Technical Article

How to Achieve Microvoltage-level Precision in Thermopile Applications

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Thermopiles are useful noncontact sensors for measuring not only temperature but also detecting select gases. Since thermopiles may have relatively high series impedance, they present numerous challenges to circuit designers trying to obtain absolute precision across a wide temperature range while meeting required minimum resolutions. The low output voltage of a thermopile (from hundreds of microvolts to a few millivolts) requires a high gain configuration that makes low offset and temperature drift very important. This requires high-precision operational amplifiers (op amps) with low or no 1/f noise, low input bias current (IB) and very low offset shift over time - such as zero-drift amplifiers.

In this article, I'll describe best practices for interfacing zero-drift amplifiers to such sensors, including how to reduce the output noise in order to improve resolution, and explain why some circuits need matched input impedance. This is the third installment in a four-part series discussing how to increase system accuracy and efficiency with op amps built on TI's latest proprietary complementary metal-oxide semiconductor precision process technology.

Achieve ultra-high precision in thermopile applications.

Start your design today with the OPA387 ultra-high precision, zero-drift, low-input-bias current op amp.

Since most thermopile applications require a low frequency response, from a few hertz to 300 Hz, it's tempting to use a micropower low gain-bandwidth (350 kHz) zero-drift op amp such as the OPA333. However, since an amplifier's broadband noise is inversely proportional to its quiescent current (I_Q), micropower devices like the OPA333 naturally have a higher noise spectral density than their higher-bandwidth (higher-I_Q) alternatives, which fundamentally limits its resolution in thermopile applications.

Figure 1 is an example of one such thermopile detector with a 100-µV thermopile voltage (Vtp), using the OPA333 with G = 1,001. In this application, the 705-µVrms total output voltage noise is predictably dominated by the OPA333's 55-nV/√Hz broadband noise spectral density, and not by the thermal noise of the internal 10-kΩ thermopile resistance (Rtp), and results in a minimum signal-to-noise ratio (SNR) of just 43 dB, 20×log(100 mV/705 µV). Also, in order to keep the output voltage of the OPA333 in its linear range, as defined in the data-sheet under open-loop gain conditions, may require a minimum 100-mV reference voltage (Vref) for a single-supply application.

