

Source impedance and op-amp stability

Version 1, Marcel van de Gevel, 15 November 2024

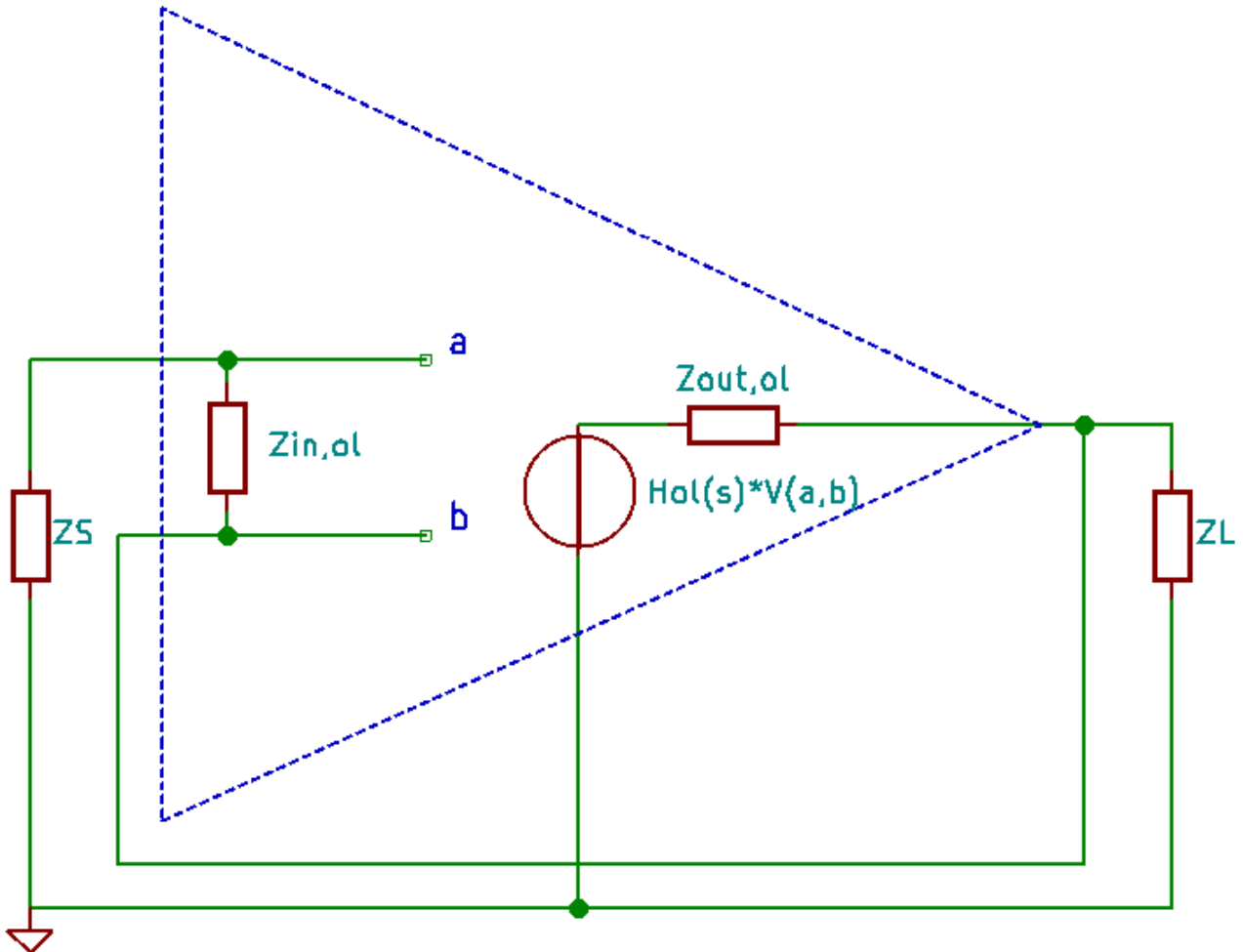


Figure 1: Simple model for an op-amp voltage follower with source and load impedance

Figure 1 shows a simple model for an op-amp, inside the dashed triangle, connected as a voltage follower and used with a source impedance Z_S and a load impedance Z_L . (A simple phono preamplifier with active RIAA correction is essentially a voltage follower at the frequency or frequencies where the loop gain passes through unity, as the feedback capacitors normally have negligible impedances at such frequencies.)

