New Universal Continuous-Time Filter with Extended Frequency Range

by Max W. Hauser

Introduction

The original LTC1562, described in the February 1998 issue of this magazine, is a compact, quadruple 2nd order, universal, continuous-time filter that is DC accurate and user programmable for the 10kHz–150kHz frequency range. The LTC1562 introduced Operational Filter building blocks, whose virtual-ground input, rail-to-rail outputs and precision internal R and C components satisfy diverse filter requirements and applications compactly.[1, 2, 3]

The design of the LTC1562 entailed choices in the internal R and C values and internal amplifiers, and these elements were optimized to minimize wideband noise. The LTC1562-2 is a new product with the same block diagram, pinout and packaging, but optimized for higher filter frequencies: 20kHz to 300kHz. The internal precision R and C components and amplifiers are different in the LTC1562-2. Besides covering a full octave of frequencies (150kHz–300kHz) above the range of the LTC1562, the LTC1562-2 also overlaps the LTC1562's utility in the range 20kHz to 150kHz. In this frequency range, the LTC1562-2 typically shows reduced large-signal distortion at a cost of slightly more noise than with the LTC1562. For example, a 100kHz dual 4th order Butterworth lowpass filter with a ±5V supply, built with the LTC1562-2 and lightly loaded, exhibited 2nd-harmonic distortion of –103dB and 3rd-harmonic distortion of –112dB at 20kHz with an output of $1V_{RMS}$ ($2.8V_{P-P}$), and maintained low distortion even with output swings approaching the full supply voltage (–83dB total harmonic distortion, or THD, at $9.7V_{P-P}$ output).

The LTC1562-2 is, therefore, the product of choice for applications above 150kHz as well as for applications in the 20kHz–150kHz range that are especially distortion sensitive. Both the LTC1562 and the LTC1562-2 can replace LC filters or filters built from high performance op amps and precision capacitors and resistors, with a total surface mount board area of $155mm^2$ ($0.24in^2$)—smaller than a dime (the smallest US coin).

Comparison to the LTC1562

The LTC1562-2 both resembles and differs from the LTC1562 as follows:

- ❑ The parts have identical pin configurations and block diagrams (four independently programmable 2nd order Operational Filter blocks with virtual-ground inputs and rail-to-rail outputs).
- ❑ In both products, the user can program the filter's center-frequency parameter (f_0) over a wide range, using resistor values that vary as the desired f_0 changes up or down from a *design-center* value. In the LTC1562, this design-center f_0 is 100kHz; for the LTC1562-2, the value is 200kHz.
- ❑ The LTC1562 is optimized for lower noise, the LTC1562-2 for higher frequencies. Thus, a single LTC1562 section can deliver 103dB SNR in 200kHz bandwidth (Q = 1), whereas a single LTC1562-2 section supports 99dB SNR in 400kHz.

