A Low Parts Count, Two-Slope Compressor

Abstract

Compressing the dynamic range of an audio signal can be of significant benefit in certain playback applications. In multimedia sound systems, for example, compressing the subwoofer signal can lend added richness to the sound, particularly at lower signal levels. With automotive sound systems, compression can raise low-level signals above the relatively high ambient noise level.

Speaker protection is also important, and a dynamic range limiter is an essential component of any system that attempts to handle overloads gracefully (inaudibly).

This paper describes a combination compressor and limiter, with adjustable threshold and compression ratio, for just these types of applications. The basic circuit is built around a single integrated circuit, the THAT 4311, a low-power, low-voltage Analog Engine® IC. The THAT 4311 (like its higher-performance, higher-power cousin, the THAT 4301) provides a high-quality voltage controlled amplifier (VCA) and RMS-level detector with three general purpose op amps. Using either the THAT 4311 or THAT 4301, the dual-slope compressor provides a very useful functional block at reasonable cost and reduced board space.

A Low Parts Count, Two-Slope Compressor

Introduction

Dynamic range compressors are one of the most common signal processors used in the development and reproduction of audio. Their ubiquity is due, in large part, to the wide variety of applications to which they may be put. They may be employed, for example, as automatic gain controls, as noise reduction systems, as "effects", as loudspeaker protection systems, or as over-modulation limiters.

Most commercially available compressors have a fixed or adjustable threshold, below which no compression occurs. Above the threshold, increases in signal level are reduced by a fixed or adjustable amount, usually expressed as a ratio of the change in signal level at the output of the device (in decibels) over the change in signal level at the device's input. A 6dB signal increase at the input of 2:1 compressor, for example, would result in a 3dB increase at the compressor's output.

The compressor/limiter circuit presented in this application note is primarily intended for use in consumer playback products, and is a departure from the normal "above threshold" compressors described above. In particular, the compressor/limiter described herein is a "below threshold" compressor combined with an "above threshold" limiter, with the transfer characteristics shown in Figure 1.

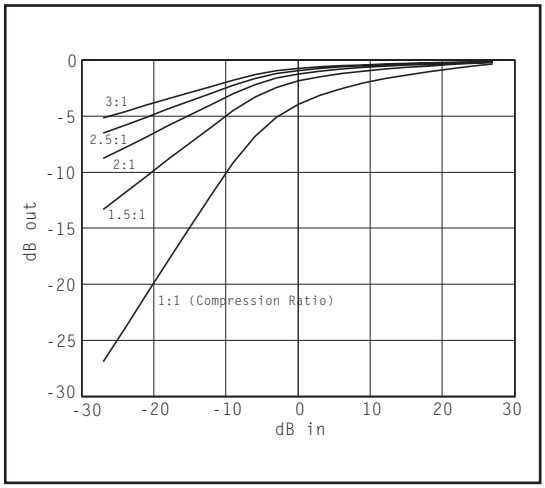

Figure 1. Two-slope compressor transfer characteristics

This type of device can be extremely useful in certain applications. In automotive sound systems, for example, a constant amount of compression will help overcome the high ambient noise levels often found in the passenger compartment. In another application, the subwoofers associated with multimedia speaker systems can

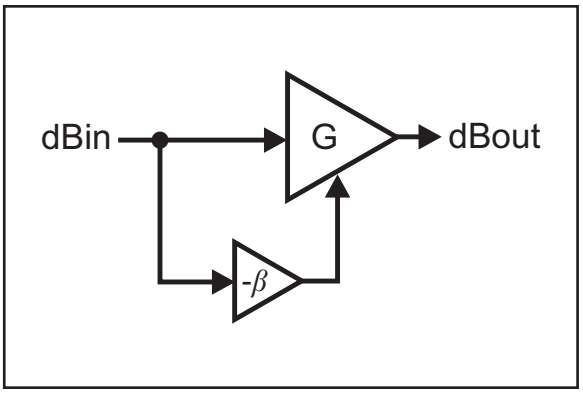

Figure 2: Basic feedforward compressor topology

be made to sound fuller, particularly at low signal levels, when they are fed with a compressed low-frequency signal.

In either case, the speaker drivers need to be protected from overload, preferably in an inaudible manner. One protection method uses diode clippers to limit signal excursion. This technique alone, however, will sound particularly bad so long as the signal remains above the clipping threshold.

Another technique uses a peak limiter to quickly reduce the signal level. A common objection to this method, however, is that peak limiters tend to react to otherwise inaudible "peaks of short duration", resulting in an audible artifact that has been described as "punching a hole in the audio".

