Application Note

JFE150 Ultra-Low-Noise Pre-Amp

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ABSTRACT

Many engineers face the challenge of amplifying small signals produced by sensors with high source impedance in a low-noise circuit. Amplifier circuit design for sensor applications such as hydrophones, guitar pickups, high source impedance microphones and turntables can benefit from a combination of discrete components and operational amplifiers. This application report discusses one way to accomplish this design challenge.

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1 Introduction

Amplifying the small signals produced by sensors in a low-noise circuit is a very common but difficult problem. Designers often use an operational amplifier (op amp) with bipolar inputs to achieve this amplification, given their inherently low flicker (1/f) and broadband noise. Bipolar op amps present another challenge when the small signal of interest is generated by a sensor with high source impedance that cannot deliver sufficient current to the input of the amplifier. Bipolar op amps have high input bias currents in the nanoampere range or greater, and lower input impedance relative to their complementary metal-oxide semiconductor (CMOS)-input and junction field-effect transistor (JFET)-input counterparts.

The bipolar input loads a sensor, such as a high source impedance microphone, that produces signals on the order of a few thousandths of a volt. This loading reduces audio sonic quality and dynamic range and distorts the signal. You can choose an op amp with a JFET front end such as the OPA145 from Texas Instruments. However, you will not be able to bias the circuit as flexibly as you could with discrete components and may sacrifice extra current for unwanted bandwidth relative to the audio bandwidth of up to 20 kHz. While CMOS and JFET input stages have comparable bias currents, JFET devices have much better noise performance. Moreover, JFETs also have higher gain (transconductance) than CMOS devices. A discrete JFET such as TI's JFE150, when followed by a bipolar op amp such as the OPA202, does offer a way to achieve high input impedance and low noise with flexible biasing, see Figure 1-1.