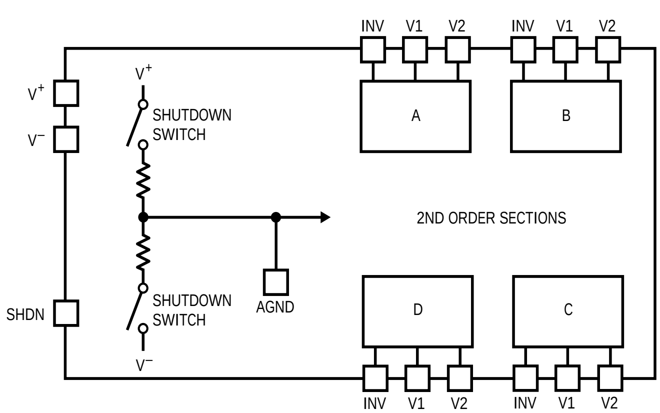

Figure 1. LTC1562-2 block diagram

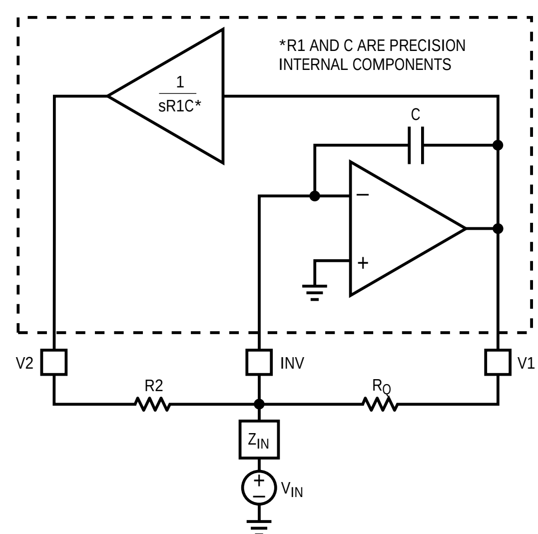

Figure 2. Single 2nd order Operational Filter section (inside dashed line) with external components added: resistor for Z_{IN} gives lowpass at V2, bandpass at V1; capacitor for Z_{IN} gives bandpass at V2, highpass at V1.

- Each chip contains precision R and C components equivalent to eight 0.25% tolerance capacitors and four 0.5% tolerance resistors, as well as twelve op amps with rail-to-rail outputs and excellent high frequency linearity.
- Both circuits operate from nominal 5V to 10V total supplies (single or split). Single-supply applications can use a half-supply, ground-reference voltage generated on the chip.
- Both chips feature a power-down mode that drops the power supply current to zero, except for reverse junction leakages (on the order of 1µA total).

What the LTC1562-2 Can Do

Figure 1 is an overall diagram and Figure 2 a per-section diagram for the LTC1562-2. These are identical to the diagrams for the LTC1562, except for the values of the internal precision components in Figure 2. In the LTC1562-2, R1 is 7958Ω and C is 100pF. External resistors can be combined with an LTC1562-2 section, as shown in Figure 2, to define a second order filter response with standardized parameters f_0, Q and gain. Design equations and procedures appear in the LTC1562-2 data sheet. For example, in Figure 2, R2 sets f_0; R_Q, a multiple of R2, sets Q; and Z_{IN} sets both the gain and the block's function. The 3-terminal blocks minimize the number of external parts necessary for complete 2nd order sections with programmable f_0, Q and gain.

A resistor for Z_{IN} in Figure 2 gives simultaneous lowpass (at V3) and bandpass (at V1) responses. The data sheet describes other ways to exploit the virtual ground INV input. For example, because the V1 output in Figure 2 shows a phase shift of 180° at the user-set center frequency, f_0, summing a V1 output with a feedforward path from the signal source yields a notch response,[2] or with different weighting, allpass (phase equalization), as used in Figure 5 later in this article. Using capacitors together with the INV input's summing capability provides further powerful techniques for zero and notch responses (which, in turn, enable elliptic highpass and lowpass filtering). For example, the two outputs of each 2nd order section have a 90° phase difference, so summing V1 through a capacitor and V2 through a resistor, into another section's virtual-ground input, gives the same notch or allpass option mentioned above but without devoting an additional section for phase shift.[4] Figures 5 and 9, described later, use this RC notch method. Moreover, a capacitor for Z_{IN} in Figure 2 yields simultaneous *highpass* and bandpass responses; the capacitor sets voltage gain, not critical frequencies, with a relationship of the form Gain = C_{IN}/100pF in the LTC1562-2. Low level signals can exploit the built-in gain capability, which raises filter SNR with low input voltage amplitudes. Such abilities to tailor the use of each block and its built-in time constants are reminiscent of an operational amplifier—whence the term "operational filter."

DC performance includes a typical lowpass input-to-output offset of 3mV and outputs that swing (under load) to within approximately 100mV of each supply rail. An internal half-supply reference point (the AGND pin) generates a reference voltage for the inputs and outputs in single-supply applications. The shutdown (SHDN) pin accepts CMOS logic levels and in 20µs puts the LTC1562-2 into a "sleep" mode, in which the chip consumes approximately 1µA (the part will default to this state if the pin is left open). The 16-pin dies is packaged in a 20-pin SSOP (the extra pins in the SSOP are substrate connections, to be returned to the negative supply for best performance).