A less audible technique that better maintains headroom while limiting harmful signal excursion combines an RMS-based limiter with a diode clipper. During peaks of short duration, the diodes clip the signal. However, because the overload lasts only a few cycles, the clipping action remains inaudible. Should the signal remain in the overload region long enough, however, the RMS-based limiter will act to bring the signal level into the normal operating regime.

The combination of compressor and limiter, built around a single VCA and RMS-level detector, deliver significant and audible benefits to multimedia, automotive, and other types of sound systems. It is this combination of constant, below threshold compression, and effective, inaudible limiting protection that is presented in the sections that follow.

The Feedforward Compressor

The basic feedforward compressor topology is shown in Figure 1. The gain in dB of block G is set by way of a control path through the block marked β.

If we analyze this circuit in the log domain, we can see by inspection that,

$$dB_{out} = dB_{in} + G_{dB}$$

The control path equation is given by,

$$G_{dB} = -\beta \; x \; dB_{in}$$

where beta is the control constant. Note that the negative sign is required for compressor action. Note, too, that the gain (G_{dB}) becomes negative (in dB) as the input goes above 0dB, and is positive when the signal is below 0dB.

Combining these equations results in:

$$dB_{out} = dB_{in} - dB_{in} \times \beta$$

This equation can be rearranged to yield

$$\frac{dBin}{dBout} = \frac{1}{(1-\beta)}$$

which is the compression ratio. Thus, if β is one, then the compression ratio will be infinite, and if β is zero, the compression ratio will be one. If β is one-half, the compression ratio will be 2:1.

Theory of Operation

The circuit shown in Figure 3, based on the THAT4311, implements a compressor that compresses below threshold and limits above threshold. This circuit is, in many regards, similar to other feedforward compressor/limiters, and the equations derived in the section above apply to its operation.

Below-threshold limiting is accomplished by feeding a portion of the RMS detector's output through the non-inverting input of the control port buffer (U1D). The below-threshold side-chain gain is a function of the setting of VR1, and results in a compression ration that varies between 1:1 and approximately 3:1.

Above-threshold limiting results from driving the VCA's Ec- control port from the output of the threshold amplifier (U1C) through the inverting input of the control port buffer (U1D) for a net side-chain gain of one. This action results in infinite compression. A

portion of the threshold amplifier output (which is inverted) is fed into the below-threshold compression path which effectively cancels the below-threshold signal, and keeps its setting from affecting the ultimate above-threshold compression ratio. This arrangement allows the circuit to compress when the input is below threshold and limit when the input is above threshold, without the below-threshold adjustment affecting the ratio required for effective limiting.

RMS Detector

THAT Corporation's RMS-level detectors exhibit true-rms response, have greater than 80 dB of dynamic range, and can handle signals with crest factors greater than 8. The input of these detectors is the virtual ground (biased at VREF) of an internal op-amp, and it is at this point that the input voltage is converted to a current. This current is full-wave rectified and fed through a series pair of diode-connected transistors. Drawing the current through the diode-connected transistors logs and doubles the signal (Note that doubling the signal in the log domain is equivalent to squaring the signal in the linear domain). The signal is then averaged by a log domain filter consisting of an internal diode biased by ITime and an external capacitor, CT (C3). This circuit performs the "mean" portion of the calculation. The square root portion of the RMS calculation is performed implicitly at the exponential control port of the VCA.

Logging, squaring and rectification of the input current results in the accumulation of several diode drops on the signal, one of which is removed by the diode-connected transistor in the log filter. The additional diode drops are removed by "bucking them out" with diodes biased by a fixed current, which in the case of the THAT 4311, is a replica of the timing current that is reflected to the log filter. When the current through the log filter diode and the "bucking" diodes equals the RMS detector's input current, the offsets will cancel exactly, and the output of the detector will be at VREF. This point is referred to as the 0dB reference level.

