Stabilizing difference amplifiers for headphone applications

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Introduction

The recent increase in popularity of high-fidelity headphones and lossless audio formats has caused many manufacturers of personal electronics to add high-quality audio outputs to their devices. As a result, 24-bit/192-kHz audio digital-to-analog converters (DACs), once reserved for home high-fidelity systems, are now being incorporated into mobile devices such as cell phones, tablets, and portable music players. These DACs deliver extremely low-distortion signals, but are unable to drive headphones directly. To take full advantage of these high-performance parts, a well-designed headphone amplifier must also be added to the system.

Traditional headphone amplifier circuit

The DAC output is often a differential signal which must be converted to a single-ended signal by the headphone amplifier circuit. In Figure 1, a traditional difference amplifier consists of an operational amplifier (op amp) and four matched resistors that amplifies the difference between the complementary DAC outputs. The amplifier also rejects signals common to both outputs, such as even-order distortion. The amplifier should not add unwanted noise or distortion to the signal, or change the system's overall frequency response. Perhaps, most importantly, the amplifier must be stable when headphones are connected to the output. As fundamental as this last point is, it is often overlooked in headphone amplifier design.

Figure 1. A traditional difference amplifier converts differential output to a single-ended signal

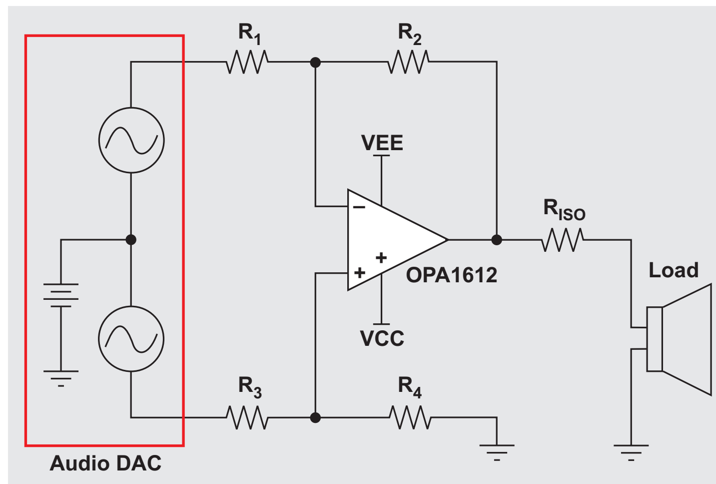
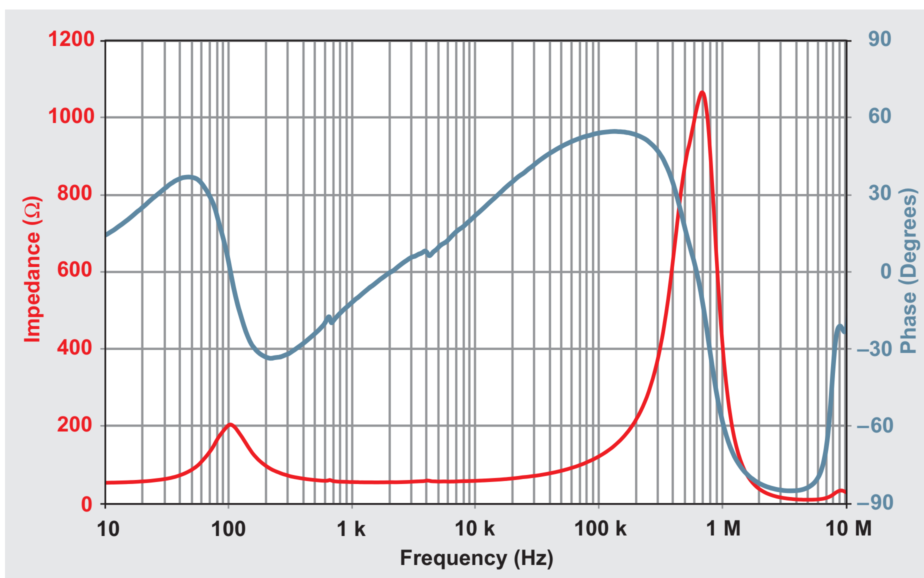