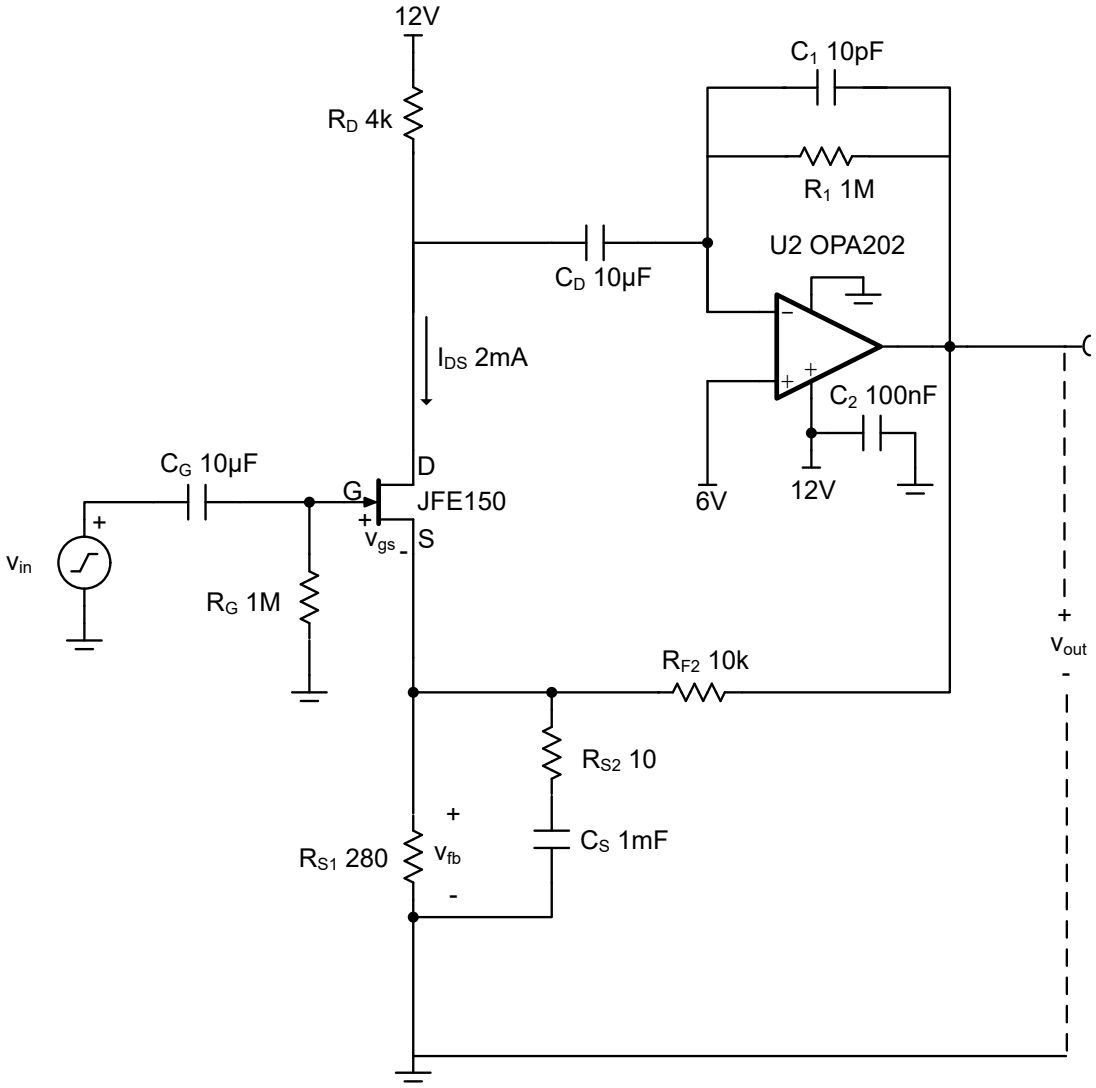

Figure 1-1. Pre-Amp With JFE150 Front End in a Closed-Loop Circuit

2 Theory of Operation

The JFET pre-amp circuit is easiest to analyze using the small-signal T-model as shown in Figure 2-1. To understand the operation of this circuit, begin by examining it at the input. A sensor generates a small-signal input voltage (v_{in}), which modulates the gate-to-source voltage (v_{gs}) of the JFET. The JFE150 is the first gain stage in the pre-amp circuit and conducts a small-signal drain-to-source current, $i_{ds} = g_m \times v_{gs}$ which fluctuates with v_{in}. The small signal current i_{ds}, is not to be confused with the DC bias current, I_{DS} = 2 mA, as shown in Figure 1-1. The transconductance gain parameter (g_m), is expressed in Siemens and v_{gs} is expressed in volts.

