THAT Corporation Design Note 121

VCA Symmetry Auto-Trim Circuit

A dominant distortion mechanism in log/anti-log voltage-controlled amplifiers (VCAs) are mismatches between internal gain-cell transistors. With no compensation for these mismatches, total harmonic distortion might typically average 0.5-0.7%.

An external symmetry trim can be used to compensate for these mismatches, resulting in performance better than 0.02% THD. Besides reducing distortion, this trim will also reduce the level of “thump”, or the sudden output DC offset change that can occur with rapid gain changes.

For applications which require low distortion, but cannot tolerate an external trim, THAT Corporation offers the THAT 2180Lx series of VCAs. These ICs, available in plastic 8-pin SIP packages, are specially selected to have low distortion even when no external trim is provided.

A surface-mount version of the THAT 2180 series was offered for a short period of time, but the thin walls of the SO package resulted in package stresses which, particularly after reflow soldering, subtly changed the internal transistor characteristics. As a result, the symmetry (and hence the distortion performance) would change unpredictably, sometimes exceeding datasheet specifications, and THAT Corporation was forced to discontinue these ICs.

This Design Note presents two “auto-trim” circuits that will allow VCAs which would normally require an external symmetry trim (the THAT2181 series) to achieve low distortion levels with no external adjustment. These circuits will even compensate for post-reflow symmetry shifts, thereby making the use of no-trim VCAs in surface mount packages once again a viable option.

The first, more “basic” technique (Figure 1) is optimized for minimum parts count, while the second, “advanced” solution (Figure 2) achieves better distortion performance at low frequencies.

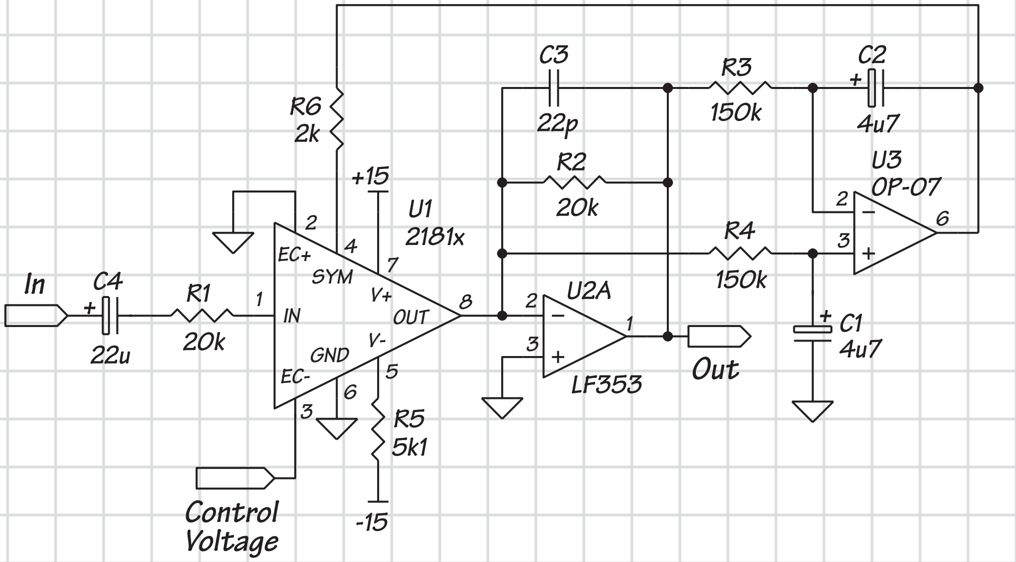

Figure 1: The basic method for implementing an “auto-symmetry” circuit

Theory and Operation

The THD that results from VCA asymmetry is second harmonic in nature, since it results from gain mismatch between the positive-going half of the gain cell and the negative-going half. Any audio frequency signal that is distorted by this mechanism will have an induced DC offset, which results in a net DC current through R2 (the trans-impedance amplifier’s feedback resistor). In both techniques (shown in Figs. 1 and 2), correction of the VCA’s symmetry is accomplished by sensing R2’s net DC.