If we program

$$I_T = 7.5\,\mu A$$

then the current reflected to the "IT" pin will be

$$I_{time} = 7.5\,\mu A$$

This also sets the 0dB reference current at:

$$I_{0\,dB} = 7.5\,\mu A$$

We can calculate the appropriate timing resistor to be

$$R_T = \frac{V_{ref}}{I_T} = \frac{2V}{7.5\mu A} \approx 264\ k\Omega$$

The desired 0dB reference level for this circuit is -10 dBu or 245 mV_{RMS}. Knowing both this and the 0dB reference current, we can calculate the required input resistance which is

$$R_{IN} = \frac{V_{0dB}}{I_{0dB}} = \frac{245\ mV_{RMS}}{7.5\ mA} \approx 324\,k\Omega$$

Since the rectified signal has already been logged by the time the "mean" portion of the RMS calculation is performed, these detectors use a log filter for averaging. This filter consists of an internal diode, biased by Itime, and an external timing capacitor, CT. The time constant can be calculated as,

$$\tau = \frac{V_T}{I_{time}} C_T$$

If we choose 16 ms (which is a compromise between the best time constants for a compressor and a limiter, the tradeoff being greater ripple--induced distortion for faster response time) as τ, then we can calculate CT:

$$C_T = \tau \frac{I_{time}}{V_T} \approx 4.7\mu F$$

These values are reflected in Figure 3. If a single τ for both compression AND limiting is unacceptable, the designer should consider the "non-linear capacitor", which is discussed in detail at the end of THAT Corporation's Application Note AN103, Signal Limiter for Power Amplifiers.

The Threshold Amplifier

The circuit immediately surrounding U1C is a soft-knee threshold amplifier. This portion of the circuit is fundamentally an inverting amplifier with an output offset adjustment which acts to set the threshold, and a fixed offset, generated by D3, to "buck out" the forward drops of D1 and D2 in the control port buffer.

The gain for the RMS detector output signal through the threshold amplifier is

$$Av = \frac{-40.2\ k\Omega}{10\ k\Omega} \approx 4$$

which results in a control voltage constant at the output of the threshold amplifier of

$$k_{CV} = 4 \times 6.1\ ^{mV}/_{dB} = 24.4\ ^{mV}/_{dB}$$

The voltage across D3 (biased by R14) is amplified by -1, and effectively cancels the offsets of D1 and D2. Thus, neglecting the effect of the threshold adjustment, when the RMS detector output goes above zero volts, D1 and D2 will begin to conduct, and the signal will be above threshold. 75 kΩ was chosen as the value for R14 since this value resulted in a current that best compensated for ambient temperature variations and the current variations in D2 that result from changes in the setting of VR1.

VR2 and R23 provide a means to adjust the level where this action occurs. When VR2 is set fully clockwise (CW), the threshold offset is:

$$Adj_{threshold} = \left[\frac{-2V \times \frac{-R10}{R23}}{24.4\ ^{mV}/_{dB}}\right] = \frac{-2V \times \frac{-40.2\ k\Omega}{165\ k\Omega}}{24.4\ ^{mV}/_{dB}} \approx 20\ dB$$

In this case, the ultimate sign of the result is a consequence of the voltage polarity, inverting gains of both the threshold amplifier and the control port buffer, and the control port polarity. Since this is relative to the RMS detector's 0dB reference level, which is -10 dBu, a fully CW VR2 results in a threshold of 10 dBu.

When VR2 is set fully counter-clockwise (CCW), the threshold offset is

$$Adj_{threshold} = \left[\frac{3V \times \frac{-R10}{R23}}{24.4\ ^{mV}/_{dB}}\right] = \frac{3V \times \frac{-40.2\ k\Omega}{165\ k\Omega}}{24.4\ ^{mV}/_{dB}} \approx -30\ dB$$

Again, this result is relative to the RMS detector's 0dB reference level, which is -10 dBu, and as a result, a fully CCW VR2 results in a threshold of -40dBu.

The Control Port Buffer

The control port of the VCA is driven by U1D, which acts as the control port buffer. Buffering is not strictly required, since the control port can be driven by a resistive divider with a non-inductive impedance of less than 51Ω without substantially increasing its THD+N. Unfortunately, the control voltage required to achieve 65 dB of attenuation across 51Ω requires greater than 6 mA of drive current, which is roughly equal to the quiescent current of the THAT4311, and in any case, cannot be handled by the on-chip reference. (This situation is also unacceptable for battery powered applications, and is generally bad practice). For this reason, an op-amp is typically used to drive the control port.

The signal fed to the control port buffer comes from two sources: the threshold amplifier and directly from the RMS detector. While the input signal is below threshold, an attenuated portion of the RMS output is fed into the non-inverting input of OA1. At this point in the circuit's operation, D1 and D2 are reverse biased, and the non-inverting gain of OA1 is essentially one. The side chain gain, which determines the compression ratio, is purely a function of R7 and the position of VR1.