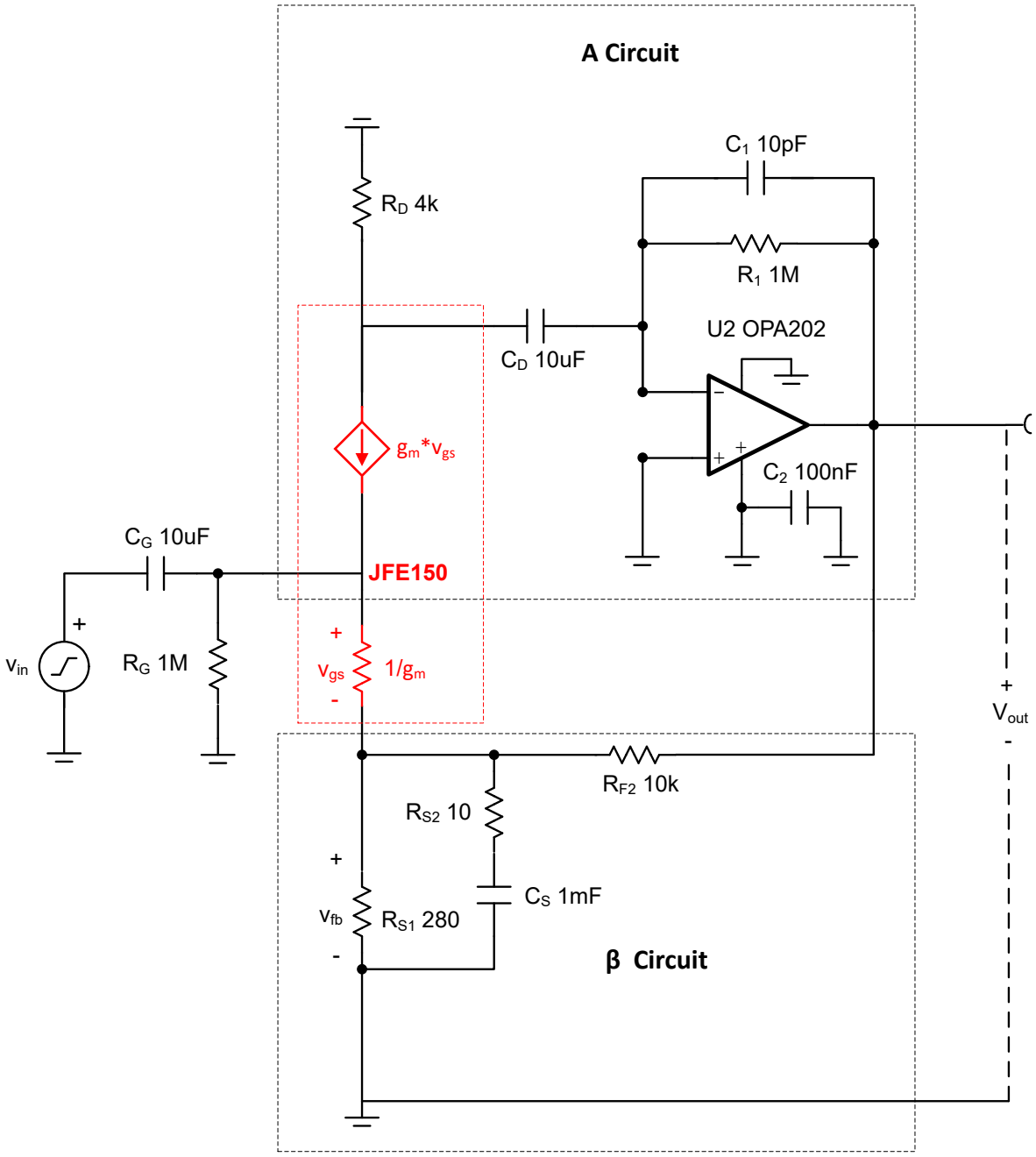

Figure 2-1. Pre-Amp With JFE150 Front End Small Signal T-Model

Combined with resistor R_1, the OPA202 forms a transimpedance amplifier that converts the current $g_m \times v_{gs}$ to a voltage, v_{out}. The OPA202 drives the loop to keep its input terminals approximately equal. As a result, most of the current $g_m \times v_{gs}$ flows through resistor R_1 in the mid-band frequencies, producing an amplified voltage at v_{out}. Equation 1 calculates the feedforward gain (A_v):

$$A_V = g_m\left(\frac{mA}{V}\right) \times R_1\,(\Omega) \quad (1)$$

Convert g_m from decibels to Siemens (mA/V) or Ω^{-1}, as shown in Equation 2, using the simulated measurement from Figure 2-2.

$$g_m = 10\text{^}\left(\frac{-36.08\ dB}{20\ dB}\right) = 15.7\ ms \quad (2)$$

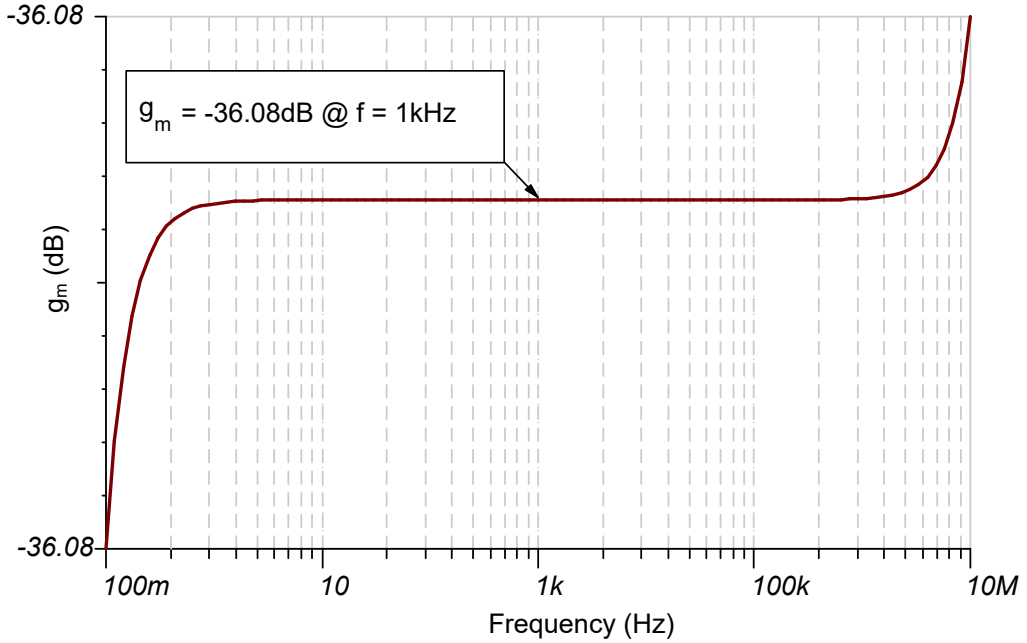

Figure 2-2. g_m (dB) vs Frequency (Hz)

