Current Amplifier Driving An Inductive Load

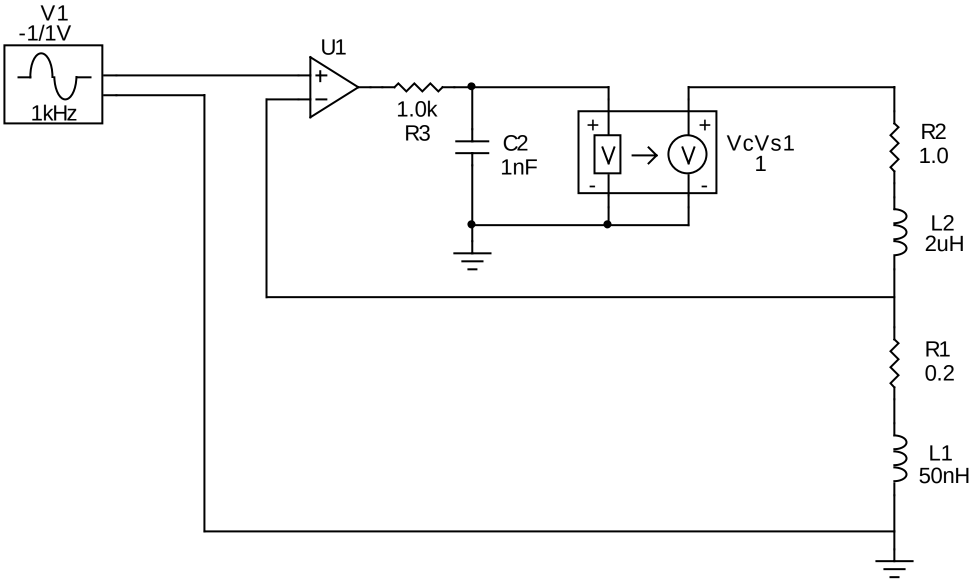
by Dennis L Feucht

Motor windings, deflection yokes, solenoids, and inductance heaters present inductive loads to amplifiers that drive them. A feedback current amplifier that can drive these loads with a flat frequency response requires careful attention to the sense resistor.

Amplifier Model

Consider the following amplifier, with sense resistor, single-pole amplifier, and LR load, as shown below, simulated in Protel CircuitMaker.

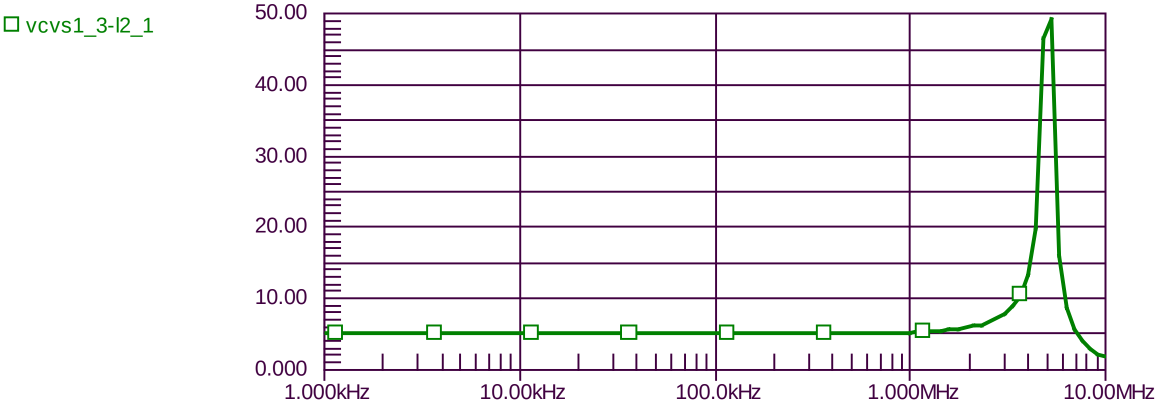
The design goal for this amplifier is a transconductance of 5 A/V, with a flat frequency response and maximized bandwidth.