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current through a differential integrator and using this error signal to servo out the VCA's asymmetry. R6, the 2 kΩ resistor connected to the symmetry port, works in conjunction with the VCA's internal 27Ω resistor to provide a 75:1 attenuator that reduces the effect of U3's input referred noise.

In these circuit configurations it is possible for the voltages across C1 and C2 to be in a polarity opposite that which the capacitors are specified for, but this voltage will not exceed 200 mV, and should not present a problem. The only really important considerations for this circuit are the selection of U2 and U3. U2 must be a low bias current audio amplifier, with BiFETs being the preferred choice. U3 should be a low offset, low bias current amplifier. Otherwise the input bias currents will be sensed by the servo, and will cause an error in the VCA servo setting.

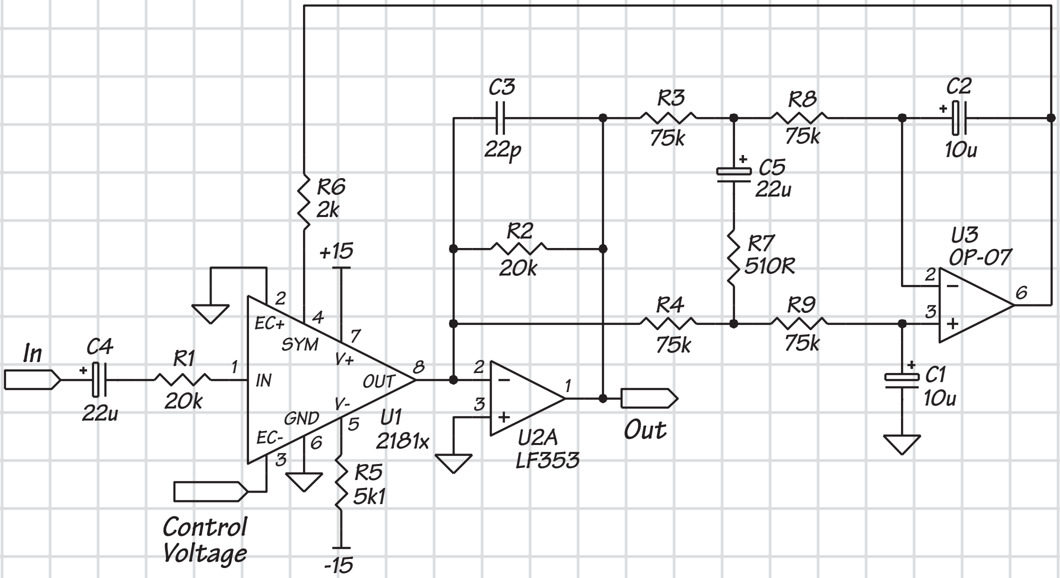

Figure 2: The advanced method for implementing an "auto-symmetry" circuit

Since the VCA's control port is a multiplier input, signal on the control port results in additional second harmonic distortion, and for this reason, the time constants of the integrators are quite long. Even so, there is a substantial amount of ripple-induced distortion at low frequencies using the basic auto-symmetry circuit.

The advanced method (Figure 2) differs only in the additional filtering applied to the error signal by splitting the input resistors and adding a pole-zero combination. The performance improvement will be evident later when the comparative results are shown.

While we've only shown a single additional pole-zero, these can be "daisy chained" for even higher order systems, with the only real complications being the additional board space and a more complex settling behavior.

Sources of Error

This technique works because symmetry errors are really just slight current gain mismatches between the positive-going log/anti-log pairs of transistors and the negative-going log/anti-log pairs. In the absence of signal, this error causes a portion of the bias current through the gain cell transistors to appear as a DC current at the VCA output, and hence as a voltage across R2. With signal present, this effect is even more pronounced. Second harmonic distortion increases approximately linearly with the voltage across R2 at a rate of 0.01% THD+N per 480 μV, assuming that R2 is 20 kΩ. Thus 4.8 mV would result in 0.1% THD+N.

This relationship holds true for current errors that result from gain cell mismatch, but the opamps contribute errors too. The LF353 was chosen because it has low bias currents, at least at room temperature. One should note that these bias currents double every 10°C, and the worst-case bias current of 200 pA at room temperature will be 8 nA at 70°C. The resulting error on R2 would then be: $V_{R2} = 8nA \times 20k\Omega = 160\,\mu V$.

