

REAL-TIME STATE-SPACE PARAMETERIZATION IN DIGITAL EQUALIZATION: A PRODUCTION-GRADE SVF IMPLEMENTATION

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ABSTRACT

We present FreeEQ8/ProEQ8, an open-source parametric equalizer using the Simper State Variable Filter (SVF) topology for modulation-stable Dynamic EQ. Both SVF and RBJ use BLT with identical prewarping and produce identical steady-state responses; SVF chosen for lower automation noise, better coefficient interpolation, improved SNR near DC. The architecture features lock-free SPSC triple-buffering for real-time safety, a variable-cadence coefficient engine reducing Dynamic EQ CPU cost by 75%, and allocation-free semantic resonance detection. Measured performance: 0.62% single-core CPU at 44.1 kHz (161× headroom). Source code, benchmarks, and CI validation available under GPL-3.0.

1. INTRODUCTION

Traditional parametric EQ implementations use the Robert Bristow-Johnson (RBJ) Audio EQ Cookbook biquad formulas [1] in Transposed Direct Form II. While mathematically correct, the bilinear transform introduces frequency cramping near Nyquist: a Bell filter at 16 kHz with $Q = 1.0$ at 44.1 kHz exhibits an effective bandwidth **199% narrower** than intended.

Industry solutions include brute-force oversampling (adding latency and CPU cost) or proprietary polynomial analog-matching curves. This paper documents a third path: the Simper SVF topology [2], which pre-warps the cutoff frequency via $g = \tan(\pi \cdot f_c / f_s)$, achieving exact cutoff placement without oversampling.

1.1. Product Architecture

The codebase produces two plugins from a single source tree:

FreeEQ8 (Free, GPL-3.0): 8-band parametric EQ using RBJ TDF-II biquads. Zero audio restrictions during real-time playback.

ProEQ8 (\$20): 24-band parametric EQ using Simper SVF with modulation-stable SVF topology. Adds 4 saturation modes, A/B comparison, and collision detection.

2. FILTER TOPOLOGY

2.1. RBJ TDF-II (FreeEQ8)

Standard biquad transfer function with coefficients per the RBJ cookbook. 64-bit double internal state, float I/O.

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Table 1: RBJ Q distortion vs frequency (Bell, $Q = 1.0$, 44.1 kHz).

Frequency	Effective Q	Error
1 kHz	1.005	+0.5%
8 kHz	1.337	+33.7%
16 kHz	2.990	+199%

2.2. Simper SVF (ProEQ8)

Pre-warped cutoff via trapezoidal integration [2]:

$$g = \tan(\pi \cdot f_c / f_s), \quad k = 1/Q \quad (1)$$

$$a_1 = 1/(1 + g(g + k)), \quad a_2 = g \cdot a_1, \quad a_3 = g \cdot a_2 \quad (2)$$

Table 2: SVF vs RBJ magnitude response at 16 kHz.

Topology	Magnitude at f_c	Error
RBJ @ 44.1 kHz	+6.000 dB	0.000 dB (identical to SVF)
SVF @ 44.1 kHz	+6.00 dB	0.00 dB
RBJ @ 4× OS	+5.993 dB	−0.007 dB

3. REAL-TIME SAFETY ARCHITECTURE

3.1. SPSC Triple-Buffer

Three buffer slots indexed by {writeSlot, midSlot, readSlot}. Audio thread writes and atomically swaps writeSlot ↔ midSlot with `memory_order_release`. UI thread reads via midSlot ↔ readSlot with `memory_order_acquire`. No mutex, no blocking.

3.2. Variable-Cadence Dynamic EQ

Dynamic EQ recomputes coefficients per-sample when active. During sustained signals, envelope changes < 0.1 dB are inaudible within a 4-sample window (0.09 ms). **Result:** 75–80% reduction in coefficient updates.

4. BENCHMARKS

All benchmarks from standalone C++ (no JUCE, no DAW). Platform: x86-64, g++ -O3.

Concurrent stress tests (400 ms, Intel i7-3720QM): 239M samples, **0 data tears**.

Table 3: Performance (44.1 kHz, 512-sample blocks).

Configuration	ns/sample	CPU Headroom
RBJ 8-band stereo	40.7	277×
SVF 8-band stereo	70.4	161×
SVF DynEQ worst-case	370.9	30.6×

5. DEMONSTRATION PLAN

The live demonstration will showcase: (1) Side-by-side RBJ vs SVF frequency response at 16 kHz; (2) Real-time spectrum analyzer with lock-free triple-buffer rendering; (3) Dynamic EQ envelope tracking on drum transients; (4) 24-band surgical EQ workflow in ProEQ8.

Requirements: Table with power outlet, external audio interface, headphones.

6. CONCLUSIONS

The SVF topology is used for modulation-stable Dynamic EQ. Source code and CI validation (pluginval strictness-level-10) available at <https://github.com/GareBear99/FreeEQ8> under GPL-3.0.

7. ACKNOWLEDGMENTS

The Simper SVF topology is due to Andrew Simper (Cytomic). The RBJ biquad coefficients and Audio EQ Cookbook are due to Robert Bristow-Johnson.

The 5-DOF constraint framework, the geometric-mean pinning approach, and the $Q \cdot \sqrt{G}$ convention are drawn from public commentary by Robert Bristow-Johnson on r/DSP (May 2026) in response to questions raised by this project. His analysis identified that cramping is a BLT property affecting both topologies equally.

The characterization of the SVF’s actual advantages — improved SNR near DC, reduced coefficient-change noise, and stable interpolation for Dynamic EQ — is due to SkoomaDentist (r/DSP, May 2026). JUCE forum feedback from Nitsuj70, holy-city, zslu98, and kerfuffle identified errors in the original paper. This work is released under GPL-3.0.

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