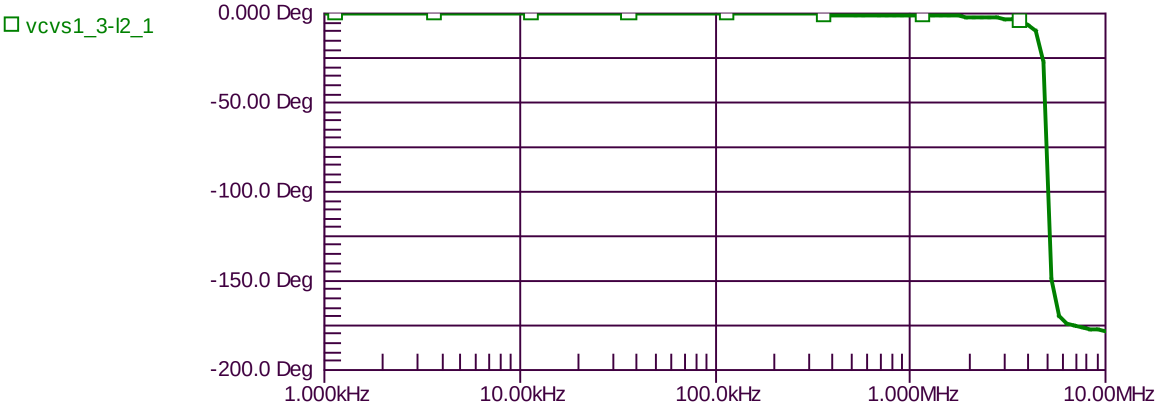


The load inductor, L_2, is modeled as a series RL with the addition of R_2. The sense resistor model is also a series RL, R_s, L_s, shown as R1 and L1 in the circuit diagram. To amplify current a voltage proportional to output current is fed back from the sense resistor. The resultant RL sense-resistor combination has an impedance of:

$$Z_S = sL_S + R_S = R_S \cdot (s \cdot \frac{L_S}{R_S} + 1)$$

Parasitic elements are usually regarded as imperfections in components because they usually degrade performance. But there are instances -- and this is one of them -- where parasitic elements can be advantageous. The zero break frequency of the inductor introduces a zero in the amplifier loop response which compensates the amplifier and load poles. Without the parasitic inductance, the frequency response is simulated as shown below: Highly peaked and far from a flat frequency response. The resulting closed-loop Bode plots of the output current with 1 V input amplitude are shown for a frequency range from 1 kHz to 10 MHz in 4 decades of horizontal scale.





Now, introduce a realistic value of 50 nH of parasitic series inductance for a two-terminal, 5 W, 0.2 Ω sense resistor. The forward-path amplifier is modeled as an ideal (infinite bandwidth) amplifier, U_1, followed by a single-pole roll-off RC circuit (R3, C2) and an ideal ×1 buffer amplifier. The overall forward-path model is one of a voltage amplifier with a single pole. For large U_1 static (dc) gain, the closed-loop gain is approximately:

$$T(s) = \frac{i_o}{v_i} = \frac{1}{R_s} \cdot \frac{1}{s(L_s / R_s) + 1}$$

For those who prefer completeness, the more general transfer function for a finite dc gain of K is:

$$T(s) = \frac{K}{K+1} \cdot \frac{1}{R_L + (K+1) \cdot R_s} \cdot \frac{1}{s^2 \left[\tau_A \cdot \frac{(L_L + L_s)}{R_L + (K+1) \cdot R_s} \right] + s \left[\frac{\tau_A \cdot (R_L + R_s) + L_L + (K+1) \cdot L_s}{R_L + (K+1) \cdot R_s} \right] + 1}$$

where, the forward-path amplifier is:

