A Low-Cost, Single Coupling Capacitor Configuration for Stereo Headphone Amplifiers

Shawn Workman *AAP Precision Analog*

ABSTRACT

This application report compares two possible blocking or coupling capacitor configurations for stereo headphone amplifiers operating from a single supply voltage. The report demonstrates that the standard two-capacitor configuration can be replaced by a single-capacitor configuration with little or no perceivable difference in sound quality. The primary advantage of a single-capacitor system is that only one large capacitor is required. In many compact multimedia systems like those in personal digital audio players, wireless phones, and personal digital assistants (PDA), these capacitors can be the largest components on the board. Therefore, eliminating one of the bulky coupling capacitors reduces cost and minimizes the area needed on the circuit board.

Contents

List of Figures

List of Tables

Effect of Coupling Capacitors

Stereo audio power amplifiers often drive headphone and line outputs. Modern multimedia systems typically use a single power supply. The output of the amplifier must then be biased to half of the supply voltage, or midrail, to prevent the negative side of the audio signal from being clipped. Most headphone jacks are standard three-terminal types that use ground as the common for the two channels as shown in Figure 1.

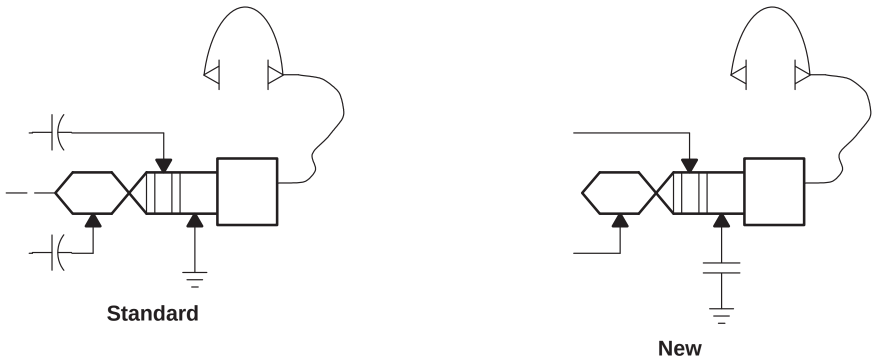

Figure 1. Standard Headphone Jacks

Connecting the headphone directly to the amplifier output without any capacitor in the path would likely damage the headphone due to dc current flow through the voice coil. Therefore, a coupling capacitor is required to block the dc offset voltage from reaching the load. These capacitors can be quite large (approximately 33 µF to 1000 µF), so they tend to be expensive, heavy, and occupy valuable circuit board area. They have the additional drawback of limiting the low-frequency performance of the system. This frequency-limiting effect is due to the high pass filter network created with the speaker impedance and the coupling capacitance. The relationship is shown in equation 1.

$$f_c = \frac{1}{2\pi R_L C_c} \tag{1}$$

For a 33-µF coupling capacitor (C_C) and a 32-Ω speaker (R_L), frequencies below 150 Hz are attenuated. Since the load impedance is typically quite small, larger values of C_C are required to pass low frequencies into the load. Table 1 summarizes the frequency response characteristics of such a configuration with a C_C of 330 µF and loads of 4 Ω, 8 Ω, 16Ω, and 32 Ω.

Table 1. Common Load Impedance vs Low Frequency Output Characteristics

R_L	C_C	LOWEST FREQUENCY
4 Ω	330 µF	120 Hz
8 Ω	330 µF	60 Hz
16 Ω	330 µF	30 Hz
32 Ω	330 µF	15 Hz

Much of the bass response is attenuated into the 4-Ω load with the 32-Ω load having the best bass response.

Coupling Capacitor Circuits

Figure 2 shows the typical approach using two coupling capacitors.

