

A High-Performance Compressor

The application below is an excerpt from the SSI2100 BBD data sheet, and details how one can build an inexpensive yet powerful compandor circuit using a SSI2162 Dual VCA plus a few op amp ICs and discretes. The result is a significant upgrade over legacy compandor chips in both audio performance and flexibility. With few or no changes, the Compressor can be adapted to a wide variety of audio applications such as analog recording, wireless systems, wavefolding, pedal noise reduction, and more.

BBDs have a relatively small useful signal range – around 40dB – which limits their signal-to-noise ratio. To improve performance, a “Compan-dor” (Compressor + Expander) is used to compress the input signal before the BBD, and then expand the output of the BBD back to the original signal range. Figure 1 shows the relationships between the three dynamic ranges (Input, BBD and Output).

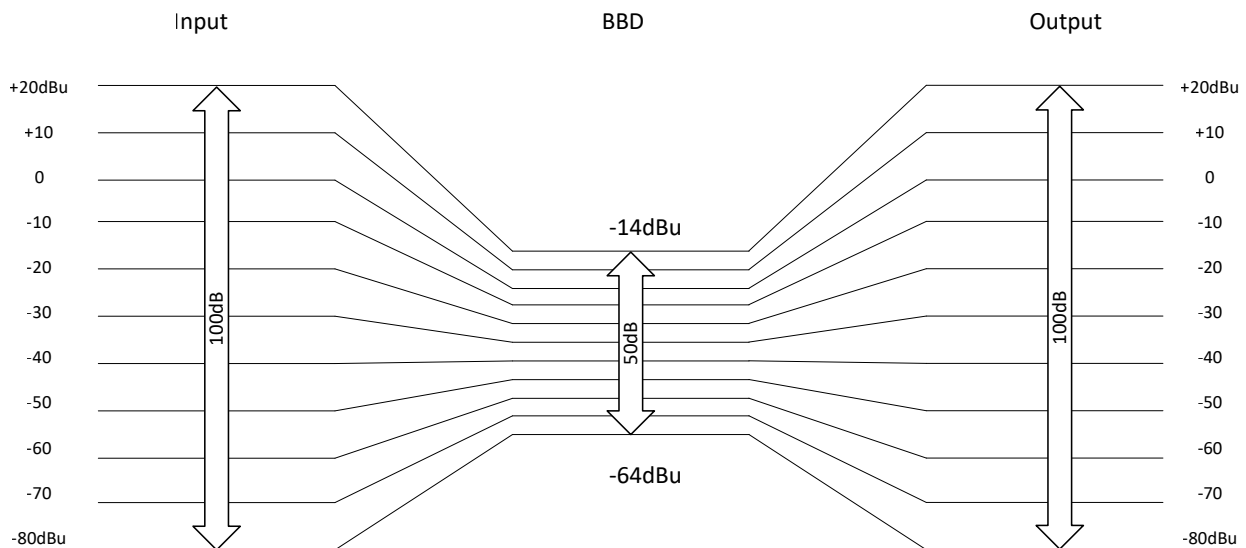


Figure 1: Basic Compressor Operation

Typical audio signals can range greatly from -80dBu to +20dBu. The compressor lifts and compresses the input to a much smaller -64dBu to -14dBu range that better suits the BBD’s input range. After passing through the BBD, the signal is then expanded back to the original -80dBu to +20dBu range. The complementary halves of the compandor work together to achieve this.

Compressor

The compressor circuit shown in Figure 2 is a feedback type, where the input to the sidechain processor comes from the compressor’s output and feeds back to control gain. For signals below about -80dBu the signal path has a fixed gain of +16dB (x6.2 from the 10kΩ VCA input and 62kΩ op amp feedback resistor). This lifts the -80dBu signal up to -64dBu.

The output signal V_{OUT} is passed on both to the BBD’s input anti-alias filter and to the input of the sidechain circuit. The signal is amplified before going into an inverting full-wave rectifier based around an op amp and two Schottky diodes. The resistors around the rectifier generate a fully-rectified and inverted current into the final op amp configured as a current-in voltage-out transimpedance amplifier. The current is then smoothed and converted to a positive voltage to control one half of an SSI2162 dual audio VCA resulting in reduction (compression) of the audio signal.

