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Choose capacitor types to optimize PC sound quality

A KEY CHALLENGE TO DESIGNERS OF AUDIO SUBSYSTEMS THAT MUST CONFORM TO WINDOWS VISTA REQUIREMENTS MAY BE CHOOSING COUPLING CAPACITORS. THESE DEVICES' CAPACITANCE VARIES WITH THE VOLTAGE ACROSS THEM AND INTRODUCES AUDIO DISTORTION. TO MINIMIZE THE EFFECT, START BY UNDERSTANDING THE INTERACTIONS AMONG THE DIELECTRIC MATERIAL, VOLTAGE RATING, DEVICE SIZE, AND VOLTAGE COEFFICIENT. THEN, GET READY TO MAKE TRADE-OFFS.

Microsoft's (www.microsoft.com) next-generation client operating system—now officially known as Windows Vista—is enhancing desktop- and notebook-PC audio quality and fidelity. Hardware manufacturers must meet strict audio-performance requirements to license the Windows Vista logo. Microsoft bases these requirements on audio-performance specifications, such as the THD+N (total harmonic distortion plus noise), dynamic range, and crosstalk. Generally, designers think of audio amplifiers as the limiting factor in performance specifications, such as THD+N. However, passive components in the signal path can introduce THD that contributes significantly to system-level distortion.

Passive components are critical to a successful audio design; they define gain, provide biasing, reject power-supply noise, and establish dc blocking between stages. Unfortunately, portable audio devices' space, height, and cost restrictions force the use of passive components with small footprints, low profiles, and low cost. Failure to understand the nonlinearity associated with these small, low-cost, passive components can affect Vista compliance (**Reference 1**).

Voltage coefficient, temperature coefficient, piezoelectric effect, equivalent-series resistance, equivalent-series inductance, leakage current, dielectric absorption, and tolerance describe how a capacitor's behavior deviates from ideal. The terms most important to understand when you design a signal path for premium audio performance are voltage coefficient and converse piezoelectric effect, which is the main contributor to voltage coefficient.

PIEZOELECTRIC EFFECT

The piezoelectric effect is a property of certain crystals that acquire electrical charges under mechanical loading. The effect originates from the displacement of ionic charges within the crystal structure. Without a mechanical load, the crystal structure is symmetric, and the resulting electric dipole moment is zero. When you apply a mechanical load, the charge distribution is no longer symmetric, and a net polarization results.

The converse piezoelectric effect is the situation in reverse: A change in the applied electric field causes a change of mechanical dimension. Large K-factor capacitors, such as those with Class 2 dielectrics, have a discernible converse piezoelectric effect in which applying an electrical signal causes a change in the capacitor's mechanical dimension. As the applied signal's amplitude increases, the capacitor's physical deformation increases, causing the capacitor's rated electrical value to change. When you place the capacitor at an audio amplifier's input to establish dc blocking between the codec and the amplifier (**Figure 1**), the capacitor's varying electrical value causes a nonlinear, signal-dependent change in the amplifier's transfer function: $T(j\omega)=K/(1-j(\omega_o/\omega))$, where $K=R_F/R_{IN}$ and $\omega_o=1/(R_{IN}C_{IN})$. The circuit's magnitude response, $|T(j\omega)|$, equals $|K|/\sqrt{(1+(\omega_o/\omega)^2)}$. A nonlinear change of capacitor impedance $(1/j\omega C_{IN})$ tends to dominate at low frequencies at which the impedance is significant in defining the gain. This phenomenon translates into audio distortion.