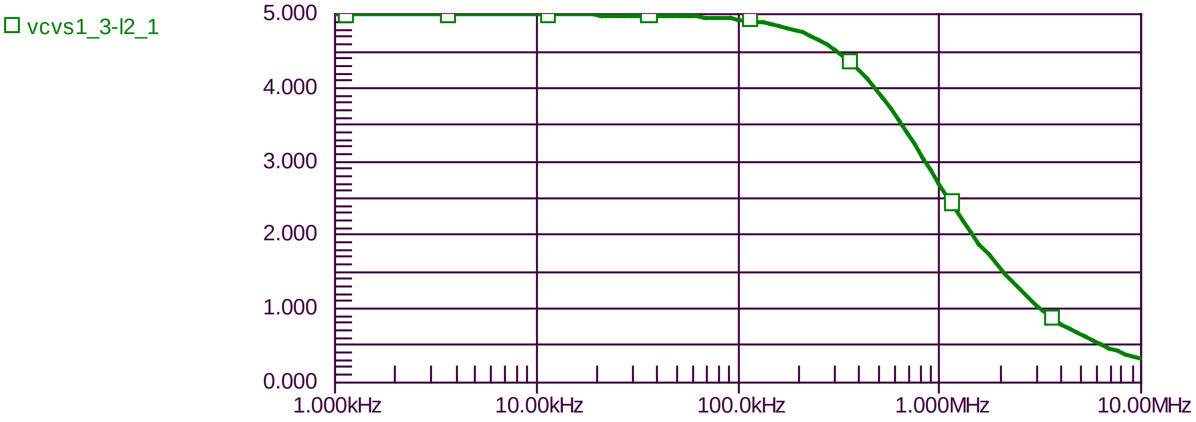
$$A(s) = K \cdot \frac{1}{s\tau_A + 1}$$

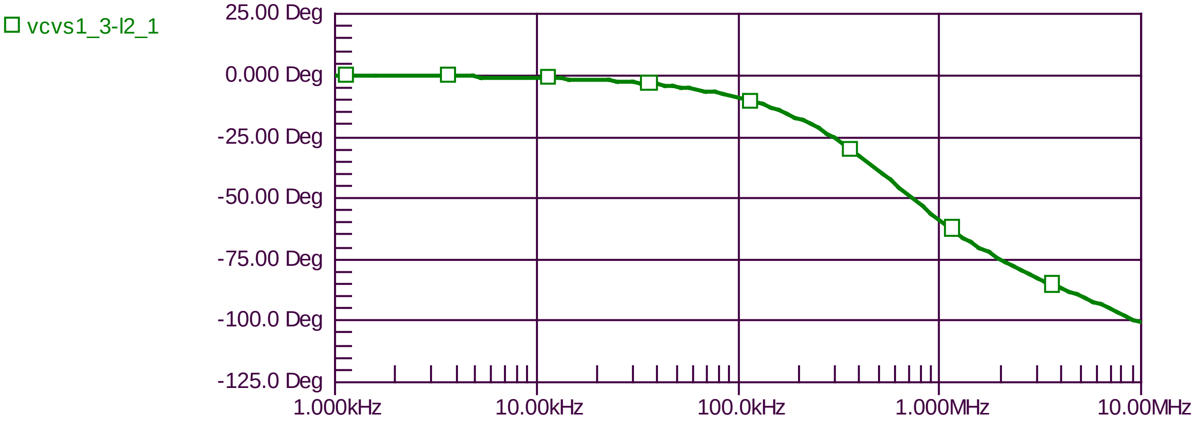
and, $\tau_A = R_3 \cdot C_2$; $\tau_L = L_2/R_2$; $\tau_s = L_1/R_1$; $R_s = R_1$ and $R_L = R_2$

For $K = 10{,}000$, the corresponding frequencies are:
$f_L = 79.58$ kHz; $f_s = 636.6$ kHz; $f_A = 159.2$ kHz

