Technical Article
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Micropower ICs Take the Heartburn Out of Heart Rate Monitor Designs

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IDEA IN BRIEF

Using a variety of the latest micropower, high-precision IC components, it's possible to design a low power heart rate monitor (HRM) that also packs in additional features. This article discusses these components and features.

The rigors of designing a portable heart rate monitor are enough to give anyone a case of angina. For starters, cardiac monitors must meet the highest standards for safety, reliability, and accuracy. Designers must also contend with the power constraints of button cell batteries. Add the market demand for added functionality but no increase in space, power, or cost to the requirement list and the heartburn sets in.

Fortunately, there's relief. Using a variety of the latest micropower, high-precision IC components, it's possible to design a low power heart rate monitor (HRM) that also packs in additional features.

The most critical function of the low power ICs is extending the battery life of an HRM, which measures a patient's heart rate in real time or records it for later study. Portable HRMs operate from batteries for long periods of time, and require low current consumption. Low voltage batteries have been used for decades as the single power source in Holter monitors and other portable ECG systems to ensure safety. The last thing a heart patient or the sensitive equipment needs is a zap of "hot" line voltage. Micropower ICs operate on low voltage and current, thus conserving battery power.

ANALOG FRONT-END OF HRM

Calculating heart rate and displaying ECG waves is the primary purpose of an HRM, which should also provide lead off detection. Figure 1 shows the block diagram of an HRM design. The analog front end uses micropower instrumentation amplifiers (in-amps) and operational amplifiers (op amps), as well as a microconverter, which includes a 12-bit analog-to-digital converter (ADC), sample-and-hold amplifier, and digital processor. The processed data is sent to a PC for display.

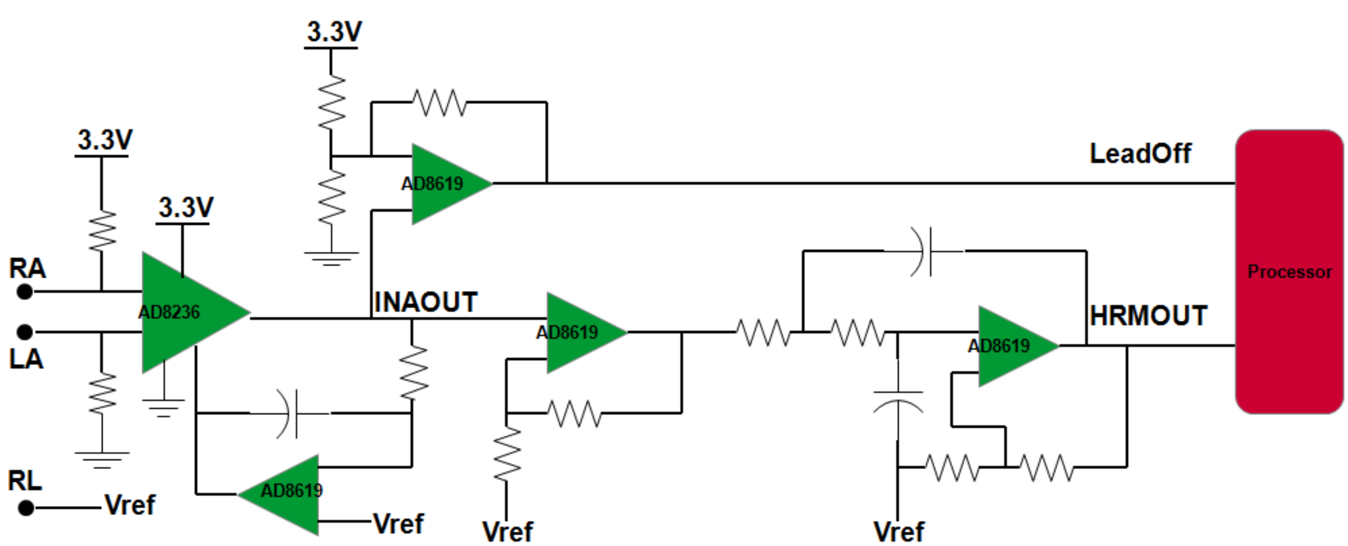


Figure 1. A Micropower In-Amp Makes an Excellent Input Amplifier for Heart Rate Monitors