This converse piezoelectric effect is by far the most significant cause of increased distortion at lower audio-band frequencies (**Figure 2**). The effect is maximized at the −3-dB bandwidth, at which the input coupling capacitor's impedance magnitude equals that of the audio amplifier, or $f_{-3dB}=1/(2\pi R_{IN}C_{IN})$. Given the typical values for an audio amplifier's

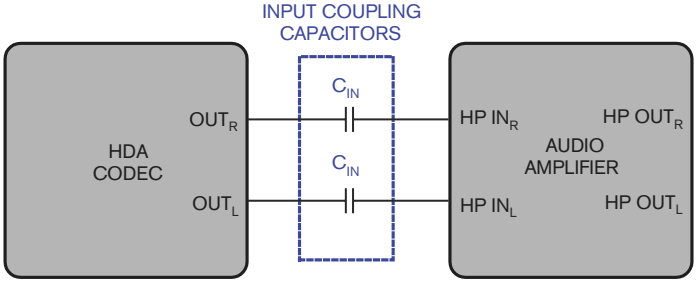


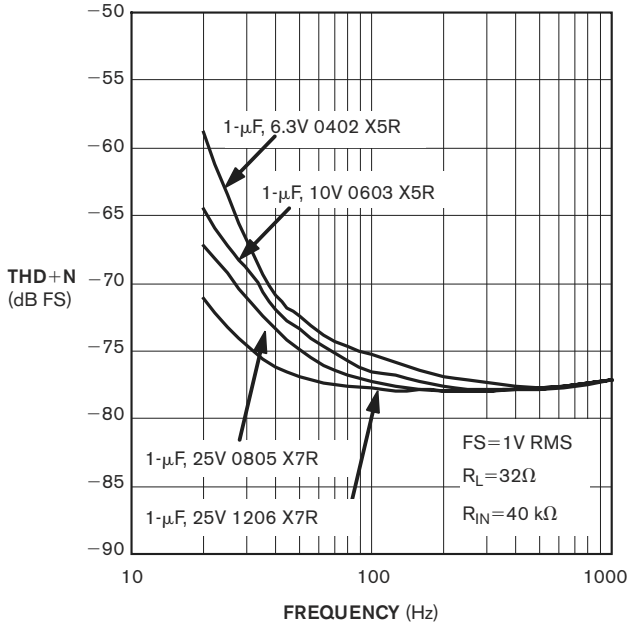
Figure 1 Input coupling capacitors establish dc blocking between the HDA (high-definition-audio) codec and the audio amplifier.

input resistance and input coupling capacitor, −3-dB bandwidth is generally less than or equal to 100 Hz.

In Class 2 low-dielectric capacitors, the converse piezoelectric effect is the major contributor to voltage coefficient—the term that describes how applied voltage affects a component's value. These capacitors react differently depending on whether you apply a changing (ac) voltage or a constant (dc) bias.

Figure 3 illustrates the typical effect of applying dc voltage to various 1-µF capacitors. This dc-voltage value is typical for ac-coupling capacitors at amplifier inputs in PC applications. Applying increasing positive (or negative) dc voltage to Class 2 dielectric materials decreases the capacitor's value. This article does not discuss the mechanics or physics that underlie this phenomenon. Instead, it simply presents measurements of the effect and guides you in selecting capacitor types to optimize PC sound quality.

Although applying increasing dc voltage tends to decrease the capacitance of a Class 2 dielectric, applying an ac voltage



NOTE: FS=FULL-SCALE.

Figure 2 Input-coupling-capacitor-induced total harmonic distortion versus frequency depends on the coupling capacitor's dielectric material, voltage rating, and package size, as well as on the capacitance.

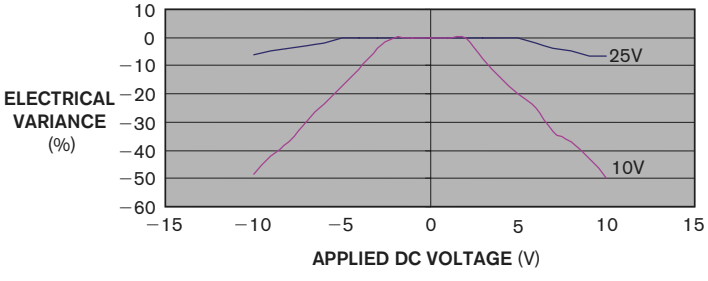


Figure 3 A smaller ceramic capacitor has a lower voltage rating than a larger unit of the same value and dielectric material. Also, a given applied dc voltage affects the smaller device's capacitance more than it does that of the larger unit. You see this effect when you compare the electrical variance with the applied dc voltage of a 1-µF±20%, 25V, X7R, 1206 ceramic capacitor with that of a 1-µF±20%, 10V, X7R, 0603 ceramic capacitor at an ambient temperature of 25°C.

