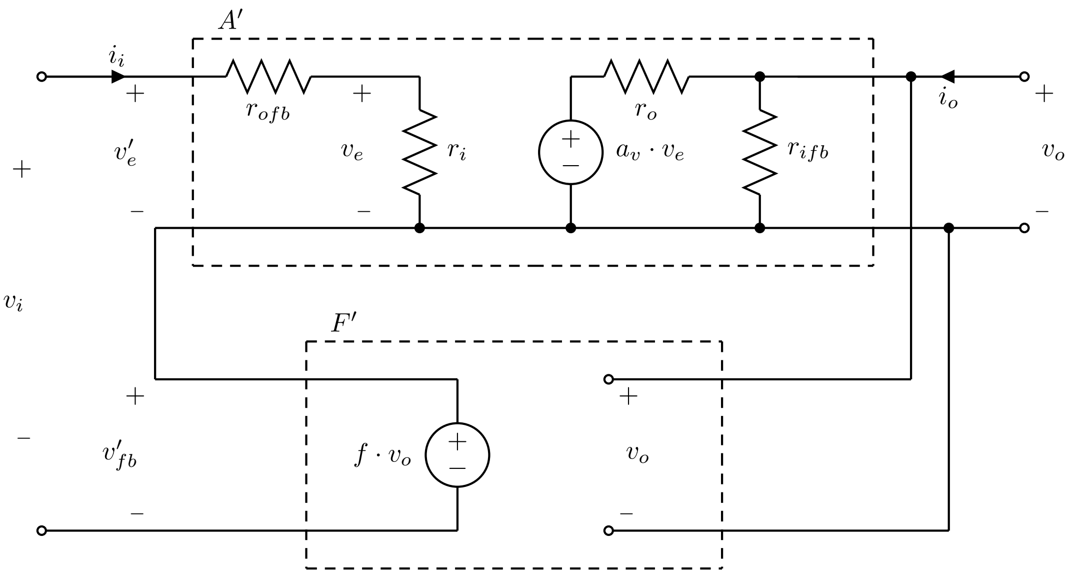

Figure 8.11: The redrawn series-shunt feedback amplifier small signal equivalent circuit that returns the feedback network back into an ideal feedback network.

8.3 Feedback Network Loading

8.4 Feedback Amplifier Frequency Response

8.5 Stability

8.6 Compensation