AN-601
APPLICATION NOTE

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Minimizing Power Consumption of iMEMS® Accelerometers

by Harvey Weinberg

Introduction

Portable battery-powered devices are perhaps the largest growth market segment today. In an effort to reduce the size and weight of these devices, battery capacity is often minimized. To maintain good performance, designers are forced to carefully examine their circuits for ways to decrease power consumption.

This application note will outline methods to reduce the power consumption of iMEMS accelerometers using both hardware and software techniques. A special section will cover some techniques that are specific to certain parts.

Basic Methods

There are three basic methods to reduce power consumption:

- Lower the supply voltage
- Turn off the accelerometer when measurements are not taking place
- Use clever software

All of the techniques outlined in this application note are no more than extensions of these methods.

Lower the Supply Voltage

Often the most straightforward and lowest cost way to reduce power consumption is to simply reduce the supply voltage. Figure 1 shows the typical power consumption versus the supply voltage for several iMEMS accelerometers.

While there are great power savings to be had by simply lowering the supply voltage, there is a price to be paid as well. As all these accelerometers are ratiometric, lowering their supply voltage will lower the sensitivity by roughly the same ratio. The exception to this is the PWM outputs of the ADXL202/ADXL210. These outputs remain fairly constant as the supply voltage changes.

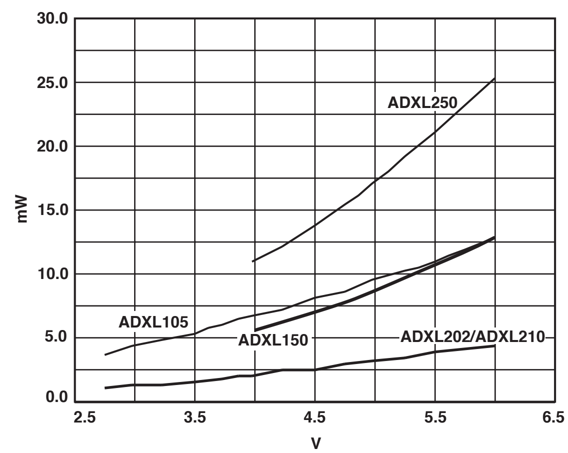

Figure 1. Power Consumption vs. Supply Voltage for Several Accelerometers

If the entire system is ratiometric (i.e., the A/D reference voltage is proportional to V_{DD}), this reduction of sensitivity is not a problem.

A potentially more serious problem is that the accelerometer's noise performance is generally degraded as the supply voltage is reduced. This cannot be mitigated by using a ratiometric system and must be kept in mind during system design.

Turn Off the Accelerometer

Turning off the accelerometer when measurement is not occurring can result in great power savings. This is particularly true in applications where the sampling rate is low. Figure 2 illustrates the average power consumed by an ADXL150 versus the power cycling (sampling) frequency (for V_{DD} = 5 V and a 25 μs A/D conversion time). Note that the Nyquist criteria must be satisfied in any case, and the sampling frequency must be at least twice the input frequency.

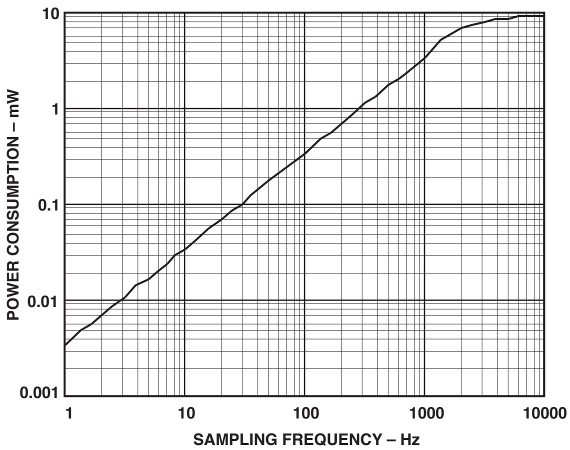

Figure 2. ADXL150 Average Power Consumption vs. Power Cycling Frequency

In iMEMS accelerometers, the turn-on time is mainly a function of the bandwidth. While higher bandwidths will allow lower power operation (due to faster power cycling rates), doing so generally results in more noise. Many systems include an antialiasing filter between the accelerometer and the A/D converter. The time constant of this antialiasing filter must also be considered when power cycling.

Table I shows the approximate turn-on time (including the internal low-pass filter) for several accelerometers. Faster turn-on times allow the user to very quickly turn on the accelerometer, measure the acceleration, and then turn off the accelerometer.