We can see intuitively that when VR1 is fully counter-clockwise, the side chain gain is zero, and the compression ratio can be calculated as,

$$C.R. = \frac{1}{1 - \frac{VR1_{eff}}{R7 + VR1_{eff}}} = \frac{1}{1 - \frac{0}{10k\Omega + 0}} = 1:1$$

Likewise, when VR1 is fully CW,

$$C.R. = \frac{1}{1 - \frac{VR1_{eff}}{R7 + VR1_{eff}}} = \frac{1}{1 - \frac{20k\Omega}{10k\Omega + 20k\Omega}} = 3:1$$

It is easily verified that when VR1 is set at 25% CW, C.R.=1.5:1; at 50% CW, C.R.=2:1; and at 75% CW, C.R.=2.5:1.

When the input signal goes above threshold, current flows through D1 and D2. OA1's inverting gain for this signal approaches

$$A_{OA1} = \frac{-R13}{R12} = \frac{-10k\Omega}{40.2k\Omega} \approx -\frac{1}{4}$$

and this coupled with the gain of -4 in the threshold amplifier, results in a net gain of one through this path. The gain through the non-inverting input of OA1 approaches zero (when the RMS signal is well above threshold), since the current through R11 ultimately cancels that through R7. The resulting above-threshold compression ratio is therefore

$$C.R. = \frac{1}{1-1} = \infty:1$$

which makes the circuit a limiter when the input is above threshold.