A micropower in-amp makes an excellent input amplifier. The low power, small size, high common-mode rejection ratio (CMRR) over frequency, and rail-to-rail input and output are well-suited for battery-powered applications. A high-performance micropower in-amp solves many of the typical challenges of measuring body surface potentials, which range from 0.2 mV to 2 mV. The optimum in-amp for this application should have high CMRR to help reject common-mode signals, such as line noise or high frequency EMI from operating room equipment. The rail-to-rail output facilitates a wide dynamic range, allowing for higher gains than typical in-amps. In addition, designers should look for micropower in-amps that implement a natural RC filter that reduces high-frequency noise when series input resistors are used in front of the amplifier.

Following the micropower in-amp in the main signal chain is an integrator feedback network implemented with a 4.7 µF capacitor and a 100 kΩ resistor to set the −3 dB cutoff frequency of the high-pass filter. It rejects any differential dc offsets that may develop from the half-cell overpotential of the electrode. A micropower op amp provides an additional gain of 13× to amplify the weak signal. An active second-order, low-pass Bessel filter removes signals greater than approximately 50 Hz.

Because the circuit is battery-operated, tying the circuit's reference voltage to the patient allows the patient to serve as the reference, thus increasing the common-mode rejection. This is important when measuring ECG signals. Note some machines will generate power from pedaling, so no isolation is used.

REFERENCE

This design assumes the ECG signal ranges from 0.2 mV to 2 mV. To prevent the signal from being clamped and maximize the dynamic range of ADC (0 V to 1.25 V), 0.625 V bias is added. As shown in Figure 2, a resistor divider and a buffer generate a 0.625 V reference, which is also used to bias the ECG signal as shown in Figure 1.

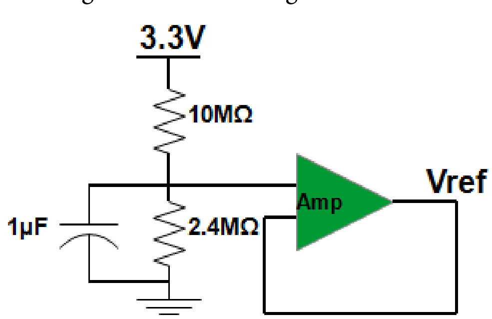


Figure 2. A Resistor Divider and a Buffer Generate 0.625 V Reference

LEAD OFF DETECTION

The HRM should provide an alert if an electrode is making poor electrical contact. When used in conjunction with two 20 MΩ resistors at the inputs of the micropower in-amp (see Figure 1), the resistors offset the inputs when an electrode falls off a patient. In normal operation, the output of the micropower in-amp is the reference voltage; if an electrode falls off, the output goes to 0 V. Figure 3 shows the lead off detection circuit; the output of the micropower in-amp is connected to the input of the detection circuit.

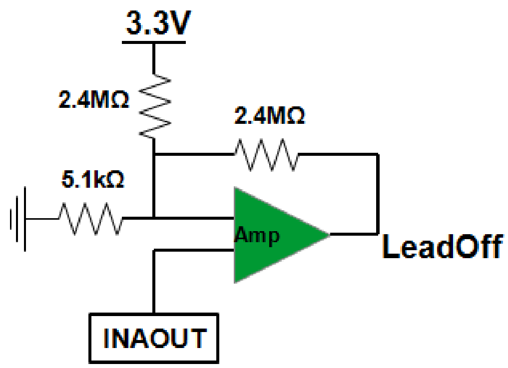
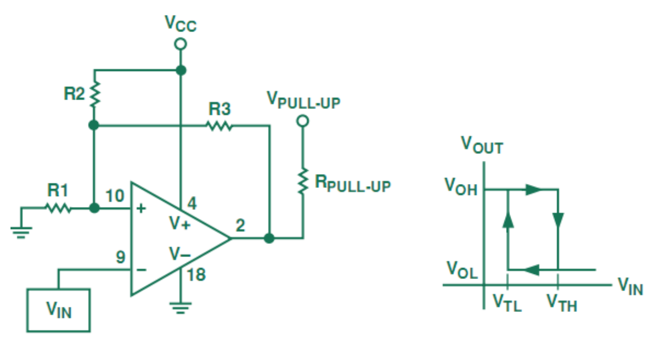