Table I. Accelerometer Turn-On Time

Model	Bandwidth	Turn On
ADXL202/ADXL210	5000 Hz	460 µs
ADXL105	12 kHz	700 µs
ADXL150/ADXL250	1 kHz	360 µs
ADXL190	400 Hz	750 µs

Adding a single-pole low-pass filter (antialiasing) to the accelerometer output will lengthen the turn-on time by $5/(2\pi f)$ seconds, where f is the corner frequency of the filter.

For example, restricting the bandwidth of an accelerometer to 50 Hz by adding a single-pole low-pass filter would add 15.9 ms to the settling time.

Low Power Design Example

Most low power designs appear in devices that measure movements that take place infrequently. These applications are ideal for power cycling. A good example is an automatic shutoff gas valve. In the event of an earthquake, the valve shuts down the natural gas supply to prevent ruptured gas pipes from leaking. Minor tremors (as can be created by large trucks passing by) and single impulse shocks (as would be generated by bumping into the valve) should be ignored.

Earthquakes are low frequency (below 20 Hz), low *g*, multiaxis events, so we will use an ADXL202 and sample at 40 Hz (25 ms) to avoid aliasing.

In this design, we can assume that vibrations of less than 200 m*g* can be ignored (an earthquake is defined as having sufficient energy to cause accelerations greater than 200 m*g*). So our peak-to-peak noise floor must be less than 200 m*g*. Using a peak-to-peak to rms ratio of 6.6, we find:

$$rms\ noise = 200\ mg/6.6 = 30.3\ mg$$

So we will select a bandwidth that will result in an rms noise floor that is less than 30.3 m*g*.

$$Noise = Noise\ Density \times \sqrt{bandwidth \times 1.6}$$

For the ADXL202 with a typical *noise density* of 500 $\mu g/\sqrt{Hz}$:

$$Noise = 500\ \mu g/\sqrt{Hz} \times \sqrt{bandwidth \times 1.6}$$

Rearranging the equation;

$$Bandwidth = (noise^2)/(1.6 \times noise\ density^2)$$

In this example, the maximum bandwidth is approximately 2.3 kHz. Using the closest standard value, we can set the bandwidth to 2 kHz. Therefore C_X and C_Y are 0.0022 µF and the noise floor is approximately 28 m*g* rms (185 m*g* peak to peak).

For the ADXL202, the turn-on time is approximately:

$$T_{ON} = 160 \times C_X = 0.3\ ms$$

where C_X is in µF. The 0.3 µs is the turn-on time of the accelerometer itself, while the 160 × C_X (or C_Y) term is the settling time of the bandwidth limiting filter. Using a 0.0022 µF capacitor, the turn-on time to steady state is approximately 650 µs. The analog outputs and an A/D converter will be used, so a conversion time of 25 µs must be added. So the total ontime is 675 µs.

Therefore the average power consumed is:

$$600\ \mu A \times (0.675\ ms/25\ ms) = 16.2\ \mu A$$

with a 5 V supply. Lowering the supply voltage to 3 V will reduce the average current consumption to 10.8 µA.

Obviously, 200 m*g* peak-to-peak noise is too high to make a good measurement. Therefore, if a measurement of greater than 200 m*g* is made, the sampling speed can be increased for a few seconds to 800 Hz and groups of 20 samples can be averaged. This will bring the noise floor down to approximately 6 m*g* rms (42 m*g* peak to peak), allowing more precise measurement. More power will be used at this time, but as this happens infrequently, the average power consumed will still be under 20 µA.

Software can then determine if the higher acceleration (>200 m*g*) was actually caused by an earthquake or just a single impulse event due to jostling and take appropriate action.

The ADXL202/ADXL210

With its PWM outputs, the ADXL202/ADXL210 is a special case and merits special attention when power cycling.

Using the PWM Outputs

The duty cycle modulator of the ADXL202/ADXL210 runs asynchronously to the rest of the accelerometer. Since we have no way of knowing what state the PWM output will be in when the accelerometer analog output data is valid, we must wait at least one T2 period after the specified turn-on time (to ensure the data is valid).

This leads to two conclusions:

1. Using the analog outputs and an A/D converter rather than the PWM outputs will allow faster power cycling and therefore the lowest power operation.
2. If we choose to use the PWM outputs with power cycling, we should use the shortest T2 time possible. However, using a short T2 implies using a fast counter, which is normally inconsistent with low power operation.

