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.\textsuperscript{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\textsubscript{RMS} (2.8V\textsubscript{p-p}), and maintained low distortion even with output swings approaching the full supply voltage (~83dB total harmonic distortion, or THD, at 9.7V\textsubscript{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\textsuperscript{2} (0.24in\textsuperscript{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:

\begin{itemize}
  \item 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).
  \item In both products, the user can program the filter’s center-frequency parameter (f\textsubscript{0}) over a wide range, using resistor values that vary as the desired f\textsubscript{0} changes up or down from a design-center value. In the LTC1562, this design-center f\textsubscript{0} is 100kHz; for the LTC1562-2, the value is 200kHz.
  \item 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.
\end{itemize}
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 leakage (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 f0, Q and gain. Design equations and procedures appear in the LTC1562-2 data sheet. For example, in Figure 2, R2 sets f0, Q, a multiple of R2, sets Q; and ZIN 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 f0, Q and gain.

A resistor for ZIN 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, f0, summing a V1 output with a feedforward path from the signal source yields a notch response, 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. Figures 5 and 9, described later, use this RC notch method. Moreover, a capacitor for ZIN in Figure 2 yields simultaneous highpass and bandpass responses; the capacitor sets voltage gain, not critical frequencies, with a relationship of the form Gain = CIN/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 at the user-set center frequency, f0, summing a V1 output with a feedforward path from the signal source yields a notch response, 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. Figures 5 and 9, described later, use this RC notch method. Moreover, a capacitor for ZIN in Figure 2 yields simultaneous highpass and bandpass responses; the capacitor sets voltage gain, not critical frequencies, with a relationship of the form Gain = CIN/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.

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**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.
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, 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 60µVRMS, for a maximum SNR of 95dB (compared to 100dB with the LTC1562 equivalent at half as much bandwidth). THD in a 1VRMS output (2.8VP-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/(2fC). 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 2fC (512 kbits/second or 512 symbols/second for Figure 5) while simultaneously limiting the transmitted spectrum to a bandwidth approaching the theoretical minimum, which is fC. 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 fC, 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 (RFF1 from the input and RB1 from a bandpass section in the “B” quarter of the LTC1562-2) yields the allpass equalization. Subsequently, RIN4 and CIN4 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. Figure 5 operates from a single supply voltage from 5V to 10V (the AGND pin furnishes a built-in
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. 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.

![Figure 9. 175kHz 8th order elliptic highpass filter](image)

Figure 9. 175kHz 8th order elliptic highpass filter

### 400kHz Dual 6th Order Lowpass Filter

Although it is outside the 300kHz f0 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 f0 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 RQ resistors in Figure 11 downwards to correct for Q enhancement encountered when the designed f0 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 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

![Figure 11. 400kHz dual 6th order Butterworth lowpass filter](image)

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

![Figure 10. Frequency response of Figure 9's circuit](image)

Figure 10. Frequency response of Figure 9’s circuit

![Figure 12. Frequency response of Figure 11’s circuit](image)

Figure 12. Frequency response of Figure 11’s circuit
band gain can be higher than 0dB or if internal nodes are allowed to have gains higher than 0dB. Please contact the LTC Filter Design and Applications Group for further details.

The low noise behavior of the filter makes it useful in applications where the input signal has a wide voltage range. This is true provided the filter magnitude response does not change with varying input signal levels, that is, the filter gain is linear. The gain linearity measured at the 100kHz theoretical center frequency of the filter is shown in Figure 7. The gain is perfectly linear for input amplitudes up to 1.25VRMS (3.5Vp-p) so an 84dB dynamic range can be claimed. The input signal, however, can reach amplitudes up to 3VRMS (8.4Vp-p, 92dB SNR) with some reduction in gain linearity.

LTC1735/LTC1736, continued from page 6

Conclusion

The LTC1735 and LTC1736 are the latest members of Linear Technology’s family of constant frequency, N-channel high efficiency controllers. With new protection features, improved circuit operation and strong MOSFET drivers, the LTC1735 is an ideal upgrade to the LTC1435/LTC1435A for higher current applications. With the integrated VID control, the LTC1736 is ideal for CPU power applications. The high performance of these controllers with wide input range, 1% reference and tight load regulation makes them ideal for next generation designs.

References

4. LTC1562 Final Data Sheet.

LTC1562-2, continued from page 10

level is 44µVRMS over a bandwidth of 800kHz or 98dB below the maximum unclipped output.

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Other Applications

The LT1505 can also be used in other system topologies, such as the telecom application shown in Figure 5. The circuit in Figure 5 uses the battery to supply peak power demands.

By doing so, the required peak power from the wall adapter can be much lower than the peak power required by the load. The wall adapter has to supply the average power only.

Conclusion

The LT1505 is a complete, single-chip battery charger solution for today’s demanding charging requirements in high performance laptop applications. The device requires a small number of external components and provides all necessary functions for battery charging and power management. High efficiency and small size allow for easy integration with the laptop circuits. Also, by adding a simple external circuit, charging can be easily controlled by the host computer, allowing for more sophisticated charging schemes.

LT1505, continued from page 25

SW, VBAT and GND in Figure 2 will help in spreading the heat and will reduce the power dissipation in conductors and MOSFETs.

Step-Down Conversion, continued from page 30

lower cost LTC1430A replacing the LTC1649. The LTC1430A does not include the 3.3V to 5V charge pump and requires a 5V supply to drive the external MOSFET gates. The current drawn from the 5V supply depends on the gate charge of the external MOSFETs but is typically below 50mA, regardless of the load current on the 2.5V output. The drains of the Q1/Q2 pair draw the main load current from the 3.3V supply. The remaining circuit works in the same manner as in Figure 1. Efficiency and performance are virtually the same as the LTC1649 solution, but parts count and system cost are lower.

In a 3.3V to 2.5V application, the steady-state, no-load duty cycle is 76%. If the input supply drops to 3.135V (3.3V – 5%), the duty cycle requirement rises to 80% at no load, and even higher under heavy or transient load conditions. Both the LTC1649 and the LTC1430A guarantee a maximum duty cycle of greater than 90% to provide acceptable load regulation and transient response. The standard LTC1430 (not the LTC1430A) can max out as low as 83%—not high enough for 3.3V to 2.5V circuits. Applications with larger step-down ratios, such as 3.3V to 2.0V, can use the circuit in Figure 3 successfully with a standard LTC1430.