

Selecting Capacitors to Minimize Distortion in Audio Applications

Zak Kaye

Applications Engineer, Precision Analog-to-Digital Converters

Introduction

The use of capacitors in an audio signal chain is often fraught with mysticism and little quantitative analysis to justify capacitor selection. With many capacitors costing more than the integrated circuits they serve, it is a challenge to determine a solution that balances cost, size and performance.

This article offers a brief overview of capacitor technology and compares the use of various capacitors in a real-world audio application. The capacitors in this comparison are configured to AC-couple the inputs of a precision audio data converter. Analysis of the data converter output provides an easy way to compare capacitor contributions to signal-path distortion. The goal is to help you make informed decisions about capacitor selection in audio signal-chain applications.

Capacitor Technologies

Multilayer ceramic capacitors (MLCCs) are immensely popular in many applications because of their volumetric efficiency and relatively low price. The advantage of this capacitor technology lies primarily in its use of special dielectric materials. To understand why, recall that the capacitance of a simple parallel-plate capacitor follows **Equation 1**.

$$C = \frac{k\epsilon_0 A}{d} \quad (1)$$

where k is the relative permittivity of the dielectric material placed between the plates (otherwise known as the dielectric constant), ϵ_0 is the permittivity of free space, A is the area of the capacitor plates and d is the distance between the plates.

Equation 1 shows that materials with higher dielectric constants enable smaller capacitor volumes for a given capacitance value. This accounts for the large variations in the size of a 10- μ F capacitor with a particular voltage rating, since it all depends on the capacitor dielectric.

MLCC capacitors are organized into different classes depending primarily on their thermal range and stability over that range. Class II ceramics are often referred to as “high k ” because their relative permittivities range from 3,000 (X7R) up to 18,000 (Z5U). By contrast, Class I COG/NP0 capacitors tend to have relative permittivities in the range of 6 to 200. They are “high-performance” ceramic capacitors because their capacitance is more stable than most other dielectrics.

Plastic film capacitors that use materials like polyethylene or polypropylene tend to have even lower relative permittivities, typically less than 3, and also offer very good stability. **Table 1** shows the relative permittivity of some common dielectric materials used in capacitors.

Material	ϵ_r (k)
Vacuum	1
Polyethylene sulfide	3
Polyethylene terephthalate	3.3
Polypropylene	2.2
Impregnated paper	2 to 6
Mylar	3.1
Mica	6.8
Aluminum oxide	8.5
Tantalum pentoxide	27.7
Paraelectric ceramics (Class I)	5 to 90
Strontium titanate	310
Barium titanate (Class II)	3,000 to 8,000

Table 1. Relative Permittivity of Common Dielectric Materials

In portable electronics like smart speakers,^[1] it is tempting to use high-k MLCCs due to their small size and low cost. It is important to remember, though, that while their relative permittivity is very high, their capacitance changes significantly over applied voltage and temperature, which can degrade signal-chain performance. This variation in capacitance is primarily due to the use of heavy concentrations of barium titanate in the dielectric. Barium titanate is ferroelectric in nature, which means that increasing the electric field intensity inside the material decreases its relative permittivity. According to **Equation 1**, this will also lead to a decrease in capacitance. Thus, applying a time-varying voltage to the capacitor results in a time-varying capacitance, distorting the current flowing through the capacitor. The change in capacitance with applied voltage is known as the capacitor's voltage coefficient, and it can be the dominant source of distortion in the low-frequency spectrum where capacitor impedance is relatively high. Furthermore, as the signal amplitude increases, greater distortion occurs. At higher frequencies, the distortion is less noticeable due to lower capacitor impedance, leading to a negligible voltage drop across the capacitor.

Minimizing Distortion with MLCCs

Minimizing the voltage drop across the capacitor will mitigate distortion. One approach to do this is to increase the impedance in series with the capacitor to limit the current flowing through it. To demonstrate this, total harmonic distortion-plus-noise (THD+N) measurements were taken on the Texas Instruments TLV320ADC5140 audio analog-to-digital converter (ADC) evaluation module (EVM),^[2] with 4.7- μ F X7R 0805 AC-coupling capacitors on the input. This ADC has a programmable input impedance that can be set to 2.5 k Ω , 10 k Ω or 20 k Ω . **Figure 1** shows the results from a single channel with this capacitor while varying the input impedance with a 1- V_{RMS} input signal.

Figure 1 shows that distortion increases at lower frequencies and peaks at the -3-dB cutoff frequency of the high-pass filter formed by the capacitor and the

ADC input impedance. This is because the -3-dB point is where capacitor impedance equals the load impedance, which is when the voltage across the capacitor is highest. For cases with a 2.5-k Ω input impedance, the cutoff frequency is around 13 Hz, but the distortion starts much further out—around 400 Hz—and peaks around 13 Hz.