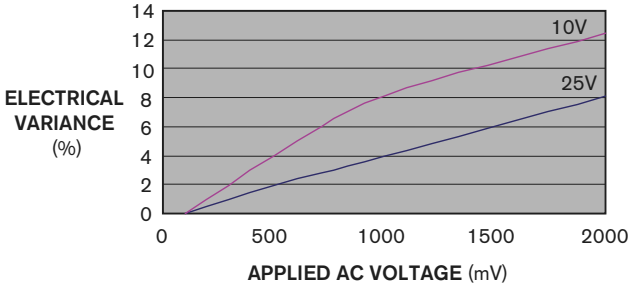
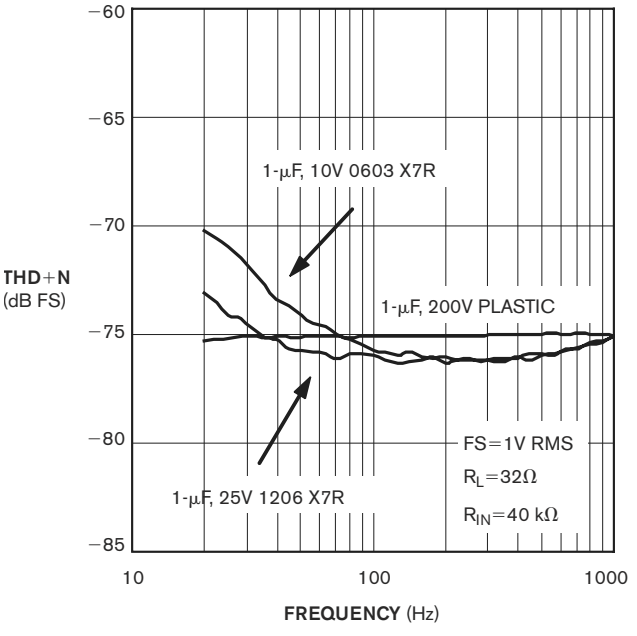


Figure 4 Increasing the amplitude of an ac signal applied to a ceramic capacitor increases the device's capacitance, as you see in these curves. The curves show electrical variance versus applied ac voltage at −3-dB bandwidth of 100 Hz of a 1-µF±20%, 25V, X7R, 1206 ceramic capacitor and a 1-µF±20%, 10V, X7R, 0603 ceramic capacitor at an ambient temperature of 25°C.



NOTE: FS=FULL-SCALE.

Figure 5 The distortion introduced by 10 and 25V, 1-µF X7R ceramic capacitors depends on the audio frequency as well as the capacitor size and voltage rating. You express the effect in terms of THD+N (total harmonic distortion plus noise), although distortion (not noise) dominates this measurement and that of Figure 6.

(within a reasonable range) tends to increase the measured capacitance (**Figure 4**). If you apply a high enough ac voltage, the capacitance will eventually decrease in the same manner as it does when you apply dc voltage. However, the high voltage required to cause this effect does not represent the voltage swings you normally find in PC-audio circuits. Therefore, the preceding analysis does not include this voltage level. **Figures 5** and **6** translate into audio performance the effect that **figures 3** and **4** illustrate.

A 1-µF, X7R-dielectric ceramic capacitor resides in series with a Maxim (www.maxim-ic.com) audio-amplifier input whose typical input impedance is 40 kΩ. The device under test varies from 10V-rated (0603 case) to 25V-rated (1206 case) units as a THD+N AP (Audio Precision, http://ap.com) sweep monitors the output distortion at frequencies less than or equal to 1 kHz. Notice the increased distortion when the setup uses the 10V-rated capacitor compared with that using the 25V-rated capacitor.