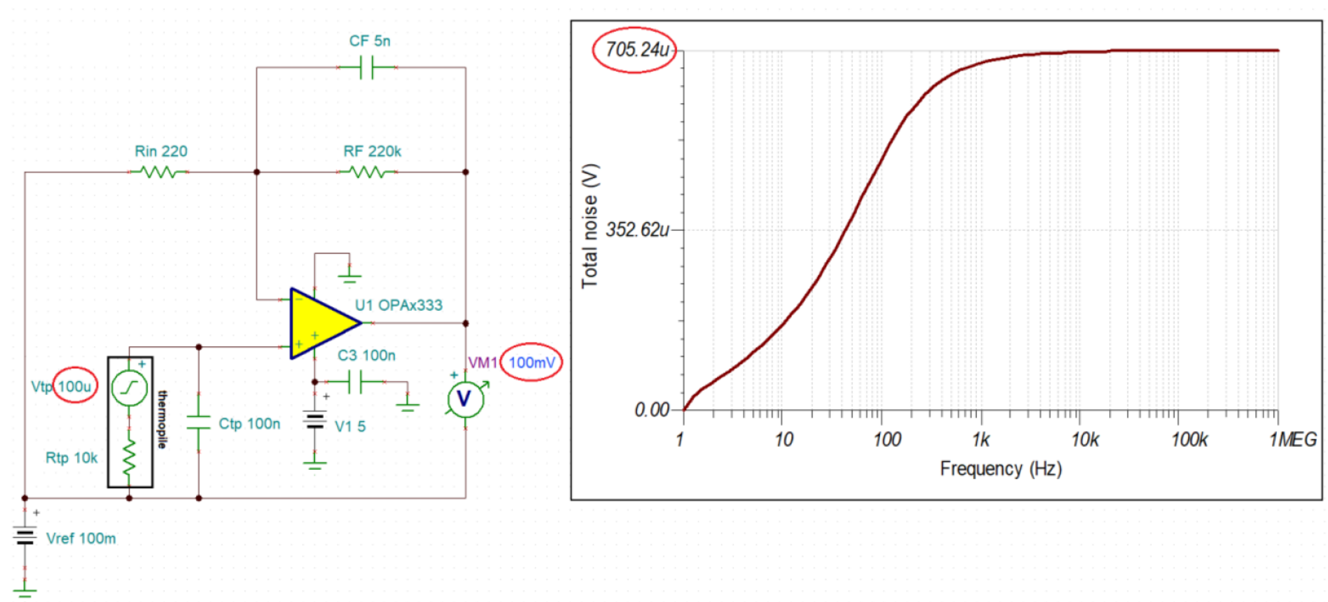

Figure 1. The OPA333 in a Thermopile Application with G = 1,001

For most thermopile applications, it's best to select an op amp so that the thermal noise of Rtp – instead of the op amp's input broadband noise – dominates the total noise. One such zero-drift op amp is OPA189 with its low broadband noise of 5.2 nV/√Hz that is well below 12.7 nV/√Hz, √(4kTR), thermal noise of the internal 10kΩ thermopile resistance - this results in the total input noise density of 13.7 nV/√Hz that is clearly dominated by Rtp thermal noise.

Figure 2 shows a schematic of a thermopile circuit using the OPA189 in a dual-supply application. The internal 10-kΩ thermopile resistance and the external 100-nF capacitor (Ctp) form a low-pass noise filter with a −3 dB cut off frequency: 159.2Hz, fc=1/(2×π×10kΩ ×100nF) – this filter is especially important in case of high thermopile Rtp where Ctp may be used to optimize the sensor noise performance and its response time.

In Figure 2, the OPA189 amplifier is likewise set to a gain of 1,001 with its −3 dB cut off frequency of 144.8 Hz set by the choice of RF||CF feedback: fc=1/(2×π×220kΩ×5nF). All this result in the much-improved output total noise of 165.6 uVrms. However, OPA189 has a higher speed internal offset correction circuitry where large impedance mismatch between the input terminals cause IB chopping spikes to be converted into an additional voltage offset error. This induces 52uV input offset, which gets amplified to the output and results in a large output error.