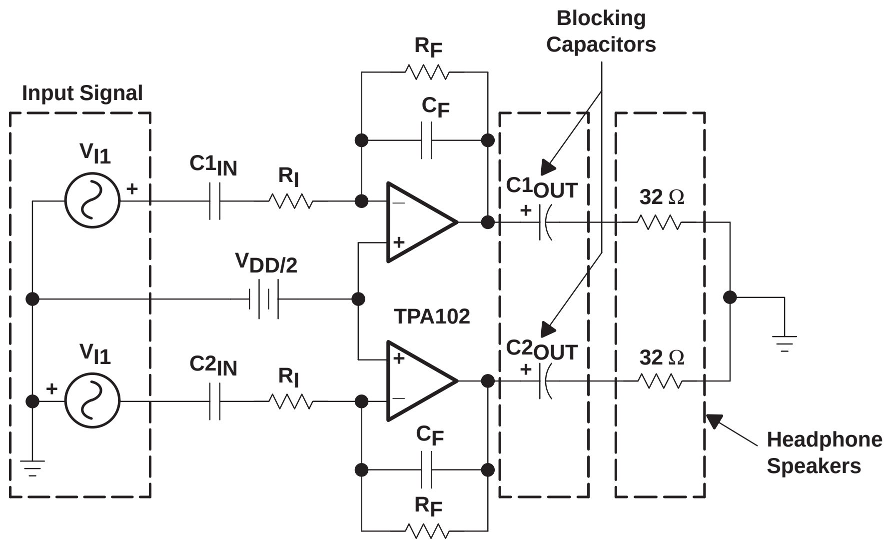

Figure 2. TPA102 Audio Amplifier-Dual Capacitor Configuration

Figure 3 shows a more desirable configuration using one capacitor. Though this is not the traditional configuration, it offers definite advantages over the two-capacitor system. Lower parts count, smaller layout area, increased reliability, and reduced costs are the most significant advantages.

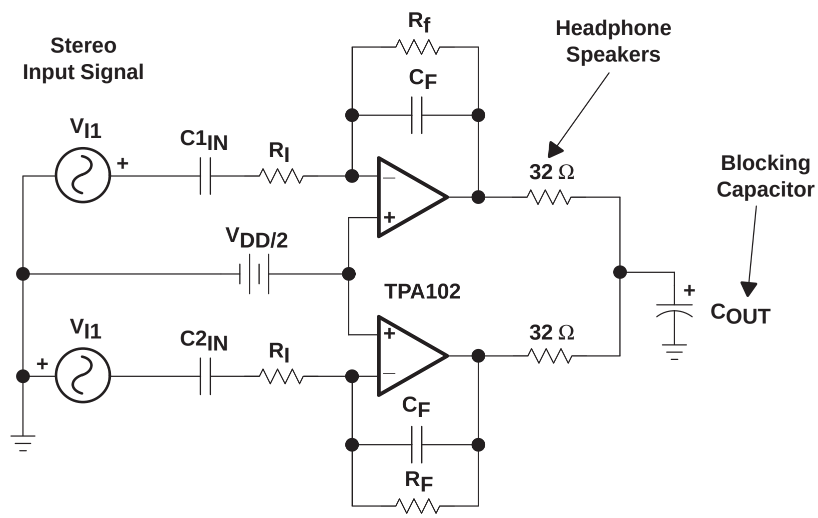

Figure 3. TPA102 Audio Amplifier-Single Capacitor Configuration

The only disadvantage of this solution is that the system exhibits a small degree of crosstalk between the two channels. To determine if the single capacitor circuit is a practical solution for a listener, the crosstalk of the single capacitor circuit must be measured. The circuit can be easily modeled as a simple RC circuit, as shown in Figure 4.

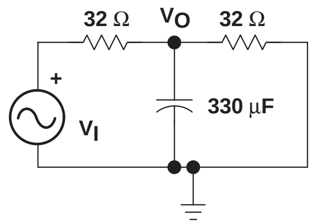

Figure 4. Single Capacitor Equivalent Circuit Model

The crosstalk is measured by driving one speaker with a source and measuring the voltage across the center leg of the circuit. This is equivalent to driving the left or right inputs of an ideal audio amplifier with a sound source and measuring the voltage response across a capacitor attached between two headphone speakers and ground. Equation 2 shows the final transfer function for the circuit.

$$\frac{V_O}{V_I} = \frac{1}{2 + s \times R \times C} \quad where\ s = j\omega \tag{2}$$

As shown in the plot of the transfer function in Figure 5, there will be less crosstalk at higher frequencies. This is because the single capacitor acts as an ac ground and naturally performs this function better at higher frequencies.