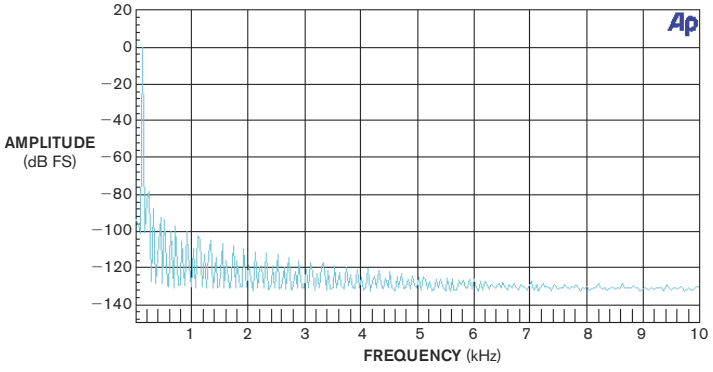


Figure 6 This FFT spectrum analysis also shows the frequency dependence of coupling-capacitor-induced distortion. Full-scale is 1V rms; input frequency is 100 Hz; and the device under test is a 1-µF, 25V, X7R ceramic capacitor (courtesy Audio Precision).

A low voltage rating (that is, high voltage coefficient) produces greater THD because the capacitor's electrical value varies more during the sinusoidal cycle. To reduce THD in the lower audio-frequency band, you must reduce the voltage coefficient of capacitance. To reduce the voltage coefficient, you should select a capacitor with a higher voltage rating. In Class 2 dielectrics, selecting a higher voltage rating is helpful when attempting to conform to Vista audio specifications. Note, however, that the capacitor's case size increases with the voltage rating. A 1-µF±20% ceramic capacitor with a 10V rating uses an 0603 case size, whereas a 1-µF±20% ceramic capacitor with a 25V rating uses a 1206 case. Regardless of the recent push for ultramobile notebook computers and ever-shrinking PCB (printed-circuit-board) area, headphone-amplifier inputs typically require large-case input-coupling capacitors to achieve Vista compliance for THD+N over the 20-Hz to 20-kHz bandwidth.

DIELECTRIC TYPE

You can regard a capacitor's dielectric type as a potential limitation on premium-THD performance. Various dielectrics affect THD differently. **Figure 7** illustrates the dc-bias depen-

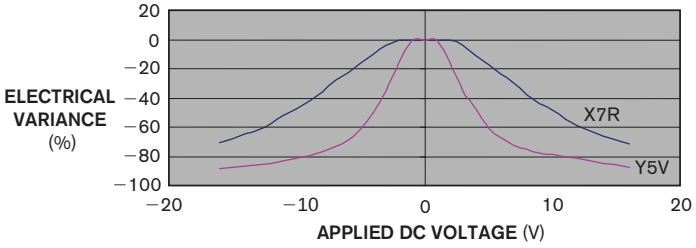


Figure 7 These curves illustrate the dc-bias dependency of two 0603-case-size capacitors with Y5V and X7R dielectrics and equal 16V ratings.

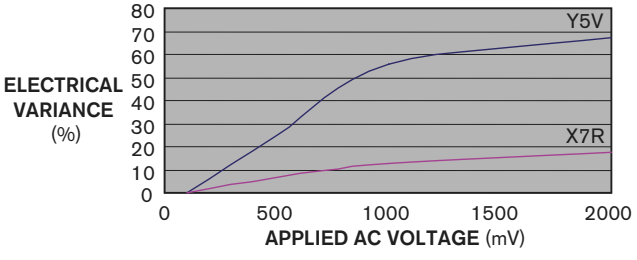


Figure 8 These curves show the variation in capacitance due to applied ac voltage for 16V-rated 0603-case-size capacitors with Y5V and X7R dielectrics.