The following application examples are tailored for specific corner frequencies, which can be modified by properly scaling the external components, as described in the data sheet and in LTC1562 application articles.[2, 3] Expert application assistance can be obtained by calling us at 408-954-8400, x3761. Pin numbers in the figures that follow are for the 20-pin SSOP package, where pins 4, 7, 14 and 17 (not shown) are always tied to the negative power supply rail. As with other filters, achieving low noise and distortion levels requires electrically clean construction (as well as equipment that can measure such performance).

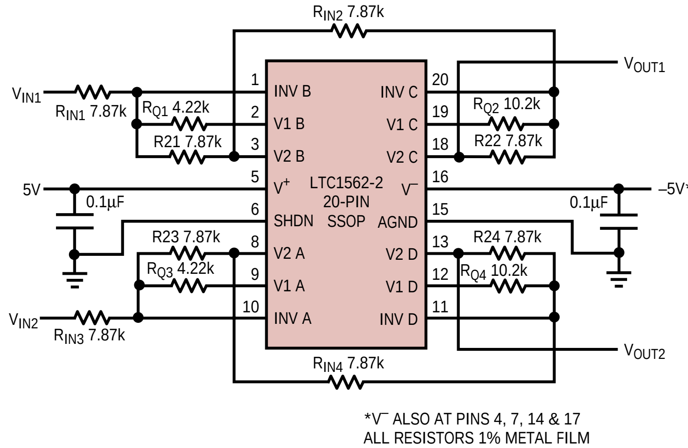

Figure 3. Dual 4th order 200kHz Butterworth lowpass filter

Dual 4th Order 200kHz Butterworth Lowpass Filter

Each half of the circuit in Figure 3 provides a classic 4th order lowpass gain roll-off (24dB per octave) with a maximally flat passband. This schematic includes power supply connections for a split ±5V supply, one of the options available for any LTC1562-2