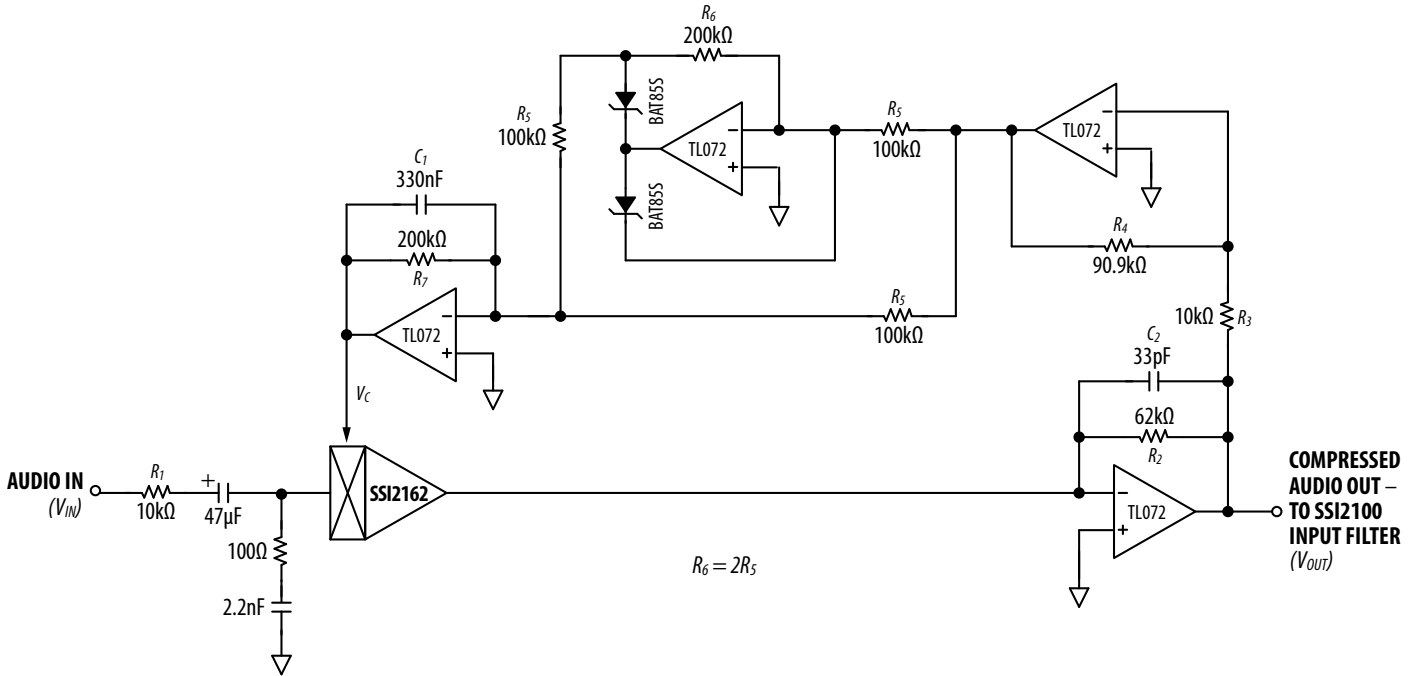


Figure 2: Compressor

The behavior of the compressor is interesting to analyze, starting with the audio signal path. The output voltage, V_{OUT} , is:

$$V_{OUT} = V_{IN} \frac{R_2}{R_1} 10^{-\frac{3}{2}V_C} \quad (1)$$

where $\frac{R_2}{R_1}$ is the fixed gain of the op amp, and $10^{-\frac{3}{2}V_C}$ is the gain of the SSI2162 VCA. The sidechain circuit is rather more complicated. Its input is V_{OUT} from which it generates V_C :

$$V_C = \frac{R_7}{R_5} \frac{R_4}{R_3} |V_{OUT}| \quad (2)$$

This particular circuit uses a peak detector whereas the signal levels are in RMS, so we need to convert from V_{PEAK} to V_{RMS} :

$$V_C = \frac{R_7}{R_5} \frac{R_4}{R_3} \frac{1}{\sqrt{2}} V_{OUT} \quad (3)$$

Substitute (3) into (1) and collect the terms:

$$V_{OUT} 10^{\left(\frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} V_{OUT}\right)} = \frac{R_2}{R_1} V_{IN} \quad (4)$$