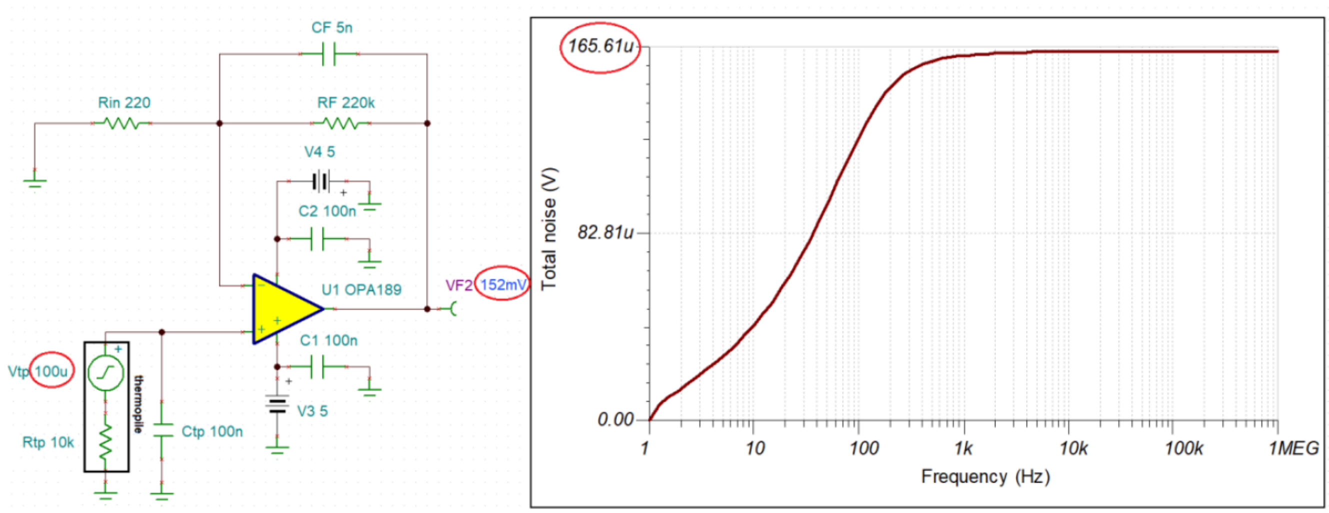

Figure 2. The OPA189 in a Thermopile Application with G = 1,001

In the case of balanced input impedance, the IB chopping spikes cancel each other. Therefore, it is possible to effectively eliminate this offset error by adding an Rtp_match 10-kΩ resistor to the inverting input terminal. Having said that, adding a matching resistor will naturally cause an increase of the total output voltage noise by a factor of approximately √2 (to 254.9 μVrms). Cin_match equal to OPA189 internal input capacitance (Cin_diff+Cin_cm) may also be needed in order to maintain good stability of the thermopile solution as shown in Figure 3.

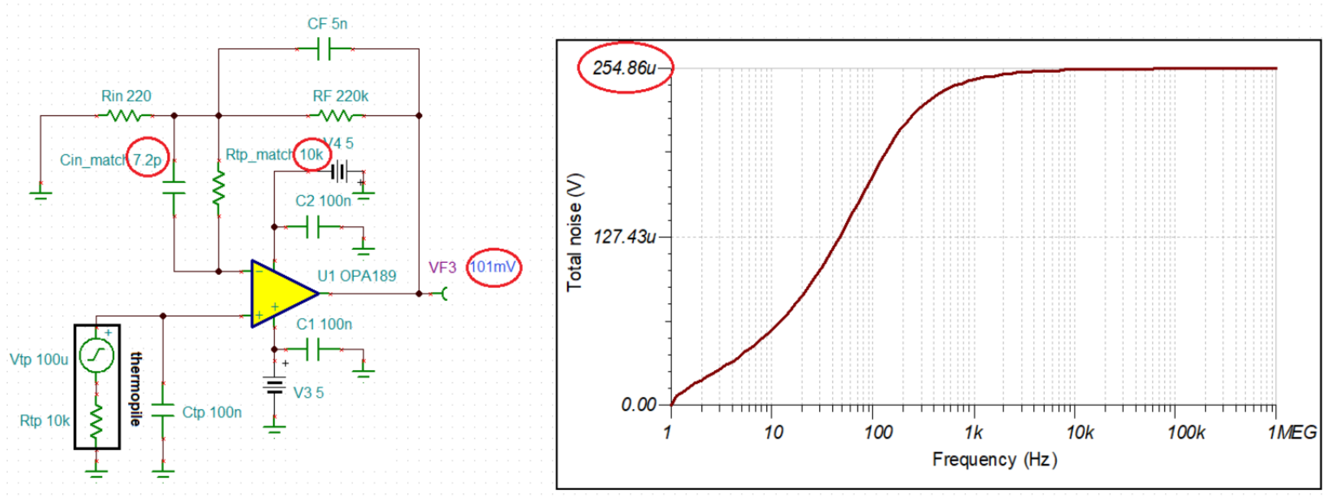

Figure 3. The OPA189 in a Thermopile Application with Matching Input Impedance

Consequently, in order to arrive at the best solution for thermopile applications, consider a low-noise chopper amplifier such as the OPA387, which features not only extremely low maximum input voltage offset and offset drift (1 μV and 0.012 μV/C, respectively) but also has a typical 8.5-nV/√Hz voltage noise spectral density at 100 Hz and very low current noise of 70 fA/√Hz at 10 Hz (contributing only 0.7 nV/√Hz across the 10-kΩ thermopile). This op amp is also much more forgiving when it comes to mismatched input impedance. Thus, using the OPA387 in the now-familiar thermopile application circuit results in lower (190.7 μVrms) total output noise and (aside from the inherent tiny offset of the amplifier) negligible output error – see Figure 4.