Equation 3 and Equation 4 show that the feedforward gain is:

$$A_V = 15.7\ ms \times 1\ M\Omega = 15.7\frac{kV}{V} \quad (3)$$

$$A_{dB} = 83.92\ dB \quad (4)$$

Because wafer process variations can yield up to 30% variations in g_m, adding a feedback network (β) maintains a predictable closed-loop gain. The β feedback network consists of resistors R_{F2}, R_{S1}, and R_{S2} and capacitor C_S, and is a series-shunt feedback network. The β network samples v_{out} by shunting the output of the OPA202 and feeds back a proportional voltage v_{fb} in series with v_{gs}. The source node of the JFET is the feedback-summing node of the circuit. In this configuration, the loop is closed. If v_{out} rises, then v_{fb} rises. An increase of v_{fb} at the source node decreases v_{gs}, resulting in a reduction of current $g_m \times v_{gs}$ that flows through transimpedance resistor R_1. The final outcome is a reduction of v_{out} which completes the negative feedback loop of the pre-amplifier. The standard closed-loop gain (A_{cl}) Equation 5 applies.

$$A_{cl} = \frac{A}{1 + A\beta} \quad (5)$$

Assuming the feed forward gain A is much greater than β, A_{cl} is approximately determined by resistors R_{F2} and R_{S2} in the mid-band frequencies. At frequency, C_S becomes a short and A_{cl} can be approximately calculated using Equation 6.

$$A_{cl} \approx \frac{1}{\beta} \approx \frac{R_{F2}}{R_{S2}} + 1 \quad (6)$$

$$A_{cl} \approx 1001\frac{V}{V} \text{ or } 60\ dB \quad (7)$$

Figure 2-3 shows the closed-loop gain vs frequency response of the JFET pre-amplifier circuit.

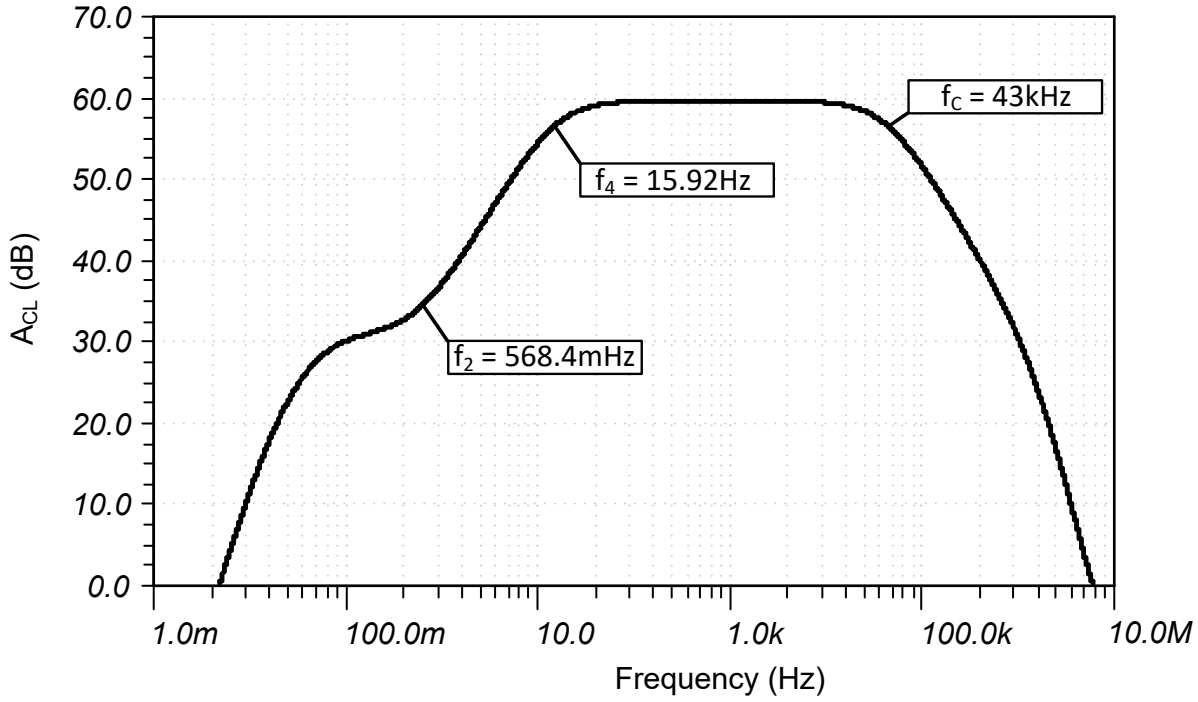

Figure 2-3. A_{cl} (dB) vs Frequency (Hz)