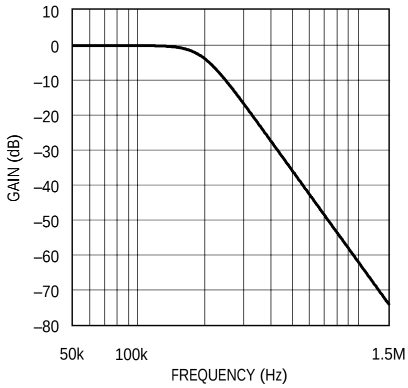

Figure 4. Frequency response of one of the two filters in Figure 3

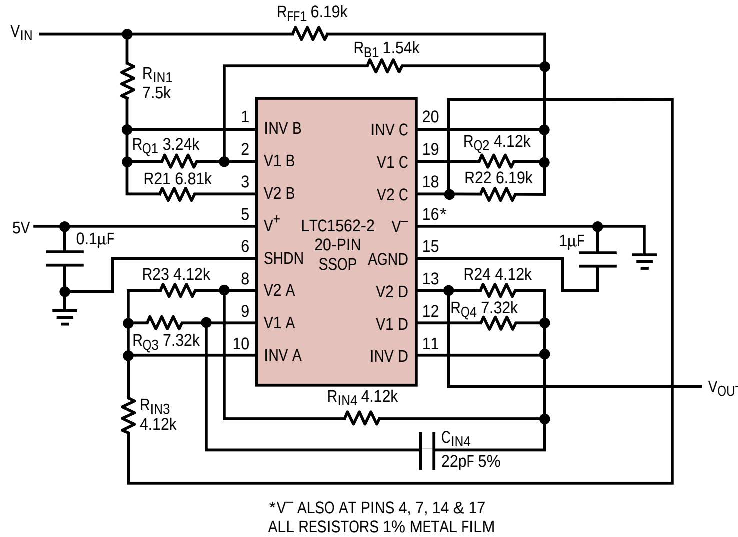

Figure 5. 256kHz linear-phase 6th order lowpass filter

application (Figure 5, in a different application, illustrates connections for a single 5V supply). The circuit of Figure 3 is a higher frequency variation of a 100kHz dual 4th order Butterworth lowpass filter using the LTC1562, which appeared in the February 1998 *Linear Technology* magazine,[1] as well as in the LTC1562 data sheet. Figure 4 shows the measured frequency response for one of the two filters in Figure 3. This ±5V circuit supports rail-to-rail inputs and outputs, with output noise of approximately 60µV_{RMS}, for a maximum SNR of 95dB (compared to 100dB with the LTC1562 equivalent at half as much bandwidth). THD in a 1V_{RMS} output (2.8V_{P-P}) was measured as –87dB at 50kHz and –72dB at 100kHz.

256kHz Phase-Linearized 6th Order Lowpass Filter

Data communication and some signal antialiasing and reconstruction applications demand filters with controlled phase (or time-domain) responses. The circuit in Figure 5 realizes a root-raised-cosine lowpass gain response (Figure 6). For data communications, this filter's time-domain pulse response (Figure 7) approximates, in *continuous time*, the ideal Nyquist-type property of crossing zero at a time interval that is equal to 1/(2f_C). When used as a pulse-shaping filter, this response has the special property of producing minimal intersymbol interference (ISI) among successive data pulses at a data rate of 2f_C (512 kbits/second or ksymbols/second for Figure 5) while simultaneously limiting the transmitted spectrum to a bandwidth approaching the theoretical minimum, which is f_C.[5] Also, data or signal acquisition (before A/D conversion) or reconstruction (after D/A conversion) can benefit from the linear-phase (that is, constant-group-delay) response (typically ±300ns group delay variation over the passband from 0 to f_C, evident in Figure 8).

The filter in Figure 5 achieves these properties by preceding a 6th order lowpass section (the C, A, and D quarters of the LTC1562-2 chip, in that sequence) with a 2nd order allpass response to linearize the phase. This combination illustrates two practical uses of the virtual-ground inputs in the LTC1562-2. Combining two feedforward paths (R_{FF1} from the input and R_{B1} from a bandpass section in the "B" quarter of the LTC1562-2) yields the allpass equalization. Subsequently, R_{IN4} and C_{IN4} sum together two signals with 90° phase difference from the two outputs of the "A" quarter, with an additional 90° phase difference caused by the capacitor, to achieve a stopband notch at a desired frequency.[4] Figure 5 operates from a single supply voltage from 5V to 10V (the AGND pin furnishes a built-in