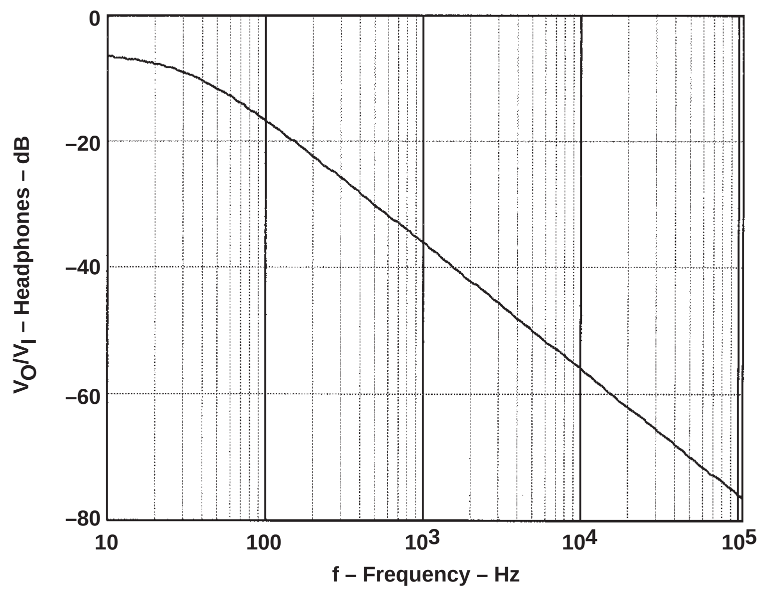

Figure 5. Crosstalk vs Frequency for a 32-Ω-Load and a Single 330-μF-Coupling Capacitor

As shown in the plot, the crosstalk is approximately –6 dB at 20 Hz and decreases to approximately –60 dB at 20 kHz with a 32-Ω load, which is typical for a set of headphones.

For a line level load, which is typically 10 kΩ, the crosstalk is essentially nonexistent as shown in Figure 6.

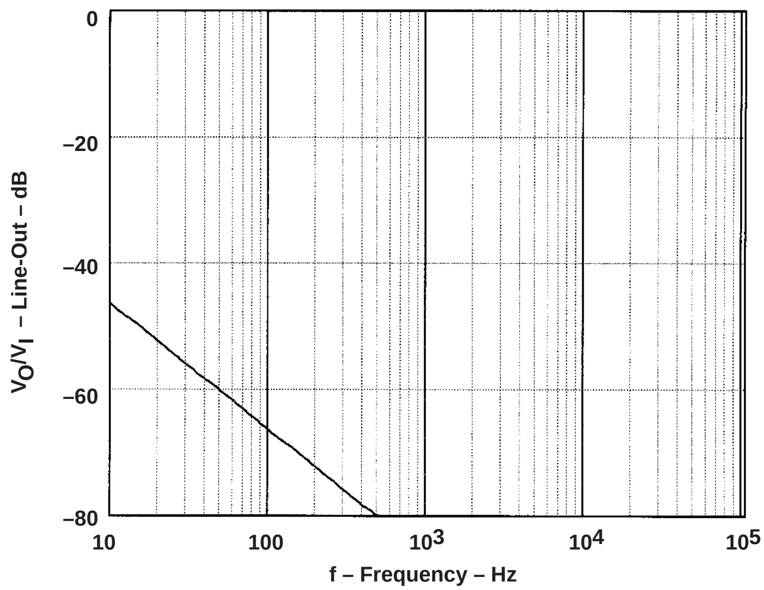

Figure 6. Crosstalk vs Frequency for a 10-kΩ-Load and a Single 330-µF-Coupling Capacitor

Effect of Crosstalk on Sound Quality

A listener's perception of sound quality is subjective and difficult to quantify. There are many factors that affect the perception of sound, but the most significant one is the nature of the ear itself. The ear is a nonlinear device and, as a result, tones interact with each other and are not perceived separately. Several of these interactive effects work in favor of the listener to help diminish the effect of crosstalk.

One such interaction effect is called masking. When listening through headphones, the ear interprets the loudest sounds and masks out the softer sounds. The crosstalk may be perceivable in each separate channel but when both ears are listening, it becomes difficult to distinguish crosstalk due to the ear's natural ability to tune in to the loudest tones.