The loop parameters A, and 1/β can be determined in simulation by breaking the loop. This is accomplished in a SPICE simulator by driving the loop with V_{Loop} as shown in Figure 2-4.

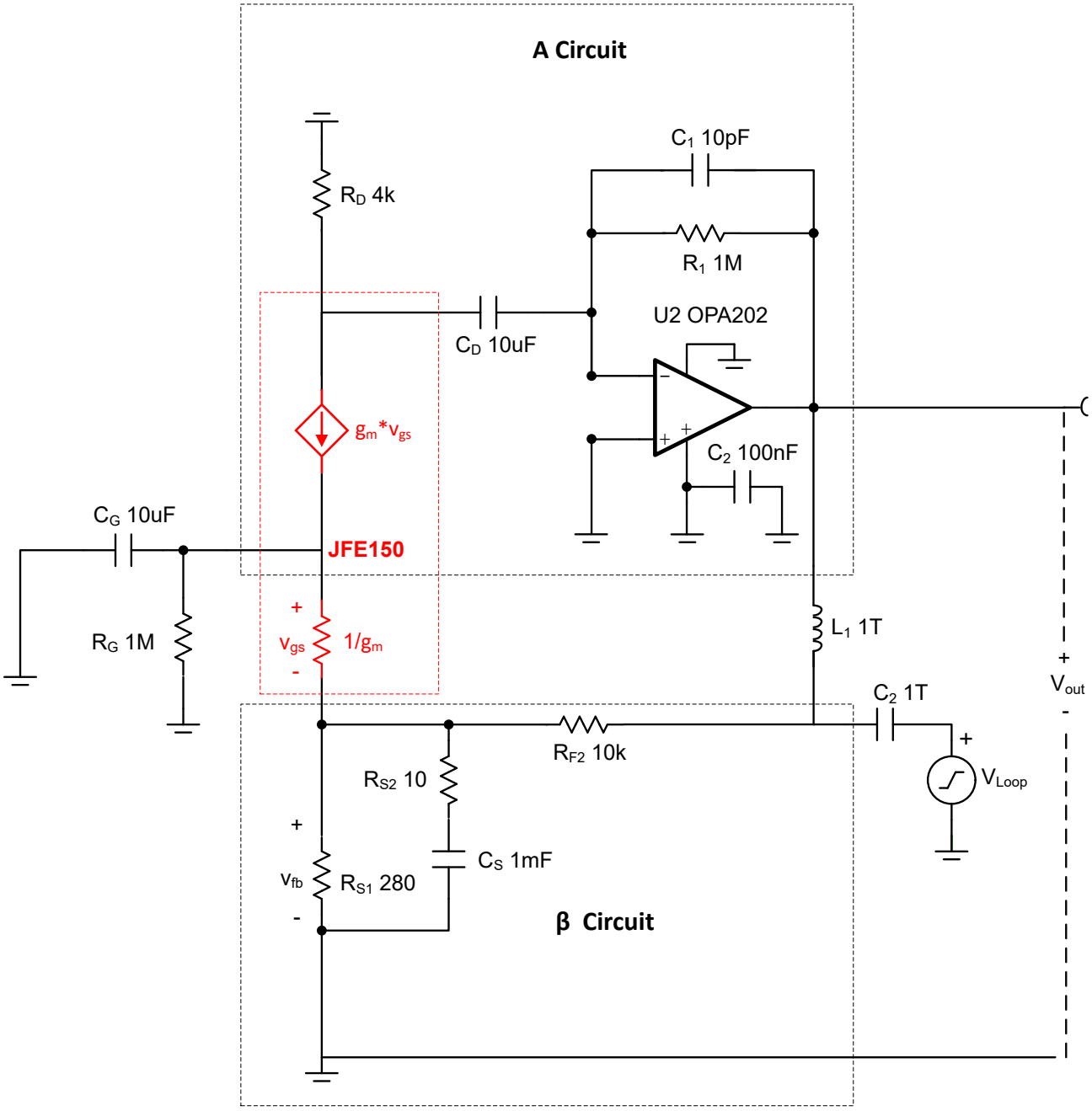

Figure 2-4. Loop Analysis for Pre-Amp With JFE150 Front End Using the Small-Signal T-Model

At high frequencies the inductor L_1 is an open and the capacitor C_2 is a short. This method isolates the circuits A and β, to plot the frequency response of each, as shown in Figure 2-5. The simulated feedforward gain A is 83.6 dB and closely matches the calculation from Equation 4. The upper –3 dB point of A_{cl} occurs when A and 1/β meet.

