R-2R Ladder vs. Delta-Sigma DAC Acoustics Audit

Resistor Tolerance Drift, Major Code Glitch Energy, and Ultrasonic Noise Shaping Dynamics

Primary Category: Audio Engineering & Precision Electronics | Target Release: Q4 2026 Telemetry | Classification: Open Engineering Reference

EXECUTIVE ABSTRACT: Digital-to-analog conversion in high-end audio divides between multi-bit discrete R-2R resistor ladders and 1-bit or multi-level Delta-Sigma modulators. While Delta-Sigma dominates consumer silicon through ultra-high THD+N measurements, R-2R ladders offer flawless time-domain step response. This audit analyzes resistor laser trimming, glitch energy, and noise shaping.

Design Topology	Discrete R-2R Ladder (NOS)	Multi-Bit Delta-Sigma (ESS/AKM)
Resistor Matching Precision	0.005% Laser Trimmed	Integrated Silicon Cap Arrays
Major Code Glitch Energy	12 nV·sec (Transition Spike)	Zero (Continuous PWM/PDM)
Ultrasonic Noise Floor	Flat to Nyquist Frequency	+45 dB Noise Rise > 100 kHz
Time-Domain Step Response	Zero Pre/Post Ringing	Linear Phase FIR Pre-Ringing
Total Harmonic Distortion	0.0004% THD+N @ 1 kHz	0.00008% THD+N @ 1 kHz

1. Discrete R-2R Resistor Ladder Physics and TCR Drift

An R-2R ladder constructs analog voltages by summing binary-weighted currents through a resistor network. To achieve true 24-bit resolution, resistor values must match within 0.001%. Temperature coefficients of resistance (TCR) drift alter linearity over operating cycles, demanding active temperature stabilization.

2. Major Code Glitch Impulse at MSB Transitions

When transitioning from code 0111...111 to 1000...000, multiple discrete switches toggle simultaneously. Slight timing skews produce transient glitch impulses up to 12 nV·sec. High-end R-2R designs incorporate fast track-and-hold de-glitching switches to suppress switching artifacts.

3. Delta-Sigma Modulators: Noise Shaping and Ultrasonic In-Band Smearing

Delta-Sigma converters achieve extreme SNR by oversampling data (typically 64x to 256x Fs) and applying high-order noise-shaping algorithms that shift quantization noise into ultrasonic frequencies above 100 kHz. Analog reconstruction filters must aggressively attenuate this noise to prevent intermodulation distortion in analog amplification stages.

4. Acoustic Impulse Response: NOS vs. Digital Interpolation Filters

Non-Over-Sampling (NOS) R-2R DACs output instantaneous square-wave voltage steps with zero pre-ringing or phase smearing. In contrast, sharp linear-phase digital FIR filters in Delta-Sigma architectures produce symmetrical pre-ringing ringing artifacts that alter transient acoustic perception.

STRATEGIC ARCHITECTURAL CONCLUSIONS:

- R-2R resistor ladders deliver superior time-domain impulse response with zero digital filter pre-ringing artifacts.
- Delta-Sigma modulators provide superior steady-state THD+N measurements but require aggressive low-pass filtering to remove ultrasonic noise.
- Laser-trimmed thin-film resistors with ultra-low TCR (< 0.2 ppm/°C) are required to prevent thermal drift from degrading 24-bit linearity.