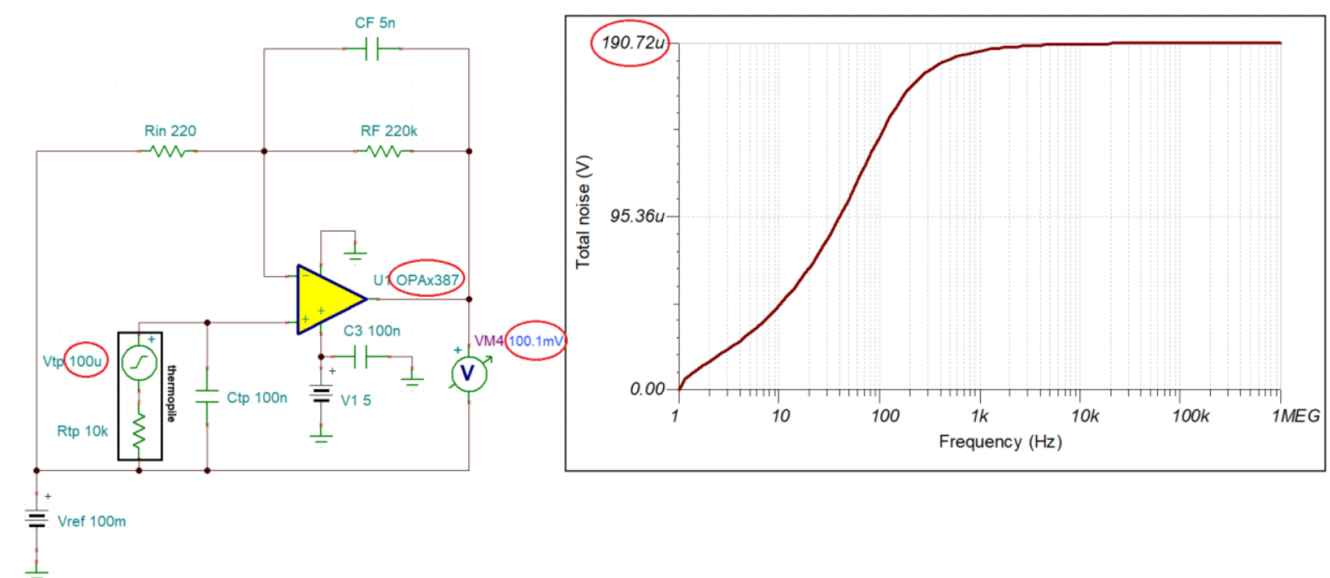

Figure 4. The OPA387 in a Thermopile Application with G = 1,001

Figure 5 shows a complete implementation of the thermopile circuit with G = 1,001, including a Vref buffer that assures linear operation of the OPA387 output stage on a single supply and an additional low-pass output filter (Ro||Co) with a cutoff frequency of 159.2 Hz. This filter further decreases the total integrated output noise down to 154 µVrms, resulting in an overall higher resolution of the solution; a minimum output SNR of 56 dB for a Vtp of 100 µV and a maximum SNR of 86 dB for a Vtp of 3.1 mV.

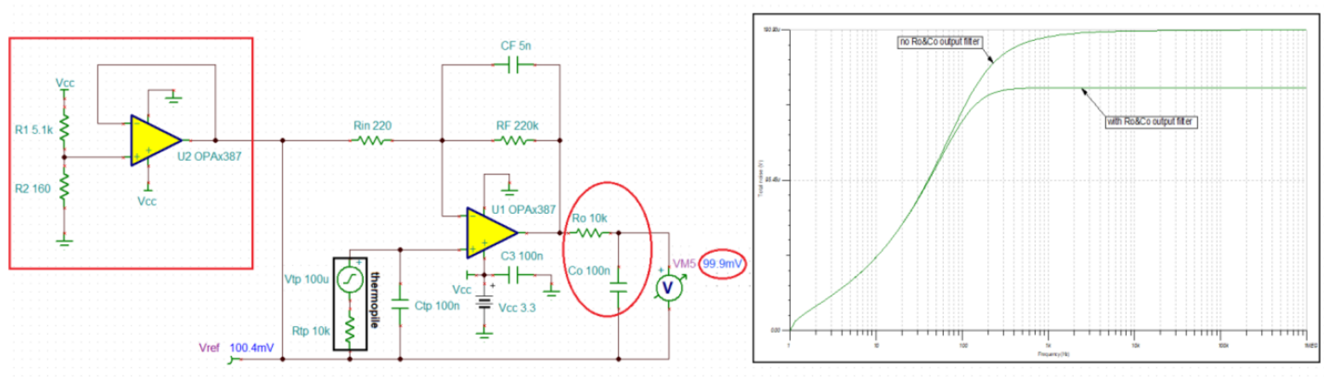

Figure 5. The OPA387 Thermopile Application with Reference Circuit and Output Filtering

