Digital Volume Control: DACs versus the Crystal Semiconductor CS3310

Mark J Medrud, Design Engineer
Jeff Rowland Design Group, Inc.
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Though commonly available and commonly used, four-quadrant multiplying DACs (Digital to Analog Converters) have a number of inherent problems when used as digitally controlled volume controls. The CS3310 volume control used in the Jeff Rowland Design Group Coherence II preamplifier is also digitally controlled, but shares none of these deficiencies and incorporates additional desirable features.

1) DACs employ silicon resistors in their "R-2R" ladders that are notorious for their measurable and audible distortions. This is not an issue when the DAC is used conventionally as a DAC. However, when it is used as a volume control, the audio signal passes through these non-linear silicon resistors and the signal is distorted.

2) It is the nature of a DAC type volume control that the signal passes through many of these resistors simultaneously. The signal also must pass through the many associated analog switches which have significant "ON" resistance compared to the resistors. (I.E.: 24 resistors and 24 switches for a 12-bit DAC.) In particular, the resistance of the analog switches increases when the signal amplitude approaches the power supply voltages.

3) Because a DAC’s steps of attenuation are evenly divided (linear steps), and an audio volume control must be logarithmic (dB steps), a DAC’s step-accuracy is very coarse and inaccurate at high degrees of attenuation. Conversely, a DAC must skip the huge majority of its available steps at the other end of the attenuation scale. Some form of digital logic must estimate which of the DAC’s steps come closest to the desired logarithmic volume step.

On the other hand, the designers of the CS3310 have shown extreme sensitivity to the needs of audio perfectionists. They have identified and addressed the issues most important to high-end and professional audio.

1) The CS3310 uses a special physical and electrical structure to cancel the nonlinearity of its polysilicon resistors eliminating distortion.

The depletion zone (the boundary) between the P type silicon and the N type that make up the resistor and its substrate (the supporting surroundings) grows greater in thickness as the junction is reverse biased with a signal. As the depletion zone grows thicker, two undesirable things happen: The capacitance between the resistor and substrate changes (decreases.) Of greater concern, the cross sectional area of the resistor shrinks, thereby increasing the resistance in proportion to the applied signal. This is the principle cause of silicon resistor nonlinearity.

Consider this analogy: Think of a silicon resistor as a soft rubber hose; the signal as water passing through the hose; and the outside air pressure as the reverse bias voltage. If the outside air pressure is increased, the hose is squeezed smaller and less water can flow. If the outside air pressure were to fluctuate, the water would fluctuate too, instead of flowing at the desired rate.

Crystal Semiconductor's engineers devised a method of applying the audio signal to a "well" (more like a trough, actually) of P type silicon surrounding the polysilicon resistor. The most important effect is that the potential between the resistor and its surroundings (and hence depletion layer thickness) remains roughly the same regardless of the signal level. The 16dB highest-level divider resistor wells receive the audio signal directly. The next lower 16dB wells receive the same signal, only attenuated by 16dB. Below 32dB of division, there is very little depletion width modulation, so the wells are tied directly to ground.

Back to the water hose analogy: The fluctuation in air pressure is canceled out so the water flows unmolested.

2) Though there are many analog switches attached to the CS3310's attenuator-divider chain, the signal only flows through the one selected. The divider resistors, as previously noted, are quite linear. The analog switches connect a voltage signal to the high impedance input of an amplifier – not a current signal to a low impedance. This means that even large changes in analog switch resistance have no effect on the division accuracy or signal linearity.

In a DAC, the signal has a complex, multitudinous route through many distortion inducing resistors and analog switches – but in the CS3310 the path is a simple one, through very transparent components.

3) The division ratios of the CS3310's attenuator stage are logarithmic by design, in 0.5dB steps. This means that there are no log-lin code conversions necessary; no steps wasted; plenty of volume control resolution; and the steps are precise throughout the attenuation range. Using a patented process, the size and uniformity of the polysilicon divider resistors is so accurately controlled that no trimming is necessary in production. Better than 0.05dB/step accuracy and channel matching is inherent in the process.

The main attenuator in the CS3310 covers a range of -95.5dB. The buffer amplifier that follows has a similar resistor divider in its gain-control that increases the volume control range by an additional +31.5dB. For gains of less than 0dB, the amplifier has a gain of 0dB. Above 0dB, the aplifier's gain increases as commanded.

A few astute audiophiles may note that varying volume by varying amplifier gain can be problematical. In the usual case, the frequency compensation (necessary for stability) varies greatly in proportion to changes in gain – and that can cause slight changes in sonic characteristics. The CS3310's designers have even covered that perfectionist's concern: The value of the compensation capacitor is varied with 10dB increments so that the over-all frequency compensation remains the same as the gain changes.

In the Coherence II preamplifier, two CS3310s are used – one for each channel since there are two attenuators in each CS3310. To maintain a balanced signal path throughout, one of each CS3310’s channels is used to control the inverting phase’s gain and the other channel is connected to the non-inverting phase. The precise gain matching between the CS3310’s channels yields respectable common mode rejection in addition to that provided by the Coherence’s input transformers.

There are quite a number of other remarkable design features incorporated in the CS3310. Please consult the data sheet for more detail, but the most interesting ones are: Zero-cross attenuator stepping to eliminate "zipper" noise. A simple serial-data communications scheme that makes it easy to connect multiple CS3310’s together and have them change at the same time. A self-calibration method that automatically cancels offset voltage. Two different mute modes, both which occur at zero-crossing. A purely resistive input impedance. Ability to drive relatively low load impedances directly. An extremely low THD+N (Total Harmonic Distortion plus Noise) in which virtually all of the residual .001% is noise, rather than distortion.