The frequency, or pitch, of a sound also affects the way the ear detects that sound. Equation 3 shows the relationship between the frequency and the wavelength of a sound wave, where the velocity of sound in air, **c**, is approximately 345 m/s, or 1131 ft/s, at normal room temperature, and frequency is in hertz.

$$c = f\lambda \tag{3}$$

From equation 3, it can be shown that for a low-frequency tone at 400 Hz, the wavelength is 2.8 feet, which is significantly longer than the distance between a listener's ears. Both ears would therefore perceive the sound at the same time. Since the brain primarily uses any time delay between the perception of a sound by each ear to locate the source of that sound, a listener has difficulty in associating the point of origin of a low-frequency sound. It is this difficulty that allows a woofer or subwoofer to be placed anywhere in a room.

By the same token, however, the ear is much better at determining the origin of mid- and high-frequency sounds. From equation 3, it can be shown that for a mid-to-high-frequency tone of 5 kHz, the wavelength is approximately 0.22 feet or 2.7 inches, which is significantly shorter than the distance between a listener's ears. The brain is then able to perceive a sound wave arriving at one ear before reaching the other, which allows the listener to deduce the direction of the sound source. It is due to this ability that the small satellite loudspeakers in a surround-sound system are typically pointed toward where the listener would usually sit.

A low-frequency crosstalk attenuation of –6 dB may at first seem unacceptable. However, the –6 dB of attenuation is at low frequencies ranging from 0 Hz to about 50 Hz, but it then decreases by about 20 dB per decade. For good stereo separation or imaging, a minimum of –15 dB of crosstalk attenuation is necessary. As shown in Figure 5, in the mid-range audio frequencies where stereo separation becomes perceivable by a listener wearing headphones, the attenuation ranges from approximately –20 dB to around –40 dB. At high frequencies, the cross-talk attenuation is on the order of –60 dB.

Test Measurements

The TPA102 EVM (literature number SLOP125) module was used to perform crosstalk tests using a 1/8″ stereo headphone jack connected to the V_{O1} and V_{O2} output pins with a single 220-μF capacitor connected between the jack and EVM ground pin as shown in Figure 7. The first test setup used a function generator connected to IN2 to generate a sinusoidal input that was manually varied from 20 Hz to 20000 Hz. The output was measured across the capacitor with a 50-Ω resistor to ground used as the load on output channel that was used because the scope probe on the spectrum analyzer had a 50-Ω termination.

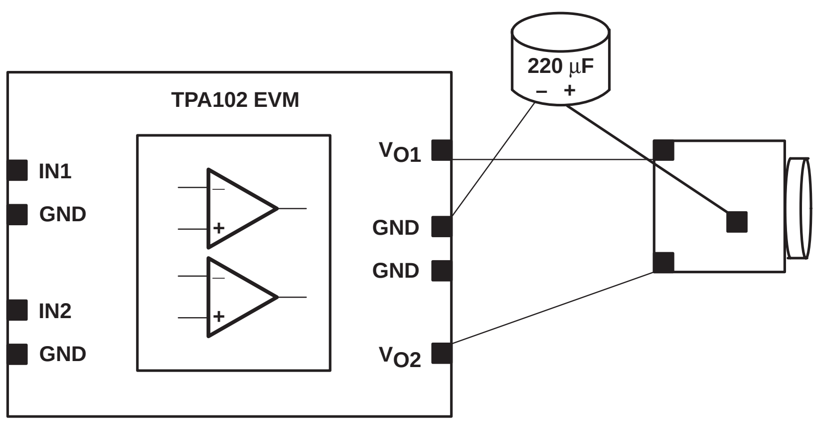

Figure 7. Lab Setup for the TPA102 EVM

As can be seen from Figure 8, the crosstalk diminishes with increasing frequency and can be dismissed at lower frequencies.

