Stabilizing difference amplifiers for headphone applications

By John Caldwell
Analog Applications Engineer

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.

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 (RISO 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.

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 (AOL) and the inverse feedback factor (1/β). In this topology, resistor RX and capacitor CX introduce a pole-zero pair in the 1/β curve. By increasing the magnitude of 1/β at the frequency where it intersects the open-loop gain curve (f1), the system can achieve reasonable phase margin without increasing the output impedance at audio frequencies or degrading the CMRR. Furthermore, adding RX and CX 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 (f1) must be less than the frequency of the second pole in the AOL curve (fP(AOL)), but greater than the pole in the 1/β curve (fP):

\[ f_P(AOL) > f_1 > f_P \]  

(1)

On the other hand, to provide the best audio performance possible, f2 and fP 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 AOL curve caused by this load capacitance can occur at 5.7 MHz where the AOL 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/βHF) must be greater than 25 dB. This is calculated using the equation:

\[
\left|\frac{1}{\beta_{HF}}\right| = \frac{2R_{X}}{R_{X}} + 2 > 25 \text{ dB}
\]

(2)

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

\[
\left|\frac{1}{\beta_{HF}}\right| > 10^{\left(\frac{25 \text{ dB}}{20}\right)} = 17.78
\]

\[
\frac{1}{\beta_{HF}} = \frac{2(1\text{kΩ})}{R_{X}} + 2 \rightarrow R_{X} < 126.7 \text{ Ω}
\]

(3)

A value of 118 Ω for RX ensures sufficient noise gain for stable operation. Next, CX 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:

\[
f_{p} = \frac{5.7 \text{ MHz}}{5} = 1.14 \text{ MHz}
\]

(4)

\[
= \frac{1}{2\pi C_{X}R_{X}} \rightarrow C_{X} = 1.183 \text{ nF}
\]
A value of 1.2 nF is very close to the calculated value for \( C_X \). The resulting zero frequency is:

\[
f_z = \frac{1}{2\pi C_X (R_X + R)} = 118.6 \text{ kHz}
\]  

(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 \( 1/\beta \) curves are shown in the magnitude plot (top). The \( 1/\beta \) 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 \( 1/\beta \) 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**

---

![Figure 5. Loop stability plots generated with TINA-TI™ model](image-url)
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 RX/CX network has extremely low output impedance, and its gain is essentially independent of the load impedance. The gain variation of the RX/CX 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-mVrms 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.

**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**


**Related Web sites**

TINA-TI™ simulation software: www.ti.com/tina-ti

Product information: www.ti.com/OPA1612

Subscribe to the AAJ: www.ti.com/subscribe-aaj
TI Worldwide Technical Support

Internet
TI Semiconductor Product Information Center
Home Page
support.ti.com

TI E2E™ Community Home Page
e2e.ti.com

Product Information Centers

**Americas**
- **Phone**: +1(512) 434-1560
- **Brazil**: Phone 0800-891-2616
- **Mexico**: Phone 0800-670-7544
- **Fax**: +1(972) 927-6377
- **Internet/Email**: support.ti.com/sc/pic/americas.htm

**Europe, Middle East, and Africa**
- **Phone**:
  - European Free Call 00800-ASK-TEXAS (00800 275 83927)
  - International +49 (0) 8161 80 2121
  - Russian Support +7 (4) 95 98 10 701
- **Fax**: +(49) (0) 8161 80 2045
- **Internet**
  - www.ti.com/asktexas
- **Direct Email**: asktexas@ti.com

**Asia**
- **Phone**:
  - **Toll-Free Number**
    - Australia 1-800-999-084
    - China 800-820-8682
    - Hong Kong 800-96-5941
    - India 00-800-100-8888
    - Indonesia 001-803-8861-1006
    - Korea 080-551-2804
    - Malaysia 1-800-80-3973
    - New Zealand 0800-446-934
    - Philippines 1-800-765-7404
    - Singapore 800-886-1028
    - Taiwan 0800-006800
    - Thailand 001-800-886-0010
- **International**: +86-21-23073444
- **Fax**: +86-21-23073686
- **Email**: tiasia@ti.com or ti-china@ti.com
- **Internet**: support.ti.com/sc/pic/asia.htm

**Important Notice**: The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI’s standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer’s applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company’s products or services does not constitute TI’s approval, warranty or endorsement thereof.

© 2015 Texas Instruments Incorporated. All rights reserved.

E2E and TINA-TI are trademarks of Texas Instruments. All other trademarks are the property of their respective owners.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products

<table>
<thead>
<tr>
<th>Audio</th>
<th><a href="http://www.ti.com/audio">www.ti.com/audio</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
</tr>
<tr>
<td>Data Converters</td>
<td>dataconverter.ti.com</td>
</tr>
<tr>
<td>DLP® Products</td>
<td><a href="http://www.dlp.com">www.dlp.com</a></td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td><a href="http://www.ti.com/clocks">www.ti.com/clocks</a></td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
</tr>
</tbody>
</table>

Applications

| Automotive and Transportation | www.ti.com/automotive |
| Communications and Telecom | www.ti.com/communications |
| Computers and Peripherals | www.ti.com/computers |
| Consumer Electronics | www.ti.com/consumer-apps |
| Energy and Lighting | www.ti.com/energy |
| Industrial | www.ti.com/industrial |
| Medical | www.ti.com/medical |
| Security | www.ti.com/security |
| Space, Avionics and Defense | www.ti.com/space-avionics-defense |
| Video and Imaging | www.ti.com/video |
| TI E2E Community | e2e.ti.com |

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2015, Texas Instruments Incorporated