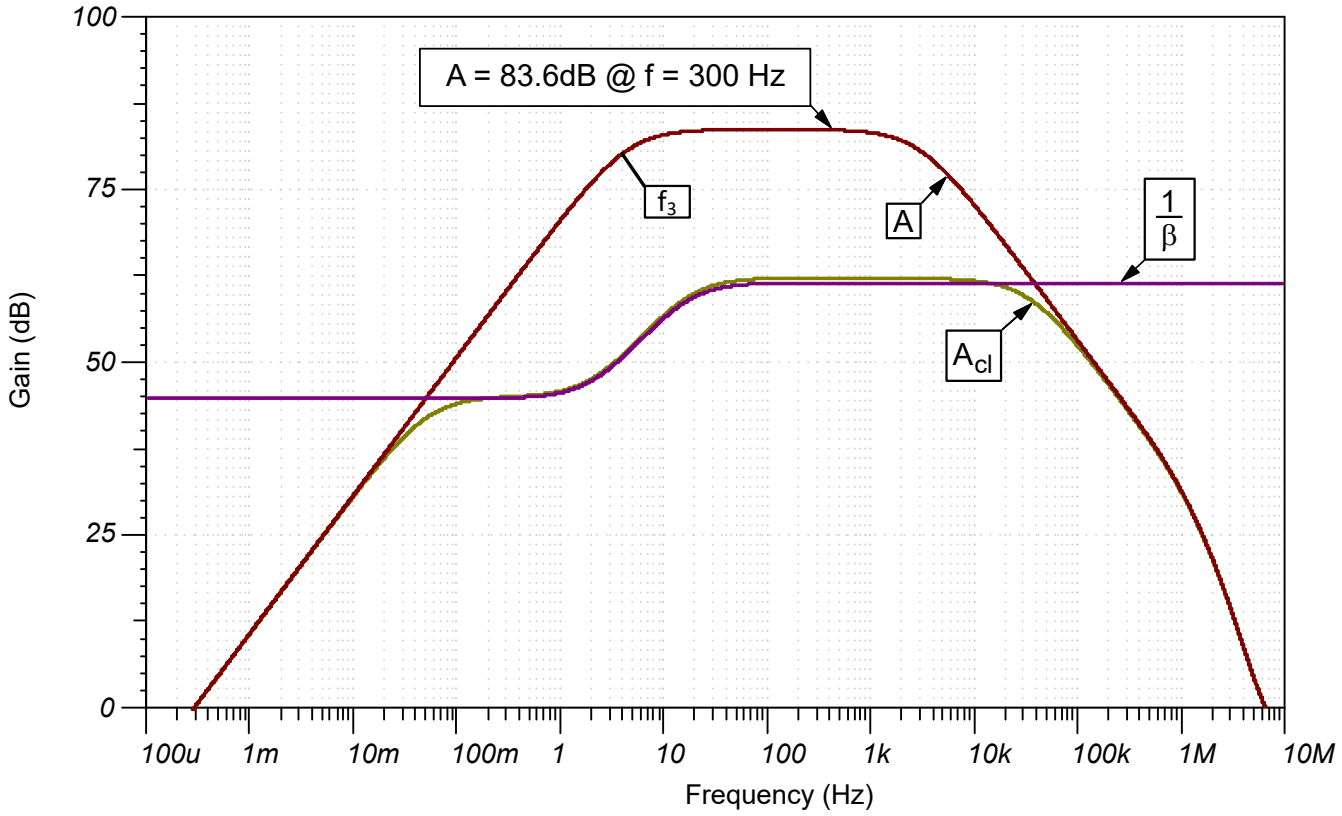

Figure 2-5. Loop Parameters (dB) vs Frequency (Hz)

The low-frequency corners $f_1 - f_4$ are straightforward to determine and are shown in Figure 2-5, Figure 2-3, and Table 2-1. Frequency f_1 determines the transfer function between v_{in} and the gate. Components R_G and C_G form a high-pass filter and the –3 dB point of this transfer function occurs at 15.9 mHz.

