$$\text{Thus } Z_{\text{inCL}} = -Z_{\text{in}}\left[1 + \beta A_{\text{OL}}\frac{Z_{\text{L}}}{Z_{\text{o}} + Z_{\text{L}}}\right] \tag{2.7}$$

Series voltage feedback increases input impedance to an extent determined by the loop gain βA_{OL}.

2.2.5 Effect on inverting amplifier

The effects of finite open-loop gain, finite input impedance and non-zero output impedance will be considered for the inverting amplifier. To analyse the effects, each parameter will have to be considered separately. First we must find a few general relationships for a non-inverting amplifier in terms of the non-infinite open-loop gain, A_{OL}.

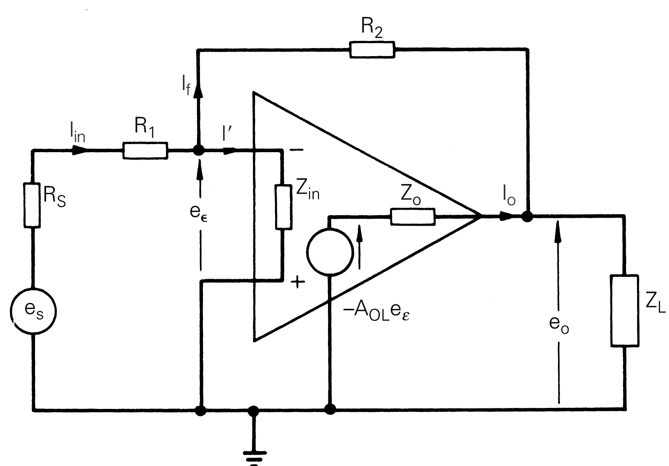

Figure 2.5 *Shunt voltage feedback*

In Figure 2.5, the externally applied input signal voltage e_s and the output voltage e_o are effectively applied in parallel to the op-amp's differential input. The signal e_ε, which drives the differential input, is a superposition of the effects of e_s and e_o.

$$e_\varepsilon = e_s\frac{R_2}{R_1 + R_2 + R_s} + e_o\frac{R_1 + R_s}{R_1 + R_2 + R_s} \tag{2.8}$$

It is assumed that $Z_{\text{in}} >> R_1 + R_s$ and that $Z_o << R_2$.

$$\text{The feedback fraction } \beta = \frac{R_1 + R_s}{R_1 + R_2 + R_s}$$

Let us now examine the effect of non-zero output impedance. The output voltage may be written as

$$e_o = -A_{\text{OL}}e_\varepsilon - I_oZ_o$$

Substitution for e_ε and rearrangement gives

$$e_o = -\frac{R_2}{R_1 + R_2 + R_s}\frac{A_{OL}}{1 + \beta A_{OL}} e_s - i_o \frac{Z_o}{1 + \beta A_{OL}}$$

The closed-loop signal gain of the circuit is thus

$$e_o = -\frac{R_2}{R_1 + R_2 + R_s}\frac{A_{OL}}{1 + \beta A_{OL}} = -\frac{R_2}{R_1 + R_s}\left[\frac{1}{1 + \dfrac{1}{\beta A_{OL}}}\right] \tag{2.9}$$

For large values of βA_{OL}, the term

$$\left[\frac{1}{1 + \dfrac{1}{\beta A_{OL}}}\right]$$

is very close to unity and the closed-loop gain is

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

The closed-loop output impedance is

$$Z_{oCL} = \frac{Z_o}{1 + \beta A_{OL}} \tag{2.10}$$

The closed-loop output impedance of an op-amp in many circuits is a tiny fraction of the open-loop impedance, typically less than 1 mΩ at low frequencies.

Compare equations 2.9 and 2.10 with equations 2.5 and 2.6. Again, notice the importance of the loop gain βA_{OL}. If the loop gain is sufficiently large the closed-loop performance is determined by the value of the components used to fix the feedback fraction β. If $R_1 << R_s$ and the loop gain is large, the closed-loop signal gain approximates to $A_{CL} = -R_2/R_1$.

Now let us consider the input impedance. In Figure 2.5

$$I_{in} = I' + I_f$$

Now $I' = e_\varepsilon/Z_{in}$ and $I_f = (e_\varepsilon - e_o)/R_2$.

$$\text{So } I_{in} = \frac{e_\varepsilon}{Z_{in}} + \frac{e_\varepsilon - e_o}{R_2}$$

If $Z_L > Z_o$, $e_o \cong -A_{OL}e_\varepsilon$, i.e. assume that there is no voltage drop across the internal output impedance.

$$\text{By substitution, } I_{in} = e_\varepsilon\left[\frac{1}{Z_{in}} + \frac{1 + A_{OL}}{R_2}\right]$$

In terms of input impedance, we have Z_{in} and additional shunt impedance $R_2/(1 + A_{OL})$. Thus the effect of the shunt feedback is to reduce the effective differential input impedance of the op-amp. And if A_{OL} is very large, the input impedance is very small (typically $< 1\ \Omega$). The overall input impedance of the inverting op-amp circuit then effectively equals the value of the resistor R_1.