Figure 2. Measured impedance of 64-Ω headphones



Headphone impedance characteristics

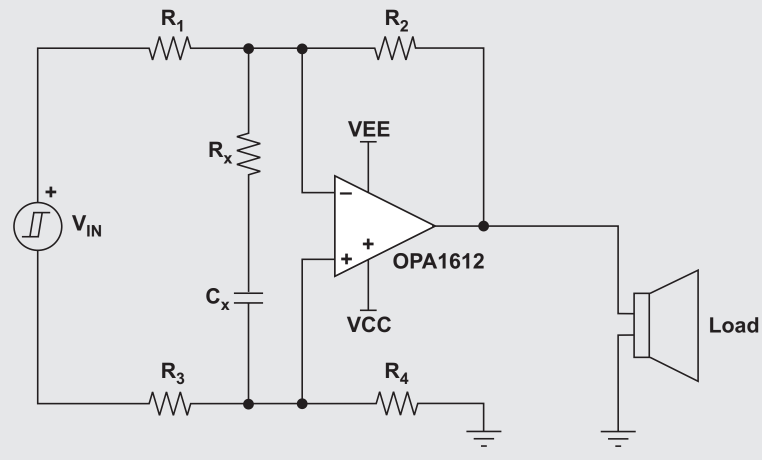
Headphones are not a simple resistive load, although their nominal impedance specifications (typically between 16 and 600 Ω) would seem to imply otherwise. Figure 2 shows the measured impedance of a 64-Ω (nominal) headphone from 10 Hz to 10 MHz (1 channel shown). The red curve gives the impedance magnitude and the blue curve is the phase angle.

Two resonant peaks are clearly evident in the impedance plot. The low-frequency resonance at 100 Hz is produced by the mechanical and electrical properties of the drivers in the headphones. The high-frequency resonance is created from the interaction of the cable capacitance with the inductance of the cable and driver voice coil. From a stability perspective, the high-frequency resonance has the potential to cause the most problems. Above this resonant point, the headphone is a capacitive load, as is evident from negative phase angle. Capacitive loads introduce a pole into the open-loop gain curve of an amplifier, degrading the phase margin and potentially causing oscillation.

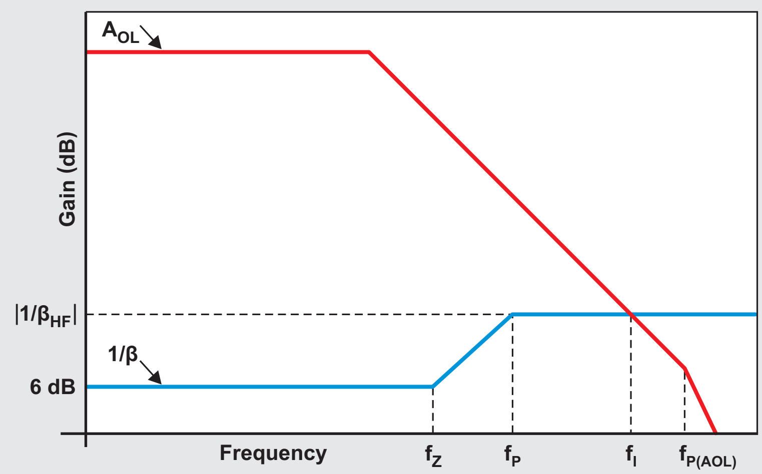
The most common solution to this issue is to add a resistor (R_{ISO} in Figure 1) in series with the amplifier output to isolate the load capacitance from the feedback loop and preserve the phase margin. While this solution is effective at maintaining stability, it also degrades the system's audio performance for several reasons. First, the output voltage of the amplifier circuit is no longer load-independent. Consider that the amplifier's output impedance forms a voltage divider with the load impedance. Because the load is not resistive, as illustrated in Figure 2, the voltage at the headphones varies over frequency.