Unfortunately, the expression in V_{OUT} is a transcendental function: V_{OUT} is in both the multiplier and in the exponent term itself. This means it is impossible to solve just by re-arranging it. To solve this we need to use the Lambert W Function, which is the inverse of:

$$f(W) = We^W$$

Note: you won't find the Lambert function on your calculator, but you will in Matlab, Maxima, GNU Octave, Python, and many other computer-based math packages. For real values the zeroth Lambert W function looks very similar to the log function: a curve that rises and bends to right like the letter "r".

To use the Lambert W function the exponent base must be scaled from 10 to e:

$$V_{OUT} e^{\left(\frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} \ln(10) V_{OUT}\right)} = \frac{R_2}{R_1} V_{IN} \quad (5)$$

Now introduce a new term:

$$u = \frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} \ln(10) V_{OUT} \quad (6)$$

so that

$$V_{OUT} = \frac{u}{\frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} \ln(10)} \quad (7)$$

Substituting (6) and (7) into (5) gives

$$\frac{u}{\frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} \ln(10)} e^u = \frac{R_2}{R_1} V_{IN} \quad (8)$$

Then re-arrange (8) into

$$u e^u = \frac{3 R_7 R_4 R_2}{2 R_5 R_3 R_1} \frac{1}{\sqrt{2}} \ln(10) V_{IN} \quad (9)$$

Take the Lambert of both sides:

$$W(u e^u) = W\left(\frac{3 R_7 R_4 R_2}{2 R_5 R_3 R_1} \frac{1}{\sqrt{2}} \ln(10) V_{IN}\right)$$

$$u = W\left(\frac{3 R_7 R_4 R_2}{2 R_5 R_3 R_1} \frac{1}{\sqrt{2}} \ln(10) V_{IN}\right) \quad (10)$$

Substitute back for u in (10):

$$\frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} \ln(10) V_{OUT} = W\left(\frac{3 R_7 R_4 R_2}{2 R_5 R_3 R_1} \frac{1}{\sqrt{2}} \ln(10) V_{IN}\right) \quad (11)$$

Finally, re-arrange (11) to give V_{OUT} only in terms of V_{IN} :

$$V_{OUT} = \frac{W\left(\frac{3 R_7 R_4 R_2}{2 R_5 R_3 R_1} \frac{1}{\sqrt{2}} \ln(10) V_{IN}\right)}{\frac{3 R_7 R_4}{2 R_5 R_3} \frac{1}{\sqrt{2}} \ln(10)} \quad (12)$$

This is now in a form that can be used to design and adjust the compressor response. Using the component values from the Figure 12 produces the expected compression transfer curve of Figure 3.

The dotted line plots the input signal and solid line the output signal. As expected, at low amplitudes the signal is boosted. At around -25dBu the compressor is at unity gain where the output line crosses the input line. By this stage the VCA is already reducing the signal level, and after this point the output rises much slower than the input. The compressor exhibits a very soft "knee" and the compression ratio gradually increases.