As expected, the change in distortion scales fairly linearly with increasing impedance. The drawback of this approach is that increasing the device's input impedance degrades the signal-to-noise ratio performance by a few decibels. Moreover, adding series resistance externally also leads to additional noise and increases the gain error. The added gain error increases system complexity, since it may require calibration. For cost- or area-sensitive designs, increasing the impedance may work fairly well, but performance-focused designs will suffer with this approach.

Another option is to increase the value of the capacitor until its impedance is low enough in the band of interest to reduce its distortion. **Figure 2** shows the change in distortion over frequency, while **Figure 3** shows the change in distortion over input amplitude as a result of varying the input capacitance for similarly rated capacitors. Note that the 47- μ F capacitor tested was in a 1206 package, and increasing the package size will also tend to slightly reduce distortion. However, the dominant effect is still the dramatic increase in capacitance.

The data in **Figure 3**, taken with a 100-Hz input signal, shows that increasing the capacitance works fairly well for AC-coupling applications. MLCCs with capacitances greater than 47 μ F are readily available in 0805 or 1206 packages.

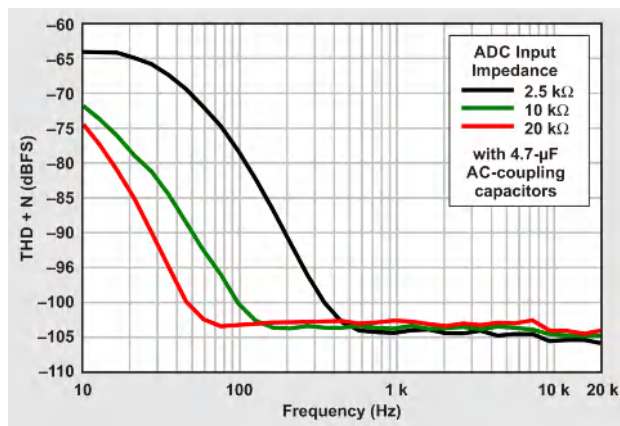


Figure 1. THD + N Variation with ADC Input Impedance

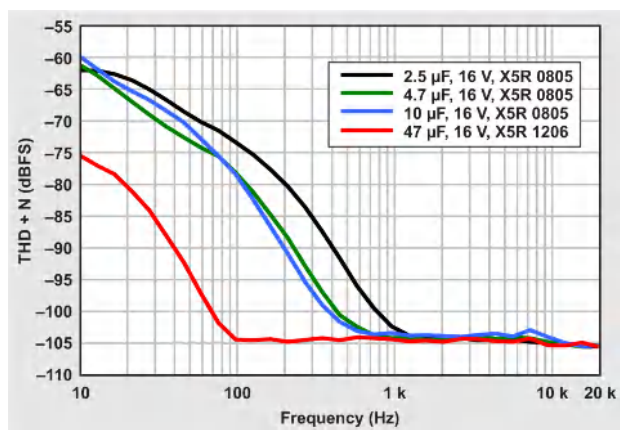


Figure 2. THD + N Variation with AC Coupling Capacitance

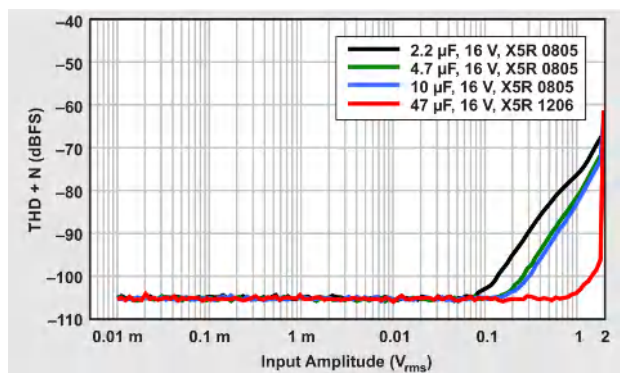


Figure 3. THD + N Variation with 100-Hz ADC Input Signal

Both of the approaches to mitigating distortion involve significantly reducing the cutoff frequency of the high-pass filter, either by increasing resistance or increasing capacitance. When using MLCCs for AC coupling, a good rule of thumb is to place the corner frequency two decades away from the specified passband. Or, worded differently, make the capacitor 100-times larger

than needed or as large as can be reasonably supported. When using excessively large capacitors, even small amounts of series resistance will result in very low cutoff frequencies. This means that undesirable low-frequency noise, such as the typical $1/f$ noise of a complementary metal-oxide semiconductor front end, will not be filtered. Applying digital filtering further down the signal chain will suppress typical $1/f$ noise. However, it is still difficult to completely eliminate the influence of the ceramic capacitor in the bass region of the audio band. Applications demanding high performance will still benefit from the use of better technologies.