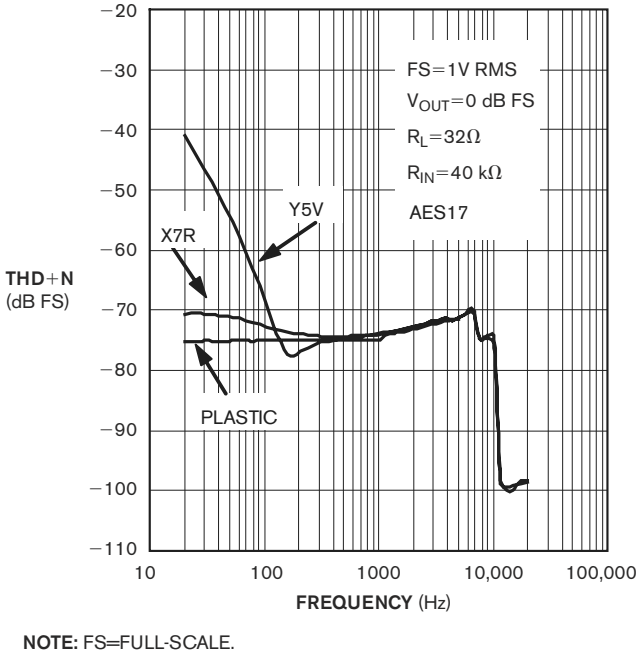


Figure 9 These curves depict the audio distortion that Y5V and X7R, 1-µF±20%, 16V, 0603-cased ceramic capacitors introduce.

MEASURING CAPACITANCE VARIATION

To obtain measurements of its capacitance variation versus applied dc voltage, connect the device under test (C_{DUT}) in series with a 1.5-kΩ±1% resistor (Figure A). C_{DUT} in series with R forms a highpass filter, allowing measurement of the capacitor's electrical value as you increase the applied dc voltage ($C_{DUT}=1/(2\pi Rf_{-3dB})$). Superimpose a 100-mV-rms ac signal on the varying dc-voltage source. Note the highpass filter's −3-dB bandwidth at each 1V-dc increment (Figure B). Vary V dc from 0V to the component's rated voltage.

Note that the resistance of series resistor R must be much greater than the audio analyzer's finite source resistance. In this case, the Audio Precision analog generator presented a 40Ω source resistance.

Also note that a 100-Hz cutoff frequency for this measurement highlights the effects of applied dc voltage above and below the −3-dB bandwidth. A 20-Hz cutoff frequency is not an appropriate choice as the analyzer measures down to only 10 Hz. Vista-Logo Program Requirements V3.09 specifies −3-dB bandwidth at 20 Hz into a 10-kΩ load. Given the −3-dB frequency and the known series-resistor value (1.5 kΩ±1%), you can extract the capacitance of C_{DUT} from Table A.

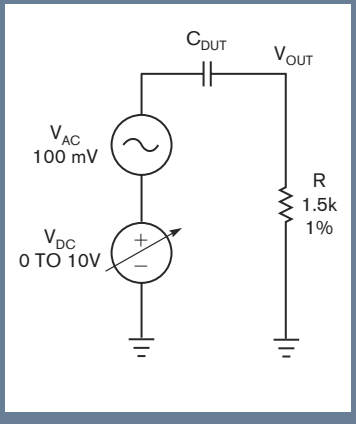


Figure A The model for the dc-test circuit consists of a variable dc-voltage source, an ac source of 100 mV rms, the capacitor under test, and a fixed resistor.

TABLE A
DEVICE-UNDER-TEST CAPACITANCE

DC-voltage applied (V)	−3-dB bandwidth (Hz)	C_{DUT} capacitance (μF)	Variance from 0V dc (%)
0	118.9	0.89	0
1	118.9	0.89	0
2	118.9	0.89	0
3	128.8	0.82	−7.7
4	138.7	0.76	−14.3
5	148.6	0.71	−20
6	158.5	0.67	−25
7	178.3	0.60	−33.3
8	188.2	0.56	−36.8
9	208	0.51	−42.8
10	237.8	0.45	−50

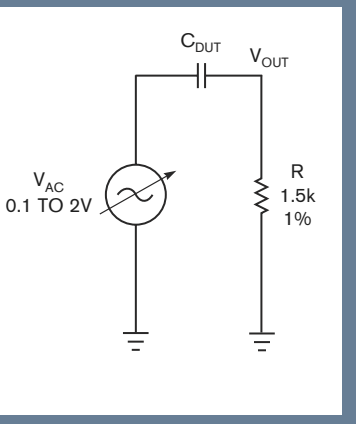


Figure C The model for the ac-test circuit is a simple series combination of a variable ac-voltage source, the capacitor under test, and a fixed resistor.