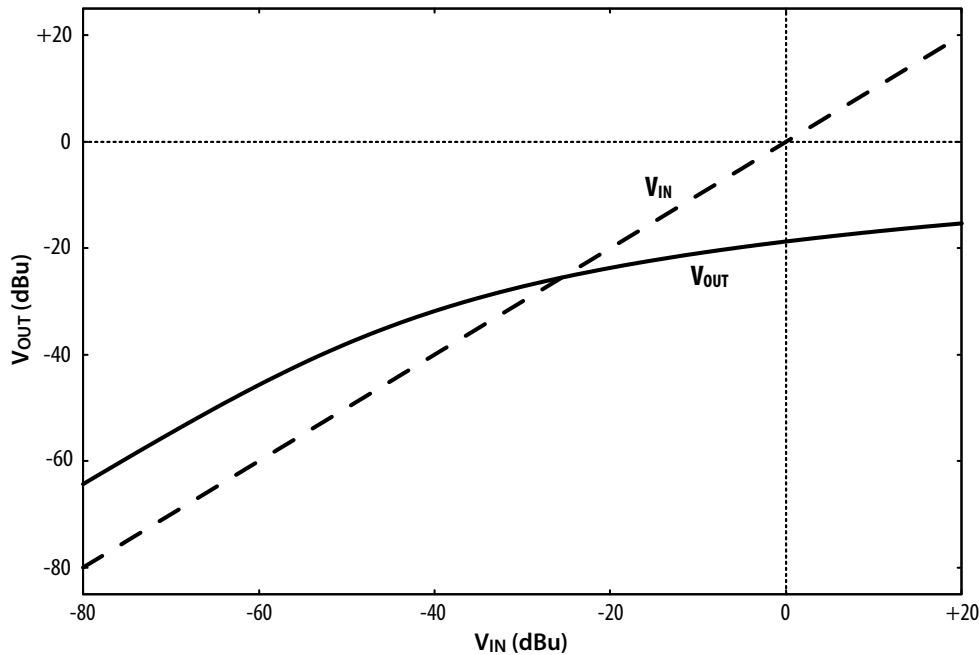


Figure 3: Compressor Transfer Curve

The other compressor aspect to consider is attack and release behavior. Attack time is of the order of 5-10ms depending on the audio material. Due to the gain of the sidechain, the attack sees a very strong drive signal which quickly ramps up the control voltage in about 1/10th of the decay time. This reduces the signal into the sidechain circuit and rapidly ends the attack.

Release time is set by the values of C1 and R7:

$$\tau_R = R_7 C_1$$

Component values shown result in about 66ms.

The key components in this circuit and their function are set out in the following table, together with typical values as shown in the schematic:

Component	Function	Value
R1	Sets the input resistance	10kΩ
R2	Sets the make-up gain	62kΩ
R3	Sets sidechain input resistance	10kΩ
R4	Sets pre-rectifier gain	90.9kΩ
R5	Sets rectifier gain	100kΩ
R6	= 2x R5	200kΩ
R7	Together with R5 sets the transimpedance amp, and with C1 sets the attack/release time constants	200kΩ
C1	With R7 sets the attack/release time constants	330nF
C2	Sets HF rolloff of the signal op amp	33pF

Expander

At the output of the BBD's filter is the expander (Figure 4). This has an equal but opposite gain response to the compressor. One significant difference to the compressor is that the expander's sidechain signal is taken from the input, not the output, and so it's of the feed-forward variety.

The audio path is very similar to the compressor: a VCA and corresponding op amp with some gain. However, at low signal levels (-64dBu and below) the output signal is attenuated by the VCA by 16dB down to -80dBu. As the input signal level increases the expander adds additional gain resulting in the output signal rising at a rate above that of the input. Referring back to the gain chart, the expander has an input range of