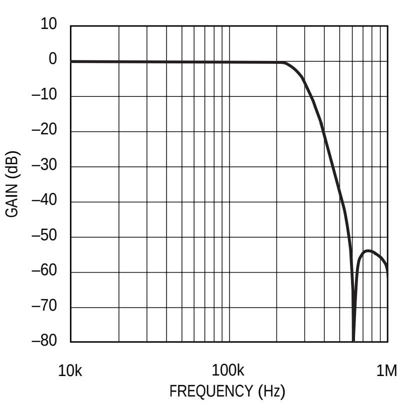

Figure 6. Gain response of Figure 5's circuit

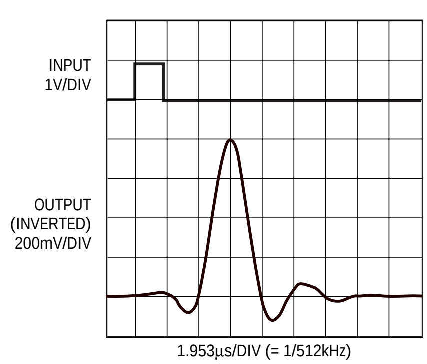

Figure 7. Time-domain response of Figure 5's circuit

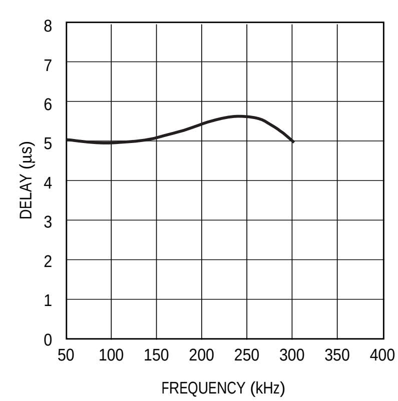

Figure 8. Group delay response of Figure 5's circuit

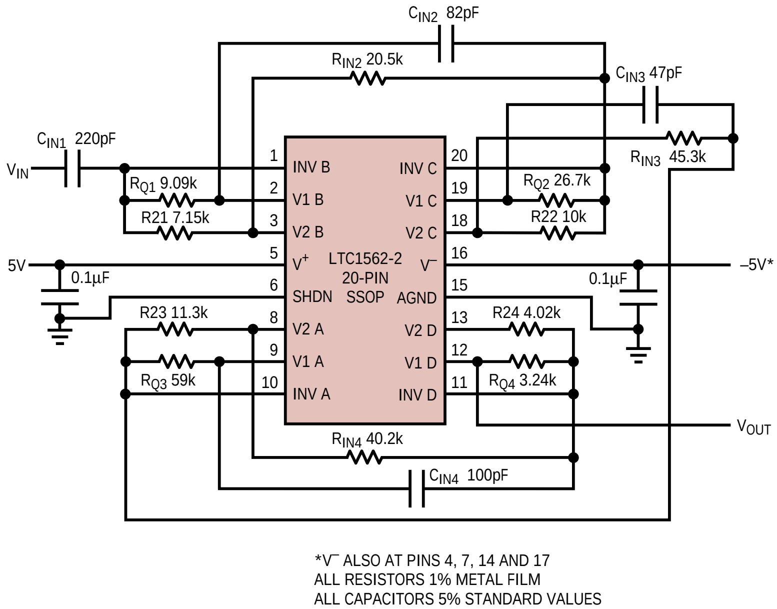

Figure 9. 175kHz 8th order elliptic highpass filter

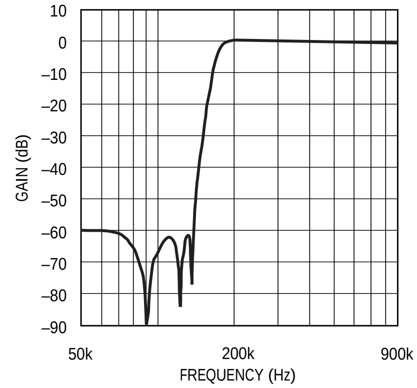

Figure 10. Frequency response of Figure 9's circuit

half-supply ground reference) and exhibits –80dB THD at 50kHz for a 500mV$_{RMS}$ output with a 5V supply.

175kHz 8th Order Elliptic Highpass Filter

In Figure 9, three response notches below the cutoff frequency suppress the stopband and permit a narrow transition band in a 175kHz highpass filter, whose measured frequency response appears in Figure 10. Each notch is produced by summing two 180°-different currents into a virtual-ground "INV" summing input, one current passing through an R_{IN} and the other (from a voltage 90° different from the first) through a C_{IN}.[4] This circuit exhibits only 44µV$_{RMS}$ of output noise over a 1MHz bandwidth and THD of –70dB with a 200kHz signal, 0.5V$_{P-P}$ output, operating from a 5V total supply.

400kHz Dual 6th Order Lowpass Filter

Although it is outside the 300kHz f_0 limit recommended for best accuracy, this dual 6th order 400kHz Butterworth lowpass filter (Figure 11) illustrates an extreme of bandwidth available from the LTC1562-2 with some compromises. The high f_0 requires unusually small resistor values, resulting in heavier loading and an increase in distortion from the LTC1562-2; it was also necessary to adjust the R_Q resistors in Figure 11 downwards to correct for Q enhancement encountered when the designed f_0 is very high.