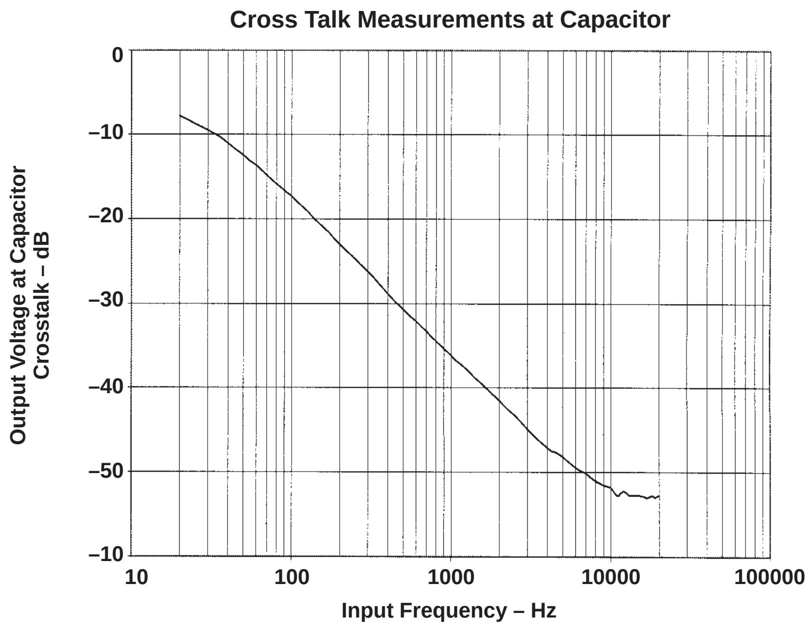

Figure 8. Crosstalk Measurement of Single Capacitor Configuration

Selecting the Single Coupling Capacitor

In the two-capacitor circuit, each capacitor must withstand the ripple current of the full audio signal from one channel. If an amplifier is able to produce 5-V peaks with a 32-Ω load on each channel, each capacitor must be able to pass approximately 150 mA of ripple current. In the single capacitor circuit, the capacitor must withstand the ripple current from both channels, as that capacitor is now the only path to ground for both audio signals. Using the same amplifier and loading as previously mentioned, the capacitor must be able to pass approximately 300 mA of ripple current. This **must** be considered when selecting the coupling capacitors, regardless of the configuration, to prevent the components from failing. However, if the amplifier is used to drive a line-level load, typically 10 kΩ, the amount of current through the capacitor decreases by two orders of magnitude, which significantly reduces the ripple current requirement.

Summary

Since the human ear cannot perceive the low-frequency crosstalk present in the single capacitor configuration, the advantages of cost savings and decreased board area far outweigh the sole disadvantage of low-frequency crosstalk. Solutions that provide headphone amplifiers in notebook computers, personal digital audio players, wireless phones, and personal digital assistants (PDA), for example, would benefit from both the cost savings and the decreased board space required. Furthermore, if the amplifier is used to drive a line-level load, the crosstalk becomes completely insignificant. Care must also be taken when choosing the coupling capacitor to allow for the maximum amount of ripple current that could appear across the component.

IMPORTANT NOTICE

Texas Instruments and its subsidiaries (TI) reserve the right to make changes to their products or to discontinue any product or service without notice, and advise customers to obtain the latest version of relevant information to verify, before placing orders, that information being relied on is current and complete. All products are sold subject to the terms and conditions of sale supplied at the time of order acknowledgement, including those pertaining to warranty, patent infringement, and limitation of liability.

TI warrants performance of its semiconductor products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are utilized to the extent TI deems necessary to support this warranty. Specific testing of all parameters of each device is not necessarily performed, except those mandated by government requirements.

CERTAIN APPLICATIONS USING SEMICONDUCTOR PRODUCTS MAY INVOLVE POTENTIAL RISKS OF DEATH, PERSONAL INJURY, OR SEVERE PROPERTY OR ENVIRONMENTAL DAMAGE ("CRITICAL APPLICATIONS"). TI SEMICONDUCTOR PRODUCTS ARE NOT DESIGNED, AUTHORIZED, OR WARRANTED TO BE SUITABLE FOR USE IN LIFE-SUPPORT DEVICES OR SYSTEMS OR OTHER CRITICAL APPLICATIONS. INCLUSION OF TI PRODUCTS IN SUCH APPLICATIONS IS UNDERSTOOD TO BE FULLY AT THE CUSTOMER'S RISK.

In order to minimize risks associated with the customer's applications, adequate design and operating safeguards must be provided by the customer to minimize inherent or procedural hazards.

TI assumes no liability for applications assistance or customer product design. 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 of TI covering or relating to any combination, machine, or process in which such semiconductor products or services might be or are used. TI's publication of information regarding any third party's products or services does not constitute TI's approval, warranty or endorsement thereof.

Copyright © 1999, Texas Instruments Incorporated