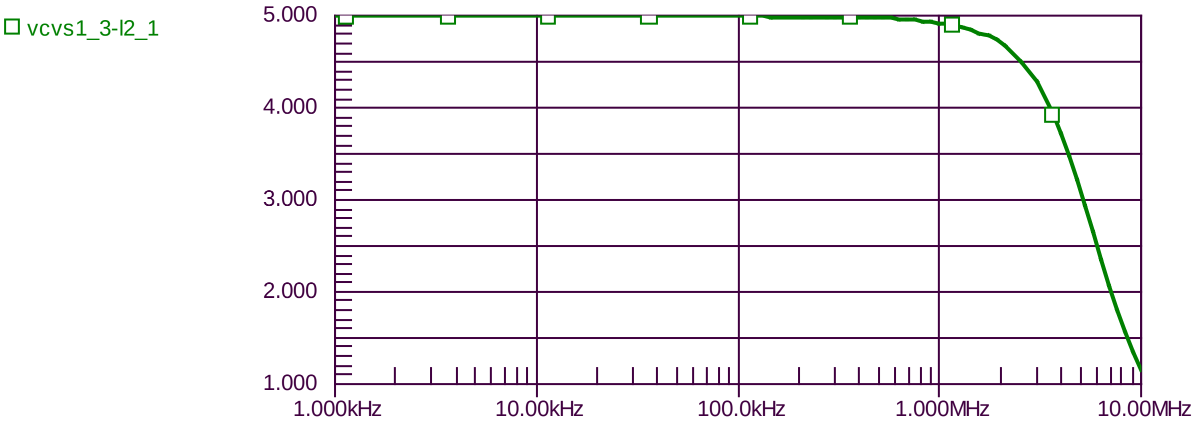
The poles of the complex pole-pair approach a frequency of $1/2 \cdot \pi \cdot (L_s/R_s)$, and infinity when K approaches infinity. The closed-loop response reduces to a dependency upon the sense resistor characteristics.

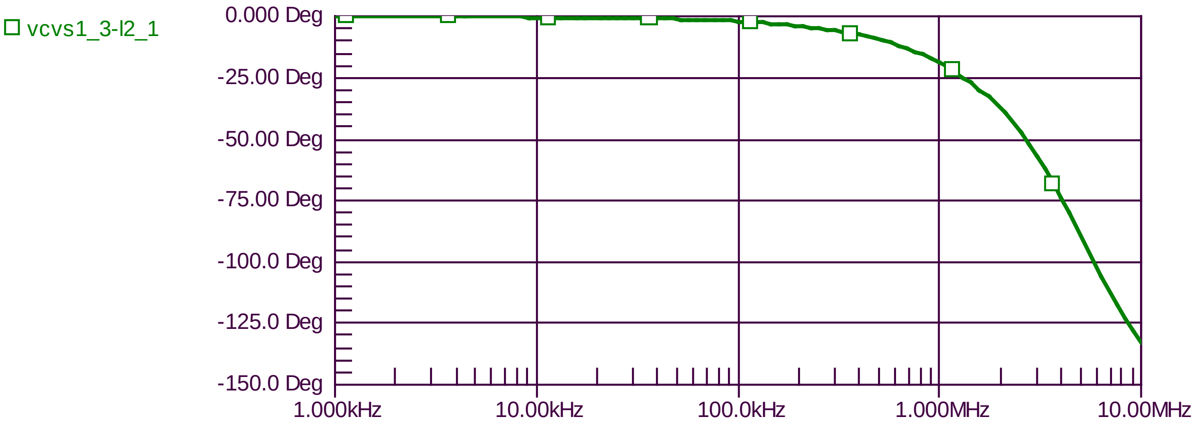
With a RL sense resistor the parasitic zero in the loop response compensates for the poles, resulting in a closed-loop response as shown below -- a marked contrast to the response with an "ideal" sense resistor.