In many audio applications such as analog filter design, the preferred solution is to use C0G/NP0 ceramic capacitors because they have much better performance and are still available in small packages. While this is a great solution, it is not always feasible. In audio signal chains, keeping resistances low minimizes noise, but doing so requires increased capacitance for a given cutoff frequency. C0G/NP0 capacitors are not easily found in values greater than $1\ \mu\text{F}$, so they have limited utility in AC-coupling and other high-pass filter applications.

Nonceramic Capacitors

For applications where the use of MLCCs must be avoided, other capacitor technologies exist. THD+N tests were also performed using the TLV320ADC6140 EVM^[3] with these capacitor types:

- A standard $1\text{-}\mu\text{F}$ 0805 X5R capacitor.
- $1\text{-}\mu\text{F}$ surface-mount-technology (SMT) tantalum capacitor.
- $1\text{-}\mu\text{F}$ through-hole aluminum electrolytic capacitor.
- A $1\text{-}\mu\text{F}$ SMT film capacitor.

Figure 4 shows the data from this testing. As expected, the $1\text{-}\mu\text{F}$ SMT film capacitor offers the best performance over the full audio bandwidth, with the electrolytic capacitor as a runner-up. The film capacitor is available in a 1206 surface-mount package with a metallized acrylic dielectric and a 12-V rating.

When tested, other 1-μF film capacitors with polyester and polypropylene dielectrics and higher voltage ratings did not significantly deviate from the performance shown in **Figure 4**. The main drawback of film capacitors is their low relative permittivity. Thus, film capacitors tend to be much larger than their MLCC counterparts.

At the time of publication, the 1206 capacitor used in this testing was the smallest surface-mount 1-μF film capacitor readily available. Surface-mount values greater than 3.3 μF will require an 1810 package or larger, or traditional through-hole box-type packages.

On the other hand, tantalum and aluminum electrolytic capacitors tend to be smaller than film. Electrolytic capacitors have polarized dielectrics, meaning their anode must be kept at a higher voltage than the cathode or else the capacitor may be damaged. Taking two sets of measurements for these capacitors demonstrates the electrolytic effect. The first test applied a +5-V DC bias to the capacitors to ensure proper polarity. The second test applied no external bias, but the TLV320ADC6140 used for testing internally biases its inputs to 1.5 V, so these capacitors were actually slightly reverse-biased. Because of this internal bias, +6.5 V was provided at the input of the evaluation module for the +5-V test case. Comparing the two sets of data shows a significant difference in performance when polarized capacitors are not properly biased. High-performance applications must guarantee a positive DC bias or avoid the use of polarized capacitors for AC coupling.

This testing is not exhaustive; it is only designed to offer some high-level insights into the performance of different capacitor technologies. Many factors influence capacitor performance, and capacitors should be chosen carefully based on application needs. There is much debate in the audio community about the best metric to use for a capacitor. This article focuses on how differences in capacitors affect distortion in a real application.

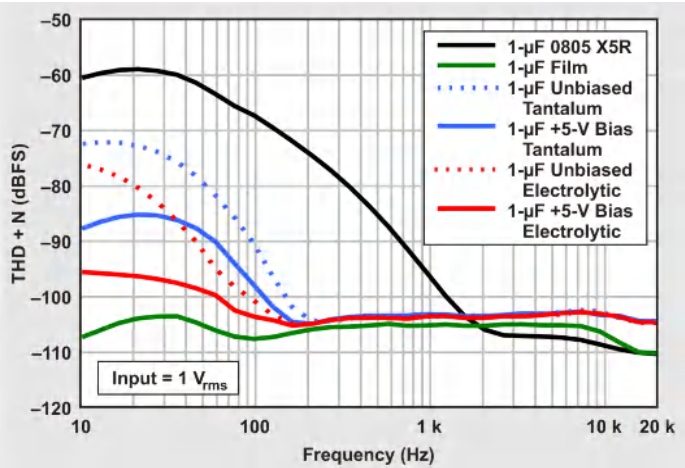


Figure 4. THD + N Variation with Non-ceramic Capacitors

Figure 5 shows the boards used for testing and **Table 2** shows all of the capacitors included in this testing and their respective characteristics.