Figure 3. The In-Amp Output Connects to the Input of the Lead Off Detection Circuit

In fact, the lead off detection circuit is a comparator with hysteresis implemented using an amplifier. A high-gain comparator determines whether an input voltage is higher or lower than a reference voltage, and outputs a voltage representing the sign of the net difference. Hysteresis gets rid of instabilities due to noise by using small amounts of positive feedback. In single-supply operation, the reference must be offset to allow the circuit to operate entirely within the first quadrant. Figure 4 shows how this can be achieved. The resistor divider (R2 and R1) creates a positive reference voltage that is compared with the input. The equations for designing the dc thresholds are shown in Figure 4.



SINGLE-SUPPLY INVERTING HYSTERESIS:

$V_{TL} = (R1||R3)*V_{CC}/((R1||R3) + R2) + (R1||R2)*V_{OL}/((R1||R2) + R3)$

$V_{TH} = (R1||R3)*V_{CC}/((R1||R3) + R2) + (R1||R2)*V_{OH}/((R1||R2) + R3)$

$HYST = V_{TH} - V_{TL}$

$HYST = (R1||R2)*(V_{OH} - V_{OL})/(R1||R2 + R3)$

Figure 4. How a Comparator Works in a Single-Supply Operation

Referring to Figure 3, R1 = 5.1 kΩ, R2 = R3 = 2.4 MΩ, V_{CC} = 3.3 V, V_{OL} = 0 V, V_{OH} = 3.3 V. Using the formula in Figure 4, we calculate:

V_{TL} = 0.006983 V

V_{TH} = 0.013966 V

Hysteresis = $V_{TH} - V_{TL}$ = 0.006983 V

In normal operation, the output of a micropower in-amp should be V_{REF}, so the comparator's output is 0 V when the lead is off. The output of the micropower in-amp is also 0 V when the comparator's output rises to 3.3 V. Depending on the interrupt mode of the microcontroller, the rising edge or high level can trigger the microcontroller's interrupt. When the lead is on again, the comparator's output will fall to 0 V and the falling edge or low level can trigger the interrupt.

SIGNAL PROCESSING IN THE MICROCONVERTER

Figure 5 shows the analog output of the HRM. We can see 50 Hz noise coupled from a 220 V power line. The acquired signal can be processed by a digital notch filter in the microconverter. For this purpose, we designed a second-order FIR filter, based on a sampling frequency of 200 Hz. Using the pole-zero placement method, the notch filter was designed to suppress the 50 Hz interference.

Figure 5. The Monitor's Analog Output Shows Noise Coupled from the Power Line

The FDATool from MATLAB, shown in Figure 6, was used to design the notch filter. In the pole-zero plot, two zeroes are placed at ±π/2 phase. With a 200 Hz sampling rate, the 50 Hz component will be removed.