Since the servo will add a symmetry error to correct for this voltage error, the THD+N that results from this error source will be:

$$THD_{Partial} = \frac{160\,\mu V}{480\,\mu V} \times 0.01\% THD + N = 0.003\%\ THD + N.$$

While this may seem insignificant, all of these errors can be additive. The maximum bias current of the THAT2181SC is 15 nA (though, since this is a bipolar device, it does not exhibit the doubling every 10°C that FET input devices exhibit), resulting in $V_{R2} = 15nA \times 20k\Omega = 300\,\mu V$ for a 2181LC. This source of error will be reduced somewhat with higher grades of the 2181 (e.g. max bias current for 2181SA=10nA).

The servo will again add a symmetry error to correct for this voltage error, and the maximum THD+N that results from this error source will be:

$$THD_{Partial} = \frac{300\,\mu V}{480\,\mu V} \times 0.01\% THD + N = 0.0063\%\ THD + N$$

Since our differential integrator is measuring the very small voltage across R2, the DC errors of the integrator also represent a source of THD+N. While the OP-07 has excellent V_{OS} specifications for its price, its I_{OS} must be considered. The maximum input referred voltage error including the effects of I_{OS} is: $V_{OS_{eff}} = 2.8\ nA \times 150\ k\Omega + 75\,\mu V = 495\,\mu V$. Which, as we have seen before, results in

$$THD_{Partial} = \frac{495\,\mu V}{480\,\mu V} \times 0.01\% THD + N = 0.01\%\ THD + N$$

Therefore, at room temperature, the maximum THD+N that we can expect is 0.017% THD+N.

Results

In Figures 3 through 5, the upper curve shows the THD+N of the untrimmed VCA, the middle curve shows the THD+N with the basic "auto-symmetry" circuit active, and the lower curve shows THD+N with advanced "auto-symmetry" circuit active.

In Figure 3, the input signal level is 0 dBV and the gain is 0 dB, in Figure 4, the input signal level is -15 dBV and the gain is 15 dB, and in Figure 5, the input signal level is 15 dBV and the gain is -15 dB.

In all three figures we see a substantial improvement in the 1 kHz THD+N, but the THD+N at low frequencies is not as good, particularly with the basic "auto-symmetry" circuit. The additional filtering in the advanced "auto-symmetry" circuit yields nearly an order of magnitude improvement at 20 Hz over the basic circuit.

In Figure 6, the upper curve shows the THD+N with the basic "auto-symmetry" circuit active, the middle curve shows THD+N with superior "auto-symmetry" circuit active and the lower curve shows the THD+N of the hand-trimmed VCA. These measurements were taken with the input = 0 dBV and the gain = 0 dB. One can see that the advanced method performs nearly as well as manually adjusting the VCA symmetry at 1 kHz, but that the effects of ripple are already encroaching on the performance of the basic circuit.

Figure 7 shows the THD+N of eighteen VCAs that we tested in our prototype, using the advanced method. One can see that most of the devices we looked at were below 0.005% THD+N, though the one device at 0.008% appears to have nearly the maximum allowable bias current for a THAT2181.

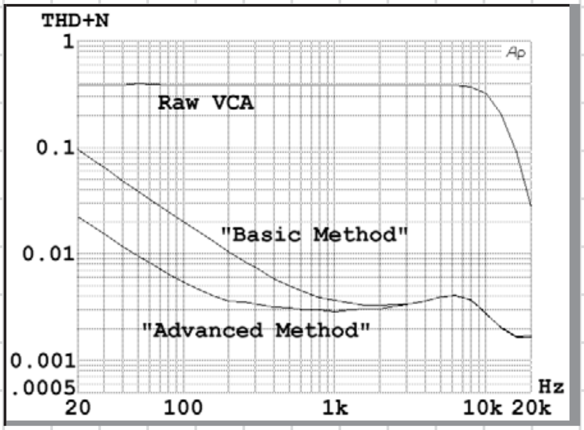

Fig 3, A comparison of the untrimmed VCA, the basic "auto-symmetry" circuit and the advanced "auto-symmetry circuit with the input = 0dBV and the gain = 0dB.