The circuit of Figure 11 supplements the eight poles of filtering in the LTC1562-2 by driving all four of the virtual-ground INV inputs from R-C-R "T" networks (in place of resistors) and thus obtaining additional real poles (a method described in the original LTC1562 application article[1] and data sheet). Two such real poles replace the Q = 0.518 pole pair of a conventional 6th order Butterworth pole configuration, to good accuracy. The measured frequency response of one 6th order section appears in Figure 12. With ±5V power, this circuit permits rail-to-rail inputs and outputs and exhibits THD, at 1V$_{RMS}$ (2.8V$_{P-P}$) output, of –92dB at 50kHz and –79dB at 100kHz. Output noise

continued on page 35

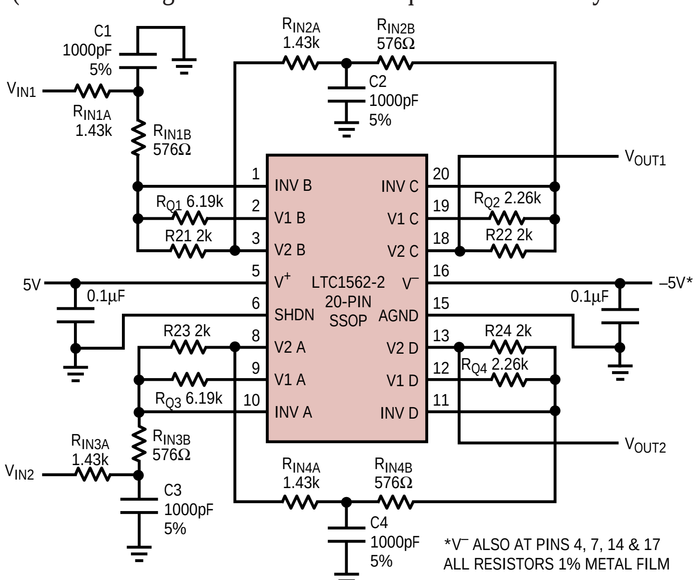

Figure 11. 400kHz dual 6th order Butterworth lowpass filter

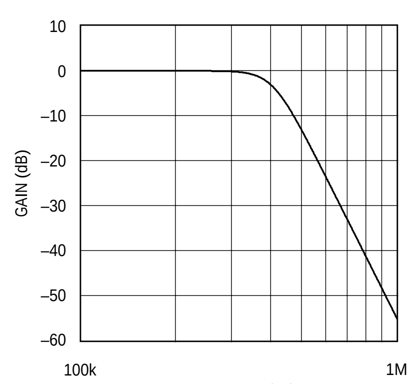

Figure 12. Frequency response of Figure 11's circuit

LTC1562-2, continued from page 10

level is 44µV_{RMS} over a bandwidth of 800kHz or 98dB below the maximum unclipped output.

Acknowledgments

Philip Karantzalis and Nello Sevastopoulos of LTC's Monolithic Filter Design and Applications Group contributed to the application examples.

References

1. Hauser, Max. "Universal Continuous-Time Filter Challenges Discrete Designs." *Linear Technology* VIII:1 (February 1998), pp. 1–5 and 32.
2. Sevastopoulos, Nello. "How to Design High Order Filters with Stopband Notches Using the LTC1562 Quad Operational Filter, Part 1." *Linear Technology* VIII:2 (May 1998), pp. 28-31.
3. Sevastopoulos, Nello. "How to Design High Order Filters with Stopband Notches Using the LTC1562 Quad Operational Filter, Part 2." in the Design Ideas section of this issue of *Linear Technology*.
4. LTC1562 Final Data Sheet.
5. For example: Schwartz, Mischa. *Information Transmission, Modulation, and Noise*, fourth edition, pp. 180–192. McGraw-Hill 1990.