Introducing

$$Z_{Lt} = \frac{Z_L (Z_{in,ol} + Z_S)}{Z_L + Z_{in,ol} + Z_S} ,$$

where $Z_{Lt} \approx Z_L$ when $Z_{in,ol} + Z_S \gg Z_L$, the loop gain is simply

$$-H_{ol}(s) \frac{Z_{Lt}}{Z_{Lt} + Z_{out,ol}} \frac{Z_{in,ol}}{Z_{in,ol} + Z_S}$$

This shows that the load and the source impedance both affect the loop gain. The effect of the load impedance is small when $Z_{Lt} \gg Z_{out,ol}$ at the frequencies of interest and the effect of the source impedance is small when $Z_S \ll Z_{in,ol}$ at the frequencies of interest. For stability, "frequencies of interest" means around the frequency or frequencies where the magnitude of the loop gain passes through unity.

A common example of violating the condition $Z_{Lt} \gg Z_{out,ol}$ around the frequency where the magnitude of the loop gain passes through unity is connecting a big capacitive load to the output of an op-amp. It is well known that this can cause oscillations. A series LC resonator or an unterminated transmission line with deep impedance dips at a low enough frequency can do the same. The usual solution is to put a series resistor between the op-amp and the load. If that isn't acceptable, an LR parallel network or a first-order series filter can be used. (The use of a first-order series filter was proposed by A. N. Thiele for audio power amplifiers many years ago, it also makes the amplifiers more robust against RF signals picked up by the loudspeaker cable.)

A practical example of violating the condition $Z_S \ll Z_{in,ol}$ around the frequency where the magnitude of the loop gain passes through unity can be found in the thread <https://www.diyaudio.com/community/threads/opa1656-phono-preamp-split-from-opa1656-thread.377331/post-6785883>, or at least that is my hypothesis. The thread starter had made the TI-recommended moving-magnet preamplifier around an OPA1656, a low-noise CMOS op-amp with 53 MHz typical gain-bandwidth product, but without the 150 pF capacitor across the input, because the cartridge had a low recommended load capacitance.

The turntable features a switch that shorts the cartridge when the record has ended. At the end of the record, when the switch closed, there was always an enormous bang. My suspicion was that the shorted cable from the turntable to the phono preamplifier acted as a quarter-wave transmission line resonator, causing a too high impedance peak, causing the op-amp to oscillate. Some rectification effects then did the rest. Connecting a 220 Ω -15 pF RC series network across the input, the dual of the LR parallel network at an amplifier output, solved it: no bangs anymore. The time constant of the RC network was based on the estimated resonant frequency of the transmission line, the required capacitance was determined experimentally. Shorting switches are also used as mute switches in some DACs and preamplifiers.

One can also analyse it in terms of impedances and admittances. When you calculate the input impedance of the voltage follower, for simplicity assuming $Z_{out,ol} = 0$, you find that the real part of the input impedance can easily go negative, particularly for a fast low-noise MOS op-amp.