You could also use a dual supply, or the LM7705 negative charge pump, to drive the OPA387's negative supply pin, as shown in Figure 6. This method would eliminate the need for Vref circuitry by allowing the op-amp output to reach system ground. The graph on the right in Figure 6 shows the first, the second and the third-order AC gain response of the thermopile circuit for the different filtering schemes I've discussed so far.

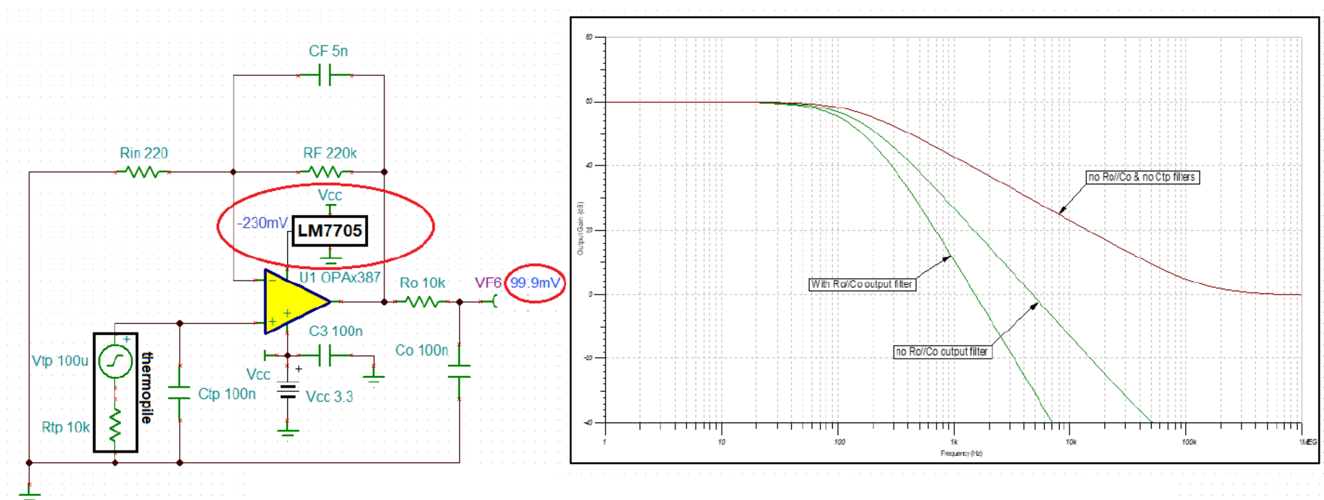

Figure 6. The OPA387 Thermopile Application with the LM7705 Negative Charge Pump and Output Filtering

Conclusion

Thermopiles with different output voltage ranges or series Rtp may require different op-amp gains or alternative filtering schemes to optimize their performance. By maximizing the amount of signal coming from the detector, you may lower the gain of the circuit (and thus lower the total output noise), improving the resolution of your thermopile application.

Zero-drift chopper amplifiers are generally preferable in thermopile applications because of their very low offset, offset drift and no 1/f noise. When selecting an amplifier, it's important to choose one with a broadband noise spectral density that is below the thermopile's Rtp thermal noise. Since op-amp broadband noise is inversely proportional to its I_Q, micropower amplifiers have higher noise than what thermopile applications typically require. Therefore, higher-speed amplifiers with higher I_Q and lower noise density, such as the OPA387, will typically offer better performance in thermopile applications.

The next installment of this series will discuss how to achieve a more accurate current limit and avoid damaging a device under test.