Table 2-1. RC Combinations and Corner Frequencies

RC Combinations	Corner Frequencies
$f_1 = \frac{1}{2\pi \times R_G \times C_G}$	15.9 mHz
$f_2 = \frac{1}{2\pi \times R_{S1} \times C_{S1}}$	568.4 mHz
$f_3 = \frac{1}{2\pi \times R_D \times C_D}$	3.98 Hz (See curve A in Figure 2-5)
$f_4 = \frac{1}{2\pi \times R_{S2} \times C_{S1}}$	15.92 Hz

Breaking the loop also allows the designer to check for circuit stability as shown with the loop gain (A × β) phase plot in Figure 2-6. The phase margin of this circuit is determined by starting the analysis when the phase of A × β is –180°. Figure 2-6 show that this occurs at $f = 3.98\ \text{Hz}$. The reason for starting at –180° is because C_D does not contribute to the phase margin. Capacitor C_D adds a 90° shift from the starting point of the analysis and is a high-pass filter zero. This can be seen in simulation by varying the value of C_D from 10 µF to 5 F or through tedious hand calculations. The phase margin = 267.4 – 180 = 87.4°.

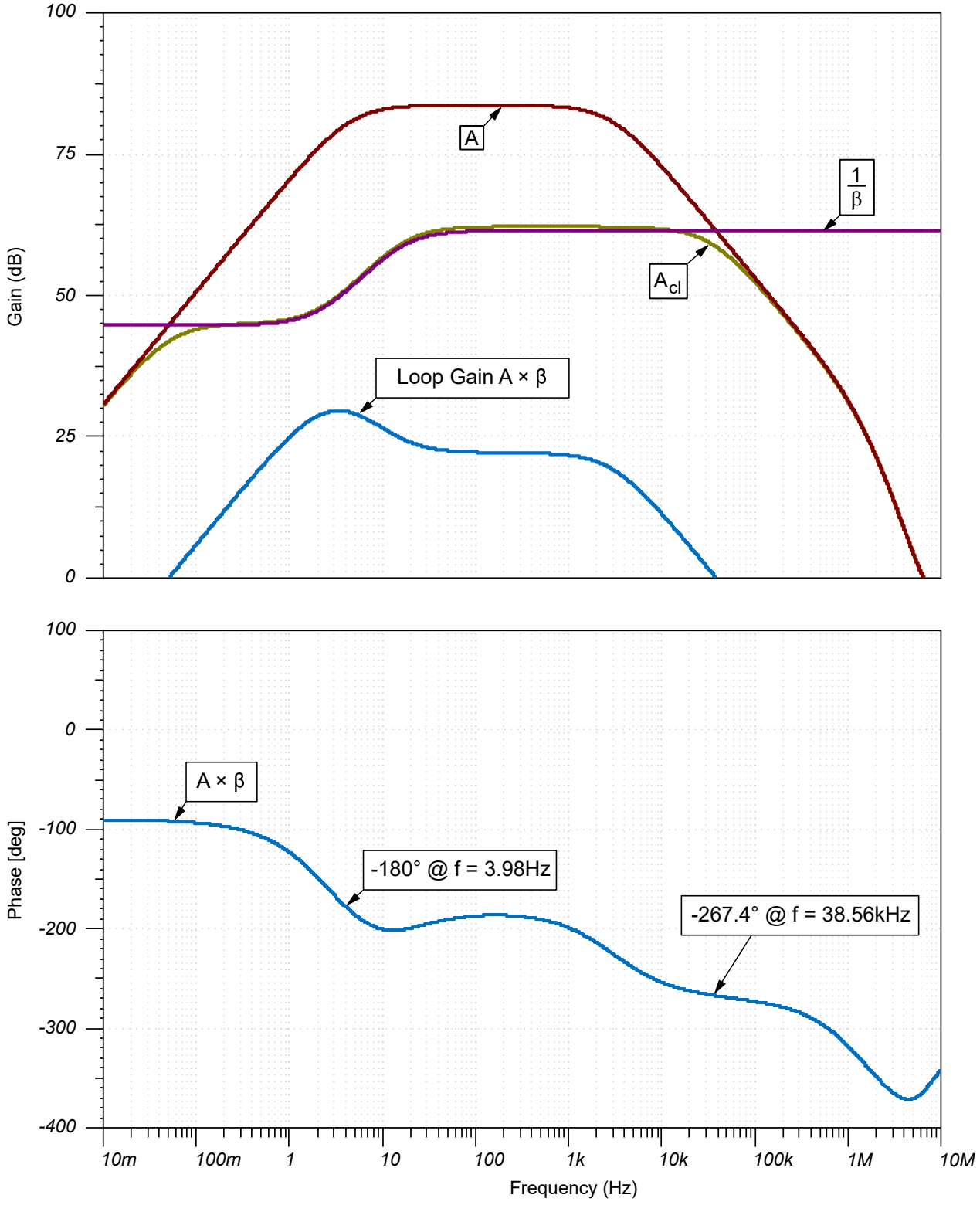

Figure 2-6. Stability Analysis

3 Noise