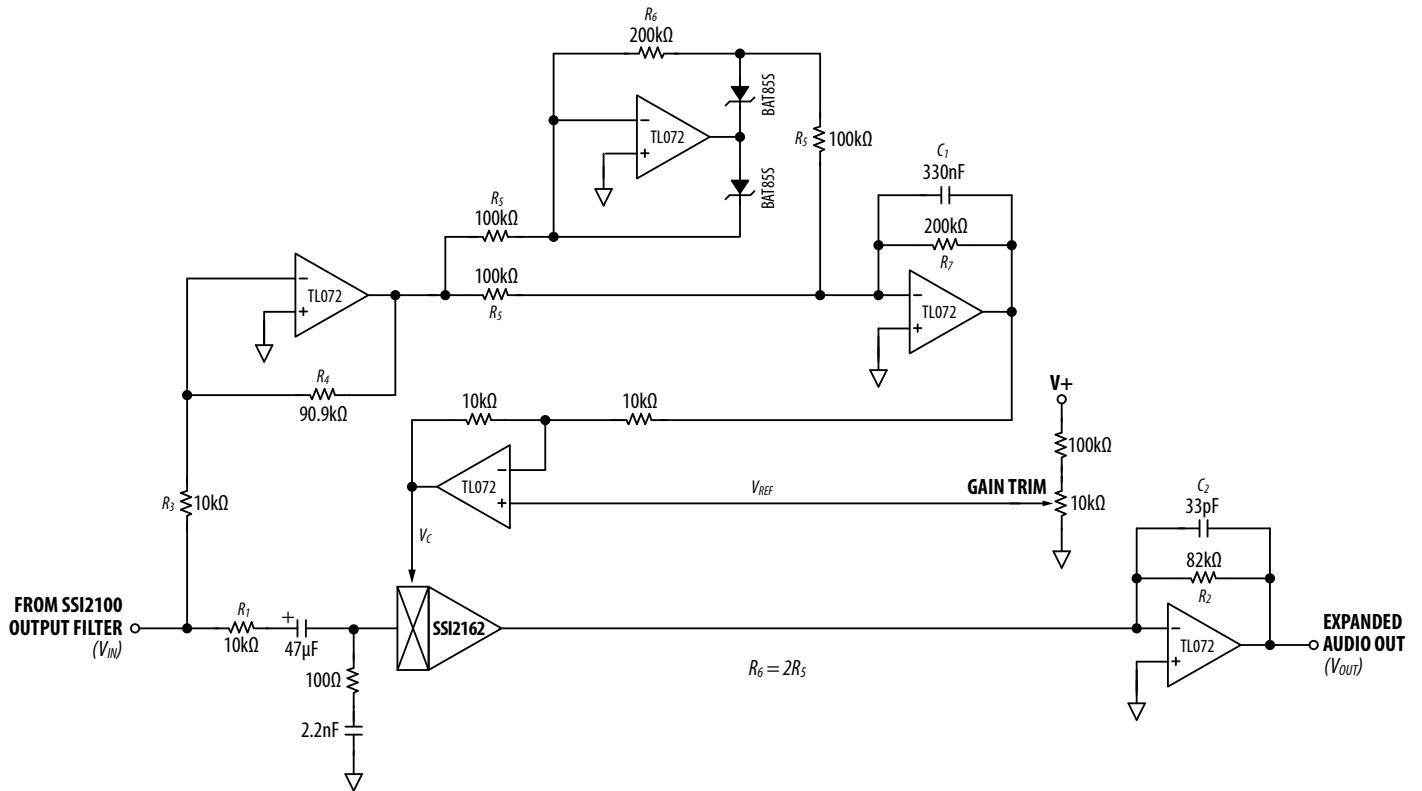


Figure 4: Expander

50dB and an output range of 100dB, meaning this is a 1:2 expander.

The sidechain circuit mirrors that of the compressor – same gain, same rectifier, same time constants – and it behaves in a similar way. The final op amp in the sidechain provides two functions. It inverts the sense of the sidechain control voltage (switching the polarity from compression to expansion), and adds an offset from the GAIN TRIM trimmer. This operates the second half of the SSI2162 to increase the signal level and so counteract the compressor.

Math behind the expander circuit is simpler than the compressor due to the feed-forward design: the output is only a function of input. Again, let's first consider the signal path. The output voltage, V_{OUT} , is:

$$V_{OUT} = V_{IN} \frac{R_2}{R_1} 10^{-\frac{3}{2}V_C} \quad (13)$$

In the expander the control voltage V_C is an inverted and offset version of the sidechain signal as derived in the compressor:

$$V_C = 2V_{REF} - \frac{R_7}{R_5} \frac{R_4}{R_3} \frac{1}{\sqrt{2}} V_{IN} \quad (14)$$

Substituting (14) into (13) gives

$$V_{OUT} = V_{IN} \frac{R_2}{R_1} 10^{\left(-3V_{REF} + \frac{3R_7}{2R_5} \frac{R_4}{R_3} \frac{1}{\sqrt{2}} V_{IN}\right)}$$

Bring out the constant term in the exponent, and then re-arranged into a simplified form:

$$V_{OUT} = V_{IN} \frac{R_2}{R_1} \frac{1}{10^{3V_{REF}}} 10^{\left(\frac{3R_7}{2R_5} \frac{R_4}{R_3} \frac{1}{\sqrt{2}} V_{IN}\right)} \quad (15)$$