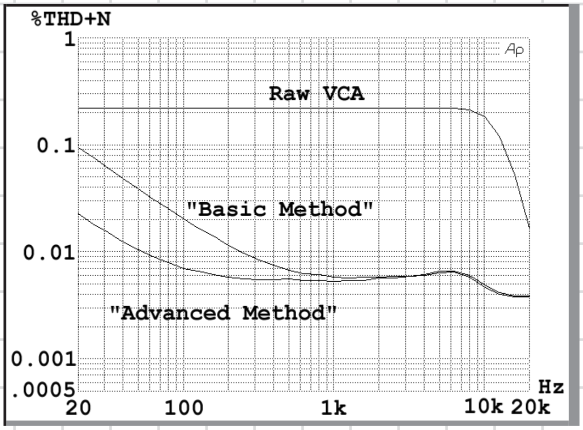

Fig 4, A comparison of the untrimmed VCA, the basic "auto-symmetry" circuit and the advanced "auto-symmetry circuit with the input = -15 dBV and the gain = 15 dB.

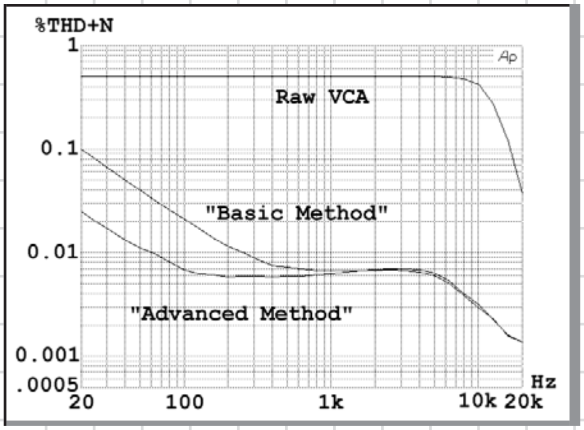

Fig 5, A comparison of the untrimmed VCA, the basic "auto-symmetry" circuit and the advanced "auto-symmetry circuit with the input = 15 dBV and the gain = -15 dB.

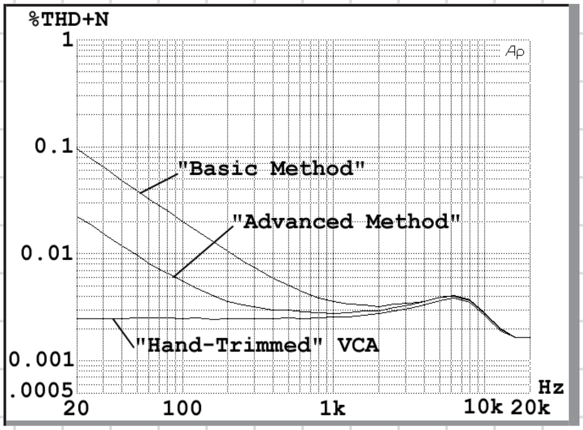

Fig 6, The upper curve shows the THD+N with the basic "auto-symmetry" circuit active, the middle curve shows THD+N with the advanced "auto-symmetry" circuit active and the lower curve shows THD+N of the hand trimmed VCA. All measurements were taken with input=0 dBV and the gain=0 dB.

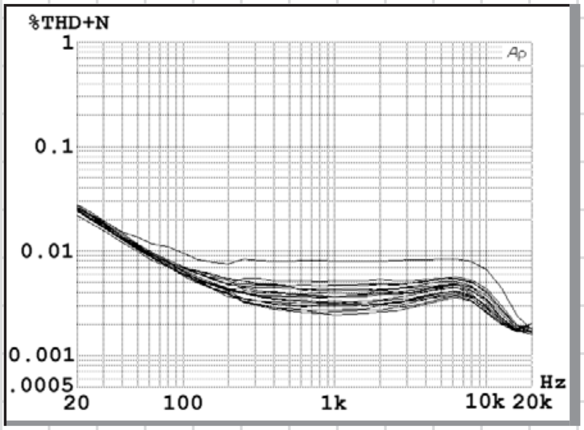

Fig 7, These curves show the distribution of THD+N of 18 different VCAs using the advanced "auto-symmetry" circuit active with input=0 dBV and gain=0 dB.