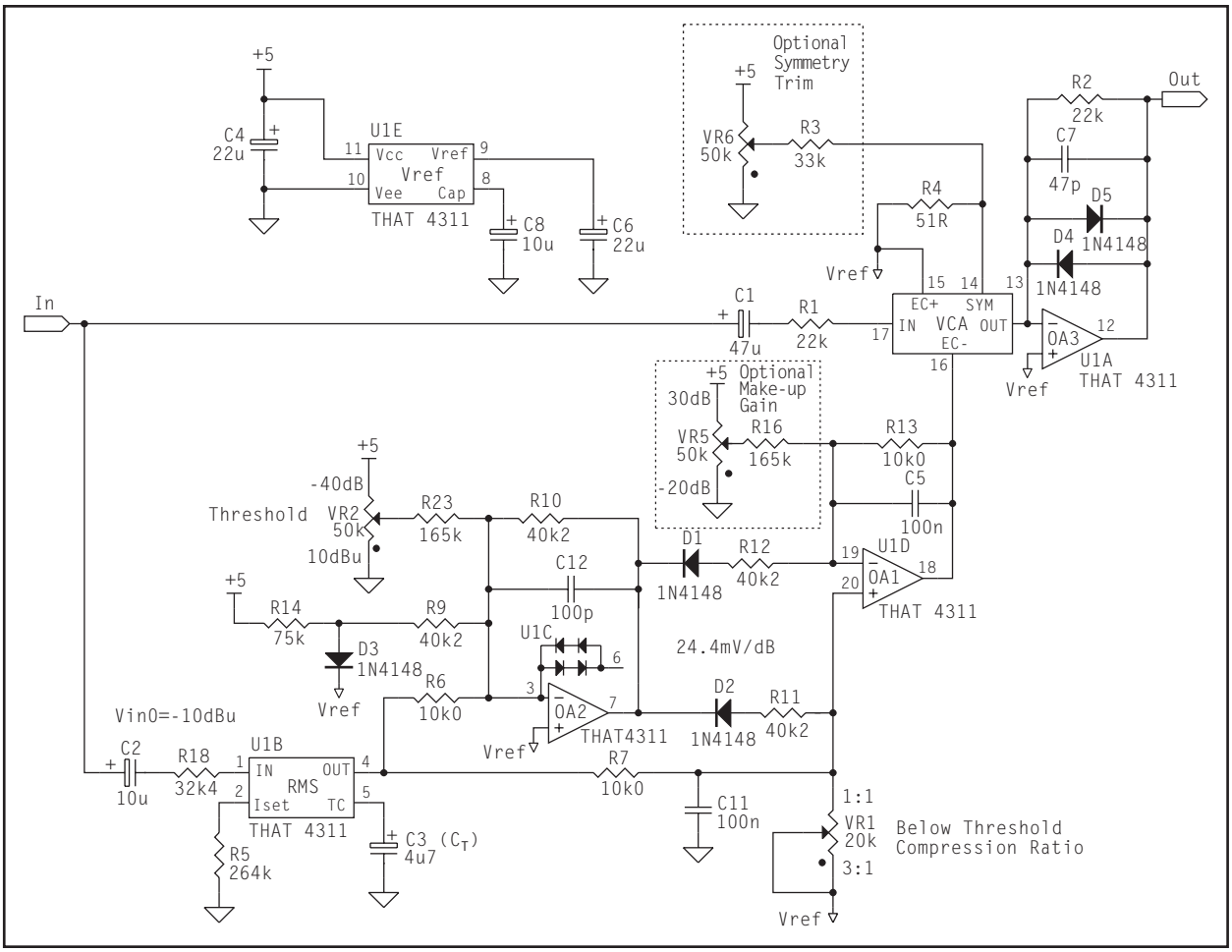

Figure 3: Multi-slope Compressor / Limiter

The control port buffer also has an optional make-up gain adjustment which is implemented by adding a voltage offset to the control port. The current through R16 is summed into the side chain at the inverting input of OA1. The amount and polarity of the current is dependent on the setting of VR2. When VR2 is set fully CW, the gain is

$$A_{make-up} = -\left[\frac{-2V\times\frac{-R13}{R16}}{6.1^{mV}/_{dB}}\right] = \frac{2V\times\frac{-10k\Omega}{165k\Omega}}{6.1^{mV}/_{dB}} \approx -20\ dB$$

The ultimate sign of the result is a consequence of the voltage polarity, inverting gain, and the control port polarity. When VR2 is set fully CCW, the gain is

$$A_{make-up} = -\left[\frac{3V\times\frac{-R13}{R16}}{6.1^{mV}/_{dB}}\right] = \frac{3V\times\frac{-10k\Omega}{165k\Omega}}{6.1^{mV}/_{dB}} \approx -30\ dB$$

The VCA

The THAT 4311 incorporates a log/anti-log VCA. These devices first log the signal, and then add an offset to the logged signal (which is equivalent to multiplication of the un-logged signal). The signal is then sent through a pair of anti-log diodes and into a transimpedance amplifier (formed by OA3 and R2), restoring the signal to the linear domain. A more detailed explanation of the internal workings of these VCAs can be found in the 2150/2180/2181 datasheets.

Mismatches in the log and anti-log diodes (which are actually transistors) produce 2nd harmonic distortion which can be as high as 0.7%, though it rarely exceeds 0.3% in production devices. This level of performance is often acceptable in computer speaker, sub-woofer, and some companding applications. For those applications where this level of performance is unacceptable, an optional symmetry trim is shown which can reduce the THD+N to below 0.1% at nominal input levels and gains.

An often overlooked aspect of limiter design is the need for a clipper. While infinite compression can ul-

timately bring the output signal below overdrive levels, the level detector has a finite response time, and during this time, subsequent devices in the signal chain which have poor overload characteristics can produce audible artifacts. This circuit uses a pair of 1N4148 diodes to implement a clipper, though there are other, more versatile solutions such as the adjustable, transistor-based clipper shown in Figure 2 of the aforementioned Application Note AN103.

The gain cell in the THAT 4311 is current source biased, and there is approximately 500 μA available to handle signal currents. The polarity of the VCA's input and output signals is the same, so the total of the peak input and output currents cannot exceed the available bias current, or the VCA will clip internally.

The clipping diodes in the feedback loop of OA3 limit the output swing to ±0.6V, and if the limiter is adjusted properly, we can calculate the maximum VCA output current

$$I_{OUT\,Max} = \frac{V_{Out}}{R2} \times \frac{0.6V_{Peak}}{22k\Omega} = 27\mu A$$

This leaves approximately 475 μA available for input signal current. Therefore, the maximum input voltage would be

$$V_{In\,Max\,Peak} = 22k\Omega \times 475\,\mu A = 10.45\ V_{Peak}$$

which is 7.4 V_{RMS}, or about 20 dBu.

Reference Considerations

The THAT 4311 has an on-chip, 2V reference about which the VCA, the RMS detector, and OA2 are internally biased. Pins are provided for filter capacitors at both the input and the output of the buffer, which are labeled CAP and VREF respectively. Setting C6=22mF and C8=10mF has proven to be effective at minimizing reference noise, and little is gained by making the values larger.

Conclusion

The THAT 4311 and its cousin, the THAT 4301, provide ideal, single chip solutions to many dynamics signal processing problems. The circuit discussed above implements a combination above-threshold limiter and below-threshold compressor. The low power consumption of the THAT 4311 make it suitable for battery-powered applications such as "stomp boxes" and "boom boxes".