Number	Type	Value	Voltage	Package
1	Ceramic X5R	2.2 μF	16 V	0805
2	Ceramic X5R	4.7 μF	16 V	0805
3	Ceramic X5R	10 μF	16 V	0805
4	Ceramic X5R	47 μF	6.3 V	1206
5	Ceramic X5R	1 μF	16 V	0805
6	Metal film	1 μF	12 V	1206
7	Tantalum	1 μF	35 V	1206
8	Aluminum electrolytic	1 μF	50 V	Radial through-hole
Not shown	Orange drop film	1 μF	100 V	Radial through-hole
Not shown	WIMA film	1 μF	50 V	Box
Not shown	Ceramic X7R	4.7 μF	16 V	0805

Table 2. Capacitors Used in Distortion Comparison

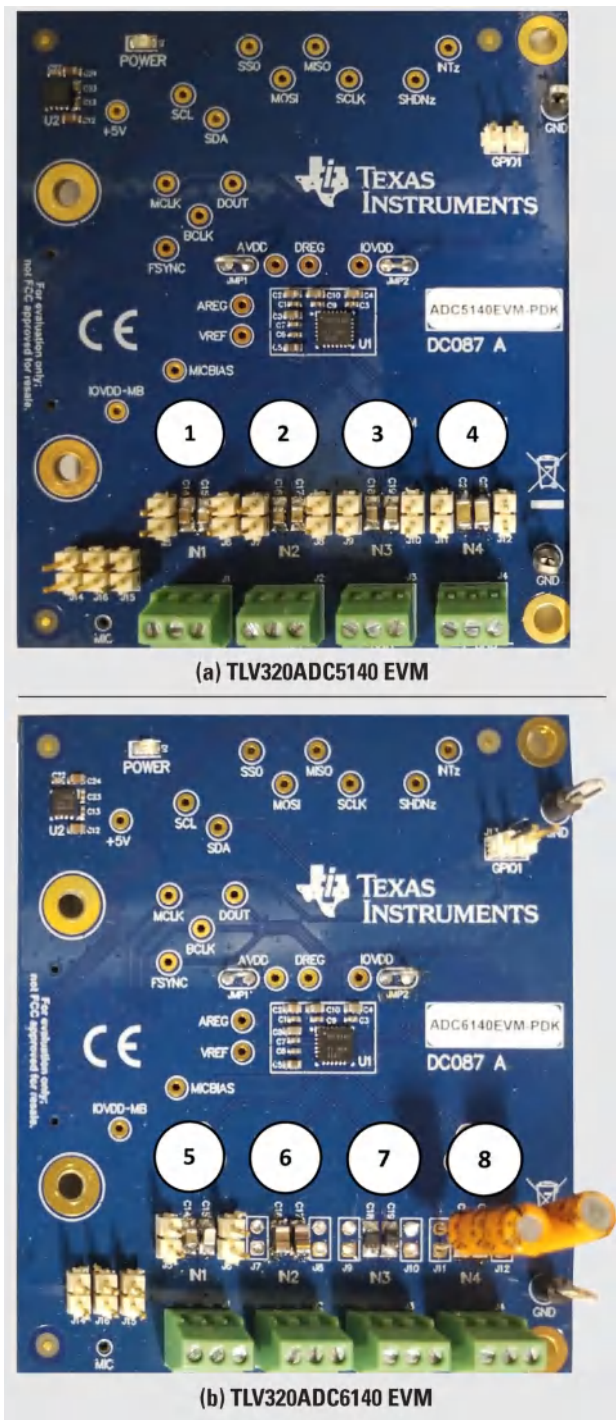


Figure 5. Evaluation Modules and Tested Capacitors

Conclusion

A lot of considerations go into capacitor selection. This article focused primarily on capacitors in AC-coupling applications for audio data converters, but the data presented is applicable to other applications as well. MLCC capacitors are very popular, but they can significantly degrade the performance of an audio signal chain. It is possible to minimize the distortion from MLCC capacitors by using larger-value capacitors and increasing the load impedance that the capacitor sees. For high-performance applications, use C0G/NP0 capacitors when available and film capacitors when practical.

References

1. [Smart speaker integrated circuits and reference designs, Texas Instruments.](#)
2. [TLV320ADC5140 quad-channel 768-kHz Burr-Brown™ audio ADC evaluation module, Texas Instruments \(ADC5140EVM-PDK\).](#)
3. [TLV320ADC6140 evaluation module, Texas Instruments \(ADC6140EVM-PDK\).](#)
4. J. Caldwell, "Signal distortion from high-K ceramic capacitors," EDN, June 16, 2013.
5. J. Caldwell, "More about understanding the distortion mechanism of high-K MLCCs," EE News, December 23, 2013.
6. Kemet Corp., "Introduction to Capacitor Technologies," 2013.

Related Web Sites

Product Information:

[TLV320ADC5140](#)

[TLV320ADC6140](#)

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.

All trademarks are the property of their respective owners.

© 2020 Texas Instruments Incorporated

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATA SHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES "AS IS" AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, regulatory or other requirements.

These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI's products are provided subject to [TI's Terms of Sale](#) or other applicable terms available either on [ti.com](#) or provided in conjunction with such TI products. TI's provision of these resources does not expand or otherwise alter TI's applicable warranties or warranty disclaimers for TI products.

TI objects to and rejects any additional or different terms you may have proposed.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2023, Texas Instruments Incorporated