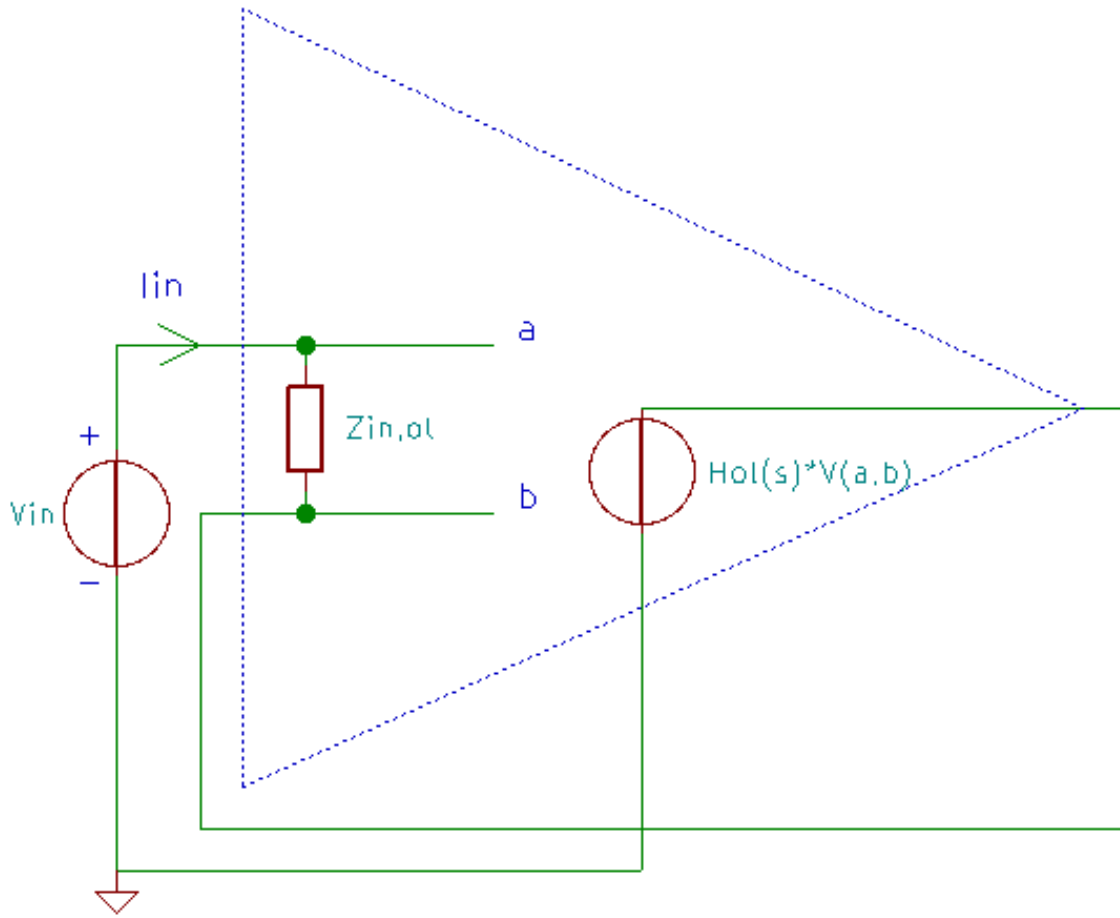


Figure 2: Schematic for calculating the input impedance

In Figure 2,

$$V_{in} = (H_{ol}(s) + 1) V_{ab}$$

$$V_{ab} = \frac{V_{in}}{H_{ol}(s) + 1}$$

$$I_{in} = \frac{V_{ab}}{Z_{in,ol}} = \frac{V_{in}}{(H_{ol}(s) + 1) Z_{in,ol}}$$

$$Z_{in, closed loop} = \frac{V_{in}}{I_{in}} = (H_{ol}(s) + 1) Z_{in,ol}$$

When the open-loop gain drops of with frequency at a first-order rate and when the open-loop input impedance is capacitive:

$$H_{ol}(s) = \frac{\omega_{GBP}}{s}$$

$$Z_{in,ol} = \frac{1}{sC_{in,ol}}$$

$$Z_{in, closed loop} = \left(\frac{\omega_{GBP}}{s} + 1 \right) \frac{1}{sC_{in,ol}} = \frac{\omega_{GBP}}{s^2 C_{in,ol}} + \frac{1}{sC_{in,ol}}$$

When $s = j\omega$:

$$Z_{\text{in, closed loop}} = -\frac{\omega_{\text{GBP}}}{\omega^2 C_{\text{in,ol}}} - \frac{j}{\omega C_{\text{in,ol}}}$$

The first term represents a frequency-dependent negative resistance, the second a series capacitance.

The differential open-loop input capacitance of an OPA1656 is specified to be 9.1 pF, see <https://www.ti.com/document-viewer/opa1656/datasheet> The large capacitance is no doubt due to the use of very large input MOSFETs to keep the $1/f$ noise small.

The gain-bandwidth product is specified to be 53 MHz, so the theoretical input impedance is

10 MHz: $-9269 \Omega - 1749 j\Omega$, admittance $-104.2 \mu\text{S} + 19.66 j \mu\text{S}$

50 MHz: $-370.8 \Omega - 349.8 j\Omega$, admittance $-1427 \mu\text{S} + 1346 j \mu\text{S}$

It's at best a very rough order-of-magnitude estimate, because the loop gain doesn't follow a -20 dB/decade slope anymore at these frequencies.

The estimated transmission line resonance frequency was 50 MHz. At this frequency, 220Ω in series with 15 pF has an impedance of $220 \Omega - 212.2 j\Omega$, admittance $2355 \mu\text{S} + 2271 j \mu\text{S}$. To the extent that these calculations can be trusted, the conductance of the RC network is large enough to make the total conductance at 50 MHz positive.