Second, the current drawn by headphone drivers is not perfectly linear. This is partly because the impedance of the driver changes as a function of where the cone and voice coil assembly is in its range of motion. As the cone progresses through its range of motion, the impedance curve may change dramatically, thus distorting the current drawn by the driver. If the amplifier has a non-zero output impedance, this distorted current will also distort the voltage signal at the amplifier output, potentially degrading audio quality[1]. A low-output impedance is crucial for achieving high performance in headphone amplifier circuits.

Figure 3. Amplifier solution for large capacitive loads



(a) Amplifier circuit with R_X/C_X network



(b) Open-loop gain and inverse feedback factor

Enhanced headphone amplifier circuit

There are some amplifier circuits that solve the problem of driving large capacitive loads while maintaining low output impedance by enclosing the isolation resistor inside the amplifier feedback loop and using a dual feedback topology[2]. However, in the difference amplifier circuit, enclosing the isolation resistor in the feedback loop degrades the circuit's common-mode rejection ratio (CMRR), which is crucial for eliminating distortion from the DAC output signal.

A solution to this problem is shown in Figure 3a. Figure 3b shows response curves for the open-loop gain (A_{OL}) and the inverse feedback factor ($1/\beta$). In this topology, resistor R_X and capacitor C_X introduce a pole-zero pair in the $1/\beta$ curve. By increasing the magnitude of $1/\beta$ at the frequency where it intersects the open-loop gain curve (f_I), the system can achieve reasonable phase margin without increasing the output impedance at audio frequencies or degrading the CMRR. Furthermore, adding R_X and C_X to the circuit does not affect the circuit's closed-loop transfer function.

For the circuit in Figure 3a to be stable, the intersection frequency (f_I) must be less than the frequency of the second pole in the A_{OL} curve ($f_{P(AOL)}$), but greater than the pole in the $1/\beta$ curve (f_P):

$$f_{P(AOL)} > f_I > f_P \tag{1}$$

On the other hand, to provide the best audio performance possible, f_Z and f_P should be as far above the audio bandwidth as possible. Above the zero-frequency, the noise and distortion of the circuit will be increased by the reduction in loop gain. As is often the case, the requirements for stability and high performance need to be balanced in the design process.

To illustrate the design of this circuit, an OPA1612 was configured to drive the headphones used for Figure 2. Figure 4 shows the TINA-TI™ simulation schematic for the design process. For simplicity, the four resistors of the difference amplifier are matched (R1, R2, R3, R4 = R).

Inductor LT is used to break the amplifier's feedback loop. The circuit's loop gain is measured by the voltage probe labeled AOLB. The feedback factor, β, is measured directly at the op amp inputs by differential voltage probe B. A differential voltage probe must be used because this technique incorporates both positive and negative feedback. The net feedback factor is the difference of the individual negative and positive feedback factors[2]. The post-processor in TINA-TI can be used to generate additional curves from these voltage probes. For example, the open-loop gain curve is generated by dividing the loop gain by the feedback factor. The 1/β curve is produced by taking the inverse of the B probe.

A 400-pF capacitor (CL) connected to the output represents the high-frequency impedance of the headphones. This value is determined by taking the impedance of the headphones (Figure 2) where the phase is most negative, which is a good representation of a worst-case capacitive loading from headphones. In simulation, a second pole in the A_{OL} curve caused by this load capacitance can occur at 5.7 MHz where the A_{OL} magnitude is approximately 25 dB. In order to satisfy the criteria in Equation 1, the magnitude of the inverse feedback factor at high frequencies ($|1/\beta_{HF}|$) must be greater than 25 dB. This is calculated using the equation:

$$\left|\frac{1}{\beta_{HF}}\right| = \frac{2R}{R_X}+2 > 25\ \text{dB} \tag{2}$$

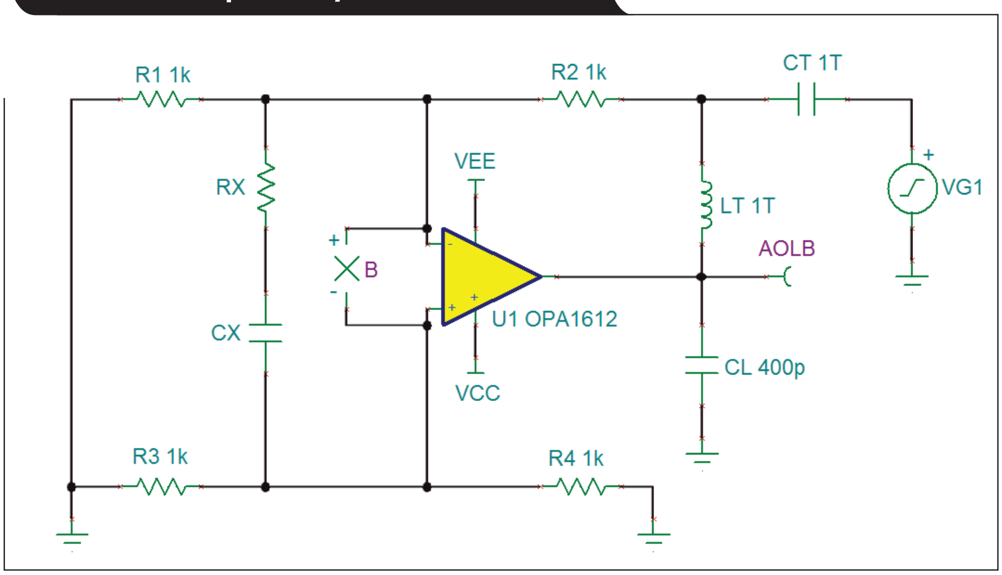
Using 1 kΩ as the value of all difference-amplifier resistors allows the value of R_X to be calculated:

$$\begin{aligned}\left|\frac{1}{\beta_{HF}}\right| &> 10^{\left(\frac{25\,\text{dB}}{20}\right)} = 17.78\\ &= \frac{2(1\,\text{k}\Omega)}{R_X}+2 \rightarrow R_X < 126.7\ \Omega\end{aligned} \tag{3}$$

A value of 118 Ω for R_X ensures sufficient noise gain for stable operation. Next, C_X was selected so that the pole frequency is well below 5.7 MHz. A conservative design rule is to place the pole frequency at one-tenth the intersection frequency, as long as the resulting zero is not near the audio bandwidth. In this example, placing the pole frequency at 570 kHz would position the zero near 57 kHz, a bit too low for high-performance audio systems. As a compromise, the pole was placed at one-fifth the intersection frequency:

$$\begin{aligned}f_P &= \frac{5.7\ \text{MHz}}{5} = 1.14\ \text{MHz}\\ &= \frac{1}{2\pi C_X R_X} \rightarrow C_X = 1.183\ \text{nF}\end{aligned} \tag{4}$$

Figure 4. TINA-TI™ simulation schematic used to determine loop stability



A value of 1.2 nF is very close to the calculated value for C_X. The resulting zero frequency is:

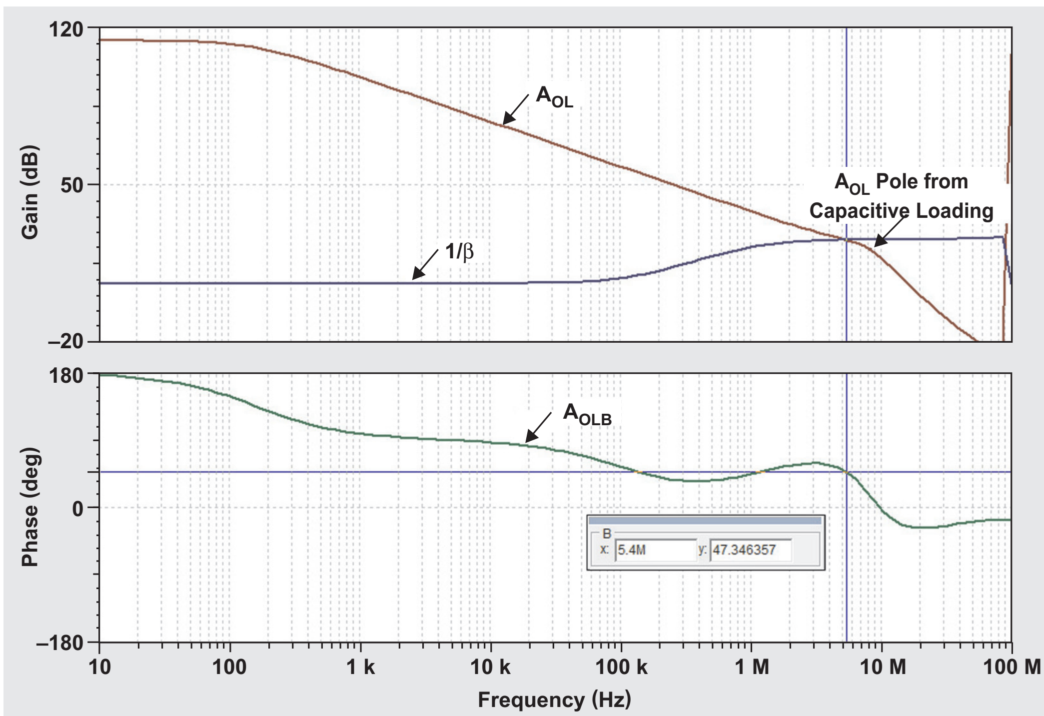
$$f_Z = \frac{1}{2\pi C_X\left(R_X + R\right)} = 118.6\ \text{kHz} \tag{5}$$

The 118.6-kHz zero frequency is sufficiently above the audio bandwidth to avoid degrading the circuit's performance.

An AC transfer characteristic simulation was performed and the results are shown in Figure 5. The open-loop gain and 1/β curves are shown in the magnitude plot (top). The 1/β curve intersects the A_{OL} curve at 5.4 MHz. At this point the phase of the loop gain (A_{OLB}, bottom) shows 47.35° of phase margin. Removing the R_X and C_X network would cause the 1/β curve to intersect the A_{OL} curve below the second pole created by the capacitive loading. In this case, the phase at the intersection point becomes –52.37°, which indicates an unstable system.

A difference amplifier circuit employing the previously calculated values of R_X and C_X was built and its measured performance was compared to a traditional difference amplifier using an isolation resistor of 47.5 Ω. The same 64-Ω headphones (Figure 2) were used as the load for these tests. It is extremely important to test headphone amplifier circuits with actual headphones because simply using a resistor will not reveal the detrimental effects of the output impedance.

Figure 5. Loop stability plots generated with TINA-TI™ model



The closed-loop gain of the two circuits is shown in Figure 6. As mentioned previously, the series resistor used for stability forms a voltage divider with the headphone impedance. The result is that the gain of the traditional amplifier circuit varies by 4.13 dB over the measured bandwidth. Conversely, the circuit employing the R_X/C_X network has extremely low output impedance, and its gain is essentially independent of the load impedance. The gain variation of the R_X/C_X circuit is 0.03 dB over the measurement bandwidth.

The effects of the series output resistor are also evident in the measured total harmonic distortion (THD) when driving the 64-Ω headphones. Figure 7 shows plots for the measured THD versus frequency for the two solutions with a 300-mV_{rms} output level. Adding a series resistor drastically reduces the THD performance due to the non-linear current draw of the headphones. At low frequencies, where the cone excursion of the headphone drivers is highest, the THD is over 55 dB worse for the traditional amplifier that employed a series output resistor.