The JFE150 pre-amplifier circuit provides very high gain at 60 dB and a flat frequency response from approximately 16 Hz up to 43 kHz. The clean roll-off at the corner frequencies provides a natural-sounding filter for audio signals without sounding abrupt at the low and high ends. This closed-loop solution also offers very low input-referred noise of 1.99 nV/√Hz in the 1/f region at 10 Hz and 1.18 nV/√Hz in the broadband region at 1 kHz, as shown in Figure 3-1. Make sure to provide a clean power supply to this circuit to not degrade its remarkable performance.

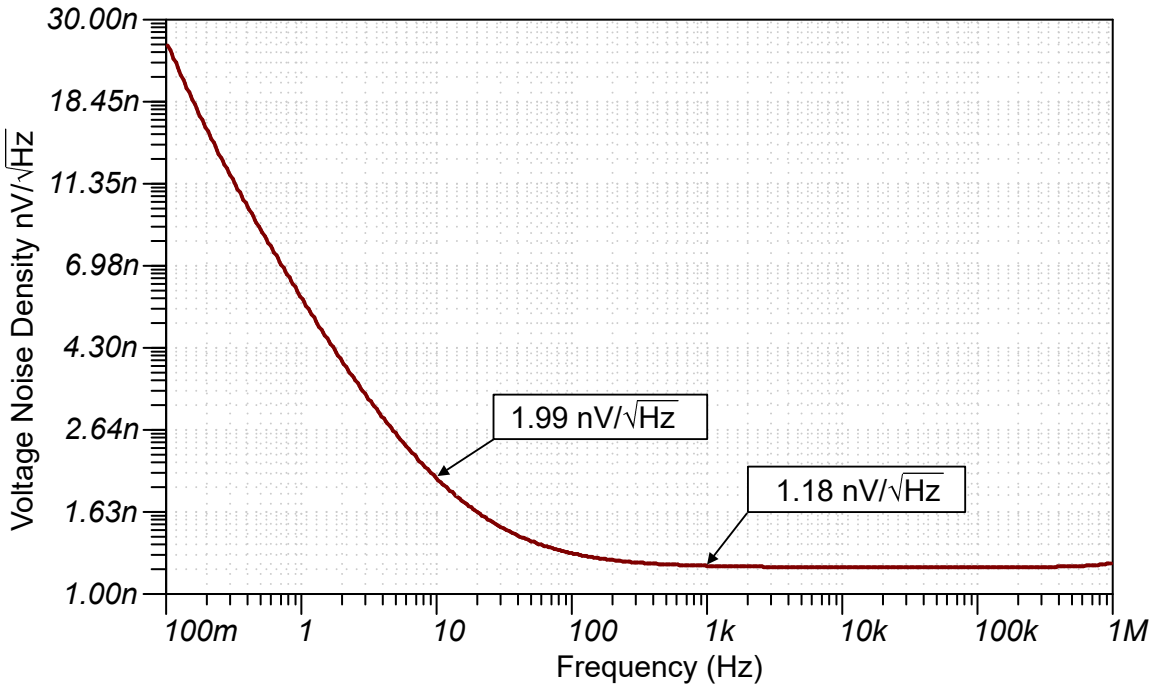

Figure 3-1. Circuit Noise nV/√Hz vs Frequency (Hz) Using an Input Referred Noise Analysis Simulation

4 Summary

Amplification of small signals in applications such as professional microphones, audio interfaces, mixers, turntables, and guitar amplifiers is very challenging. These types of applications benefit from the bias flexibility, high-input impedance, and low noise that a discrete JFET offers.

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