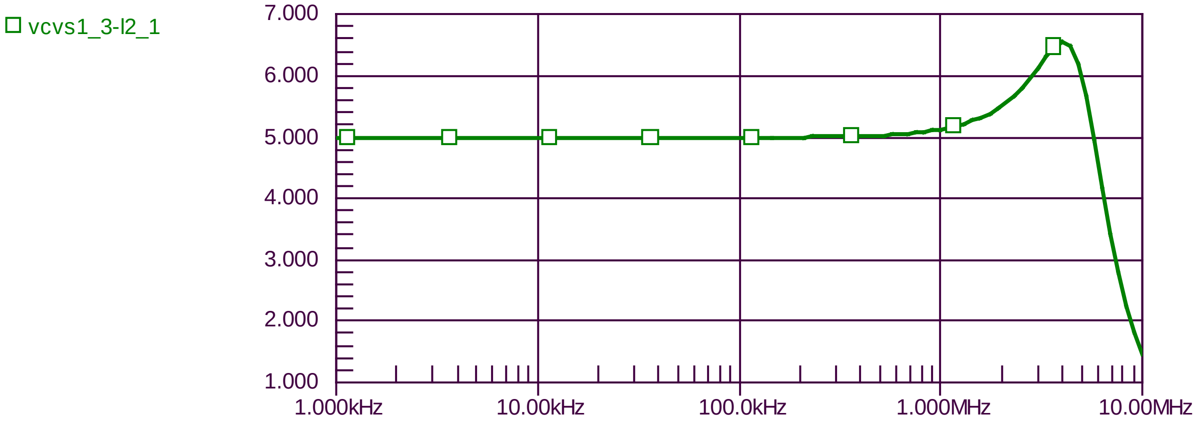


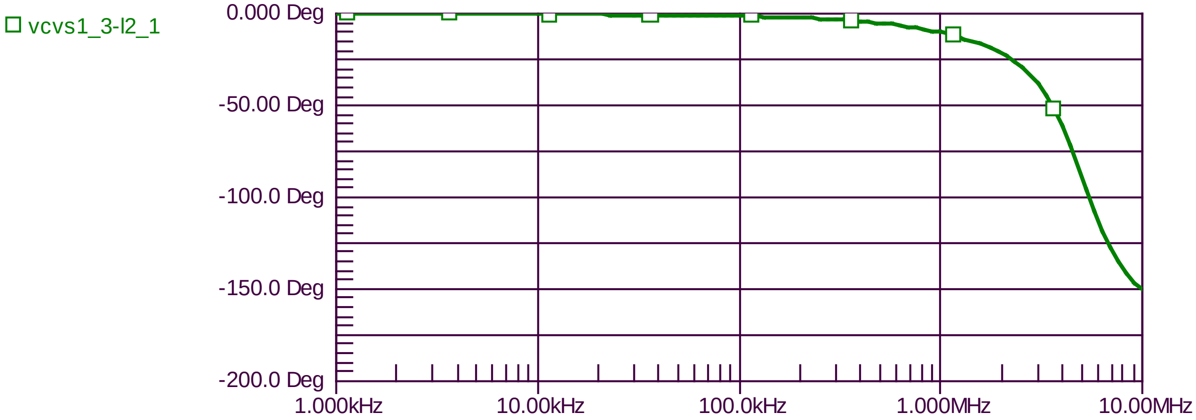
However, the disadvantage of the sense-resistor zero is also evident. While the response is flat and stable the bandwidth is significantly reduced, from over 1 MHz to somewhat above 600 kHz. Can bandwidth be extended while retaining a flat magnitude response? A faster forward-path amplifier will not extend bandwidth much because of the sense-R zero, which appears as a pole in the closed-loop response. But by using a lowerinductance sense resistor, reduced from 50 nH to 10 nH, the bandwidth is increased while the frequency response remains flat, as shown below. The bandwidth is now about 4.5 MHz.





But further reduction of L_s to 5 nH causes significant peaking to appear, as shown below.





Closure

Sense resistor series inductance can have a profound effect on closed-loop amplifier response. An ideal resistor without any series inductance will cause a feedback amplifier with series RL load to be peaked. But too much parasitic inductance will limit frequency response. Ideally, series inductance should be optimized for maximal flat bandwidth. If necessary, a series inductor may be added to a low-L sense resistor.