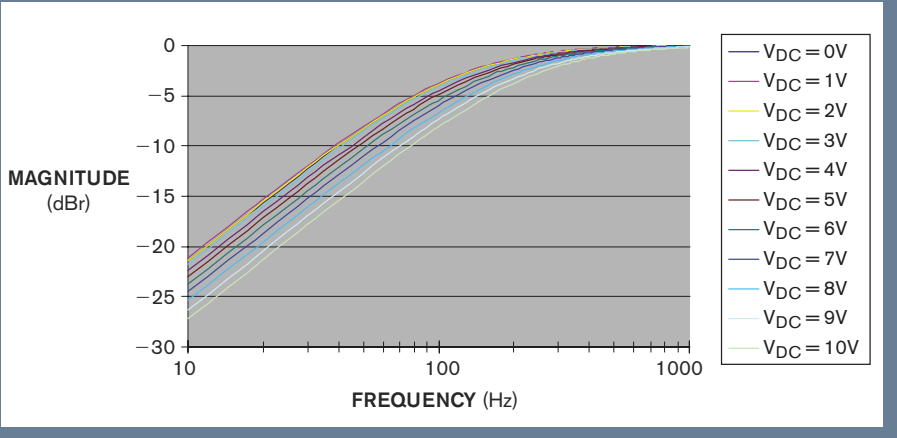


Figure B As you increase the bias voltage across the capacitor from 0 to 10V dc, the frequency response of the voltage across the resistor deteriorates–falling, at 100 Hz, from approximately 4 dB below its value at 1 kHz with zero bias to approximately 8 dB below with a 10V dc bias.

dency of two capacitors with Y5V and X7R dielectrics, both with a 16V rating in a 0603 case. The dielectric material is now solely responsible for the difference in the voltage coefficient of capacitance. The X7R dielectric shows a 65 to 70% loss at the rated voltage. The Y5V dielectric exhibits a 70 to 80% loss over the rated-voltage range. **Figure 8** shows the variation in capacitance due to applied ac voltage for capacitors with Y5V and X7R dielectrics and a 16V voltage rating in an 0603 case.

Figures 7 and **8** illustrate an effect that translates into audio performance in **Figure 9**. You quantify the effect of applied voltage in terms of THD+N. A 1-µF, 0603-case ceramic capacitor with a 16V voltage rating is in series with a Maxim audio-amplifier input whose typical input impedance is 40 kΩ. C_{DUT} varies between an X7R dielectric and a Y5V dielectric as a THD+N Audio Precision sweep monitors the output distortion at frequencies of 20 Hz to 20 kHz. Notice the increased distortion at lower frequencies with the Y5V dielectric versus the X5R dielectric. The audio amplifier's decreasing loop gain limits the circuit distortion at frequencies greater than 1 kHz. Also notice that the THD+N in **Figure 9** begins to roll off above 6.3 kHz, because of the AES-17 (Audio Engineering Society) 20-kHz filtering at the analyzer's inputs. This measurement standard implements steep filtering above 20 kHz, attenuating any third-harmonic content above an input frequency of 6.33 kHz.

When considering capacitors for the audio-signal path, select capacitors with X7R dielectrics for better THD performance. Although X5R dielectrics outperform Y5V dielectrics, X7R dielectrics offer the best—that is, lowest—THD among Class 2 dielectrics.

The space, height, and cost restrictions typically associated with portable consumer electronics force the use of passive components with small footprints, low profiles, and low cost. When you use them for audio-signal coupling, some small-footprint, low-profile, low-cost passive components can limit low-frequency THD performance in audio circuits. However, doing so compromises audio sound quality and jeopardizes Vista compliance. Despite their slight footprint and price premium, large-footprint ceramic capacitors with high voltage ratings and X7R dielectrics are the best choice for all passive components in the signal path for a Vista-compliant audio design. EDN

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REFERENCE

1 Microsoft, Windows Vista Logo Program Device Requirements, Version 3.0, www.microsoft.com/whdc/winlogo/hwrequirements.mspx#.

AUTHOR'S BIOGRAPHY

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