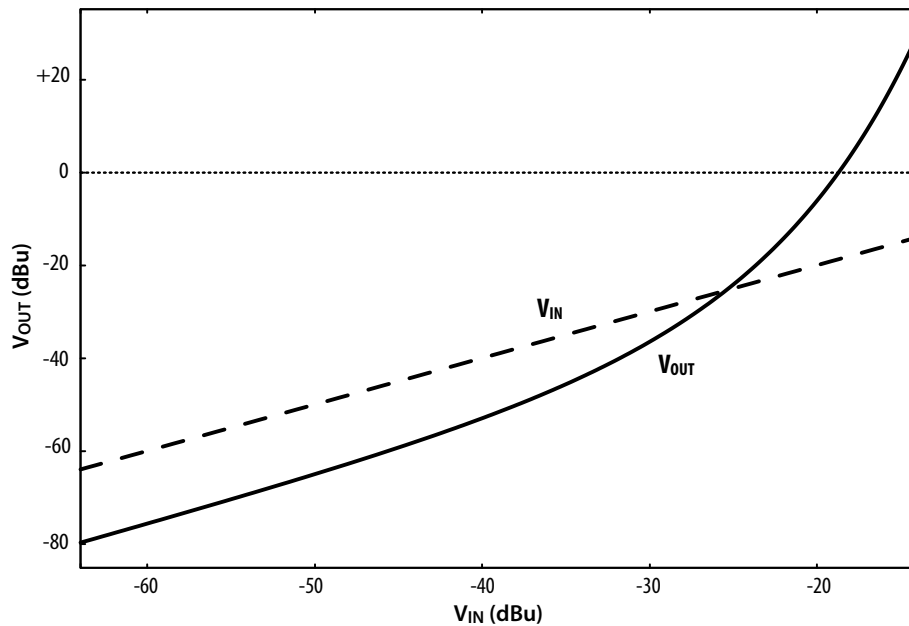


Figure 5: Expander Transfer Curve

The resulting curve of equation 15 looks like the opposite of the compressor's, as shown in Figure 5.

At very low signal levels the output (solid line) is below the input (dotted line). As the input signal increases the expander gain also increases. Again, at around -25dBu the expander is at unity gain, and then applies more gain to the signal. When combined with the compressor curve, the result is a near-perfect match where the output signal level follows the input signal level with very little difference over the range -80dBu to +20dBu.

Figure 6 illustrates the substantial SNR benefit from companding.

The SSI2162 is an ideal choice for a compandor. It has two low-distortion, low noise VCA channels and exponential sensitivity of the control inputs means they operate in a very predictable volts-per-dB scale.

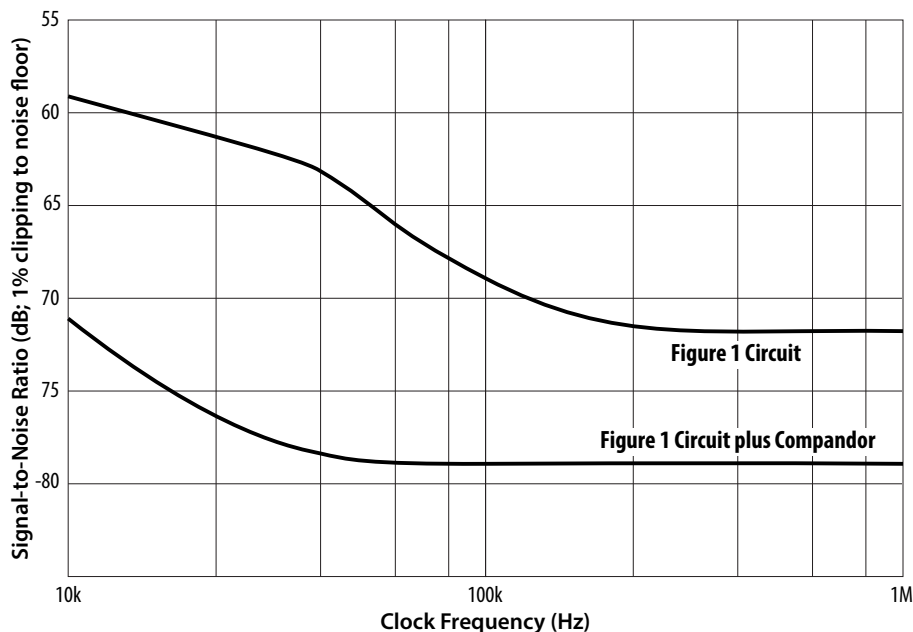


Figure 6: Companding Improves SNR over the full Clock Range