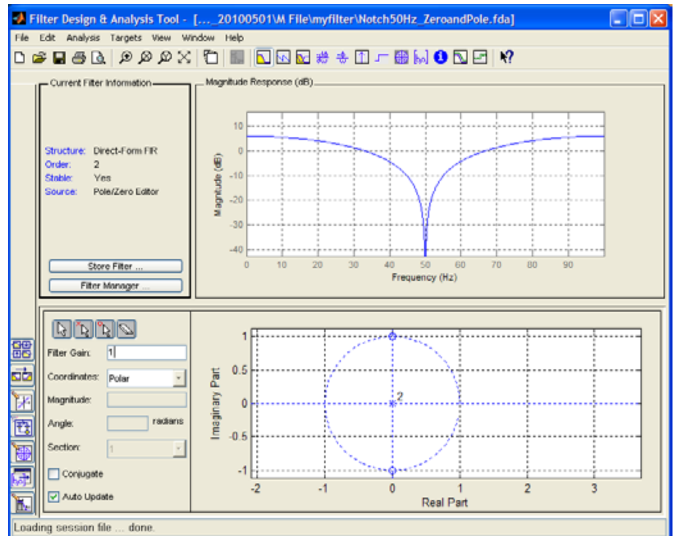


Figure 6. Using FDATool from MATLAB, a Digital Notch Filter is Designed to Remove the Noise

The zeroes are placed in a unit circle—the coefficient of the FIR is integer— so the microconverter's computing burden will be decreased greatly. The transfer function follows:

$$H(z) = 1 + z^2$$

The transfer function can be converted into a programmable recursive algorithm,

$$y[n] = x[n] + x[n-2]$$

where:

n, means the present value

n – 1 means the value in the previous instant, and so on.

According to the coefficient, the C Code is shown in Figure 7.

Figure 8 shows the ECG wave after the digital notch filter. The 50 Hz noise has been removed.

```
//Sample Rate = 200
//Attenuate 50Hz Noise,2 order
//For Pole/Zero Plot and Magnitude Response, refer to Notch50Hz_ZeroandPole.fda
int NortchFilter(int data)
{
        static int x[6],n=2;
        int y0;
        x[n]=x[n+3]=data;
        y0=x[n]+x[n+2];
        if(--n<0)
            n=2;
        y0>>=1;
        return(y0);
}
```

Figure 7. C Code of the Notch Filter

Figure 8. ECG Wave, Minus the Noise, is Displayed on the PC

Table 1. The Results of the Experiment Meet the Standard for Allowable Readout Error

MPS450 Heart Rate (bpm)	30	40	60	80	100	120	140	160	180	200
Calculation Value (bpm)	30	40	60	80	100	120	140	160	180	198
Readout Error (bpm)	0	0	0	0	0	0	0	0	0	2
Readout Error (percent)	0	0	0	0	0	0	0	0	0	1%

ACCURACY OF THE HEART RATE CALCULATION

The minimum allowable heart rate meter range is 30 bpm to 200 bpm, with an allowable readout error “of no greater than ±10 percent of the input rate, or ±5 bpm, whichever is greater,” according to the ANSI/AAMI EC13:2002 standard for cardiac monitors, heart rate meters, and alarms.

This HRM design uses Fluke’s MPS450 multiparameter ECG simulator to generate the ECG signal at the input of the HRM board at different heart rates. The microconverter samples the output of the board and calculates the heart rate value, which is then transferred to a PC for display.

POWER CONSUMPTION

The HRM is designed to operate from lithium batteries or button batteries so that it may be used in portable applications such as sports monitoring, for an extended period of time. The analog front end should be guaranteed to operate from 1.8 V to 5 V.

With a 3.3 V power supply, the analog front-end board consumes 300 μA and the microconverter consumes 330 μA (using a 1 MHz internal system clock). The total current consumption of the HRM is 660 μA. Assuming button cell capacity is 50 mA, the cell can ensure about 75 hours operating time—a very respectable duration for a portable monitor—made possible in large part by the low-power ICs.

REFERENCES

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RESOURCES

Products Mentioned in This Article

Product	Description
AD8236	Micropower Instrumentation Amplifier with Zero Crossover Distortion
AD8619	Low Cost Micropower, Low Noise CMOS RRIO Quad Op Amp

ABOUT THE AUTHOR

David Guo is an applications engineer at Analog Devices in the Precision Signal Conditioning Group. He is responsible for integrated amplifier products such as the AD8236 micropower in-amp featured in this article. He can be reached at david.guo@analog.com

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