Figure 6. Measured closed-loop gain of the two amplifiers

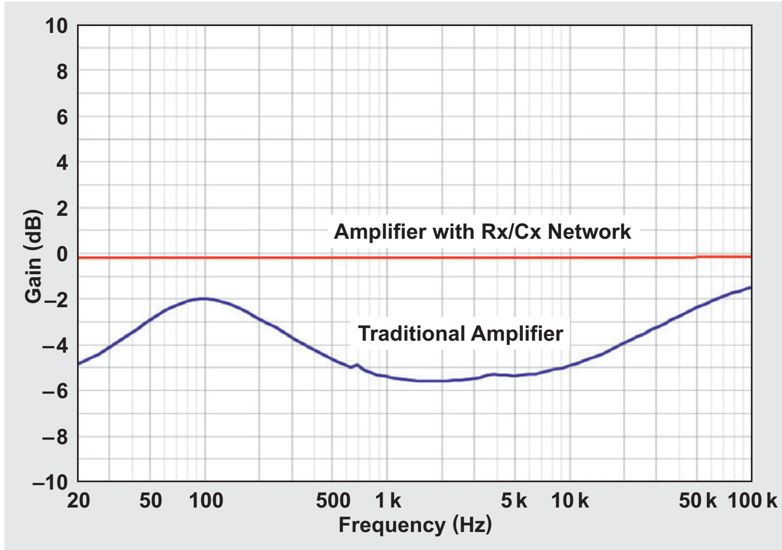
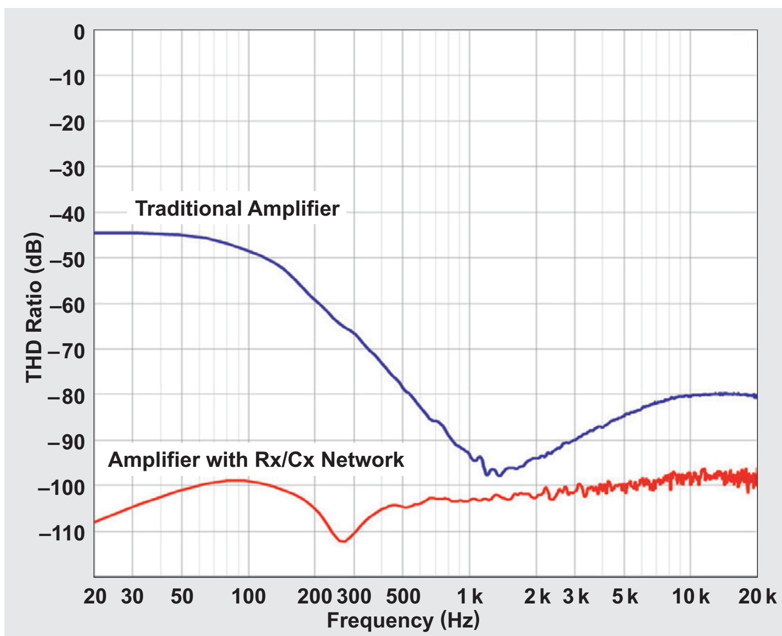


Figure 7. Measured THD of the two solutions



Conclusion

Stabilizing headphone amplifiers is a unique challenge because of the difference amplifier circuit topology and the requirements for low output impedance, low distortion, low noise, and high CMRR. The enhanced amplifier solution presented allows for stable operation into capacitive loads without increasing the output impedance at low frequencies or degrading the common-mode rejection. Using this technique, headphone amplifier circuits can be designed that are stable for typical headphone loads and provide exceptional audio performance.

References

1. John Siau, "The Sonic Advantages of Low-Impedance Headphone Amplifiers," 2001.
2. J. Graeme, "Optimizing Op Amp Performance," New York, McGraw-Hill, 1997. Print

Related Web sites

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