Although not explicitly specified in its data sheet, the maximum PWM frequency is typically 5 kHz (R_{SET} = 25 kΩ). Therefore, the additional overhead needed to use the PWM outputs will be at least 400 μs (two T2 periods—one period wait for valid data and another period for measurement) to calculate the counter time. The ADXL202 has a total dynamic range of ±4 *g* or |8000 m*g*|. At T2 = 5 kHz, 1 m*g* per count = [(1/5 kHz)/8000 m*g*] total range or 250 ns per m*g*). In addition, if we want to use such a fast T2 period and maintain 10 m*g* resolution (for the ADXL202), we would need a counter that counts in 250 ns increments.

Even if only 32 m*g* resolution (roughly equivalent to 2° of tilt) were sufficient, the counter increment would rise to 800 ns, still too fast for most low power 8-bit microcontrollers.

Using a counter that runs at 1 MHz (1 μs per count) and maintaining 10 m*g* resolution, we would have to run T2 at approximately 1.25 kHz. In this case, the T2 overhead would rise to 1.6 ms compared to the approximately 25 μs that an A/D converter would take to complete a conversion. Clearly, the overall system design becomes more involved when we are looking to minimize power consumption and use the PWM outputs of the ADXL202/ADXL210. Often the best choice when looking to minimize both component cost and power consumption is to use an A/D converter along with the ADXL202/ADXL210.

The exception to this is when the sampling rate is very low. In a system where a measurement is only made from time to time, the additional time required to use the PWM output is not a great handicap. The high resolution and low cost (i.e., no A/D converter required) may be more important than the additional power consumption.

Reducing Turn-On Time with Charge Conservation

In the majority of applications, most of the turn-on time of the ADXL202/ADXL210 is attributable to the time constant of the bandwidth limiting filter (formed by the internal 32 kΩ resistors and C_X or C_Y). The C_X and C_Y values are normally dictated by the resolution required in the application. Many tilt sensing applications are low speed in nature and are therefore good candidates for power cycling. However, these applications often require high resolution and large C_X and C_Y values are mandated, resulting in long turn-on times. In many cases, the turn-on time can be greatly reduced by conserving the charge on C_X and C_Y.

Figure 3 shows a typical circuit used for charge conservation. C_X and C_Y are switched out of the circuit (via S2 and S3) just prior to the removal of V_{DD} to the ADXL202/ADXL210 (via S1). They are switched back in just after (a few ms) V_{DD} is applied to the ADXL202/ADXL210. This removes any path for the filter capacitors to discharge (other than leakage through C_X, C_Y, and the switches themselves). In an actual system, a CMOS analog switch would be used for S1, S2, and S3.

By keeping the filter capacitors (C_X and C_Y) from discharging, we can speed up the settling time as shown in Figure 4. This allows us to turn off the accelerometer quickly and conserve power. Note that it takes the same time to arrive at steady state with or without charge conservation.

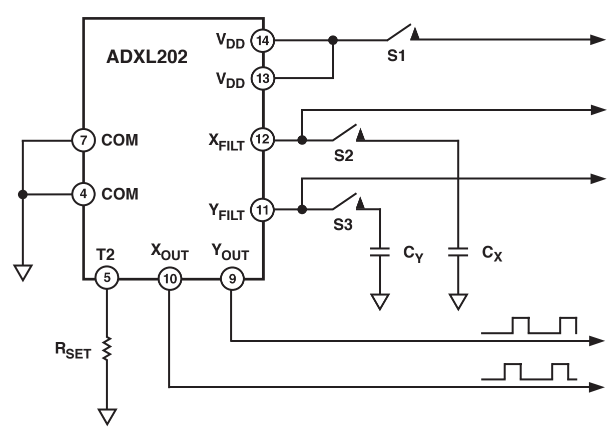

Figure 3. Charge Conservation Circuit

If the goal is to arrive at measurements that are accurate within a certain tolerance of the steady state output (100 m*g* as an example), it can be realized more quickly by using charge conservation. Figure 4 shows the C_Y (Pin 11) output of a system that is being power cycled 10 ms ON/17 ms OFF, for an effective bandwidth of about 18 Hz. With V_{DD} = 5 V and using a charge conservation architecture with C_X and C_Y 0.1 μF, the average current used is:

$$I_{AVG} = 600\ \mu A \times (10\ ms/27\ ms) = 222\ \mu A$$

After 17 ms, the C_X and C_Y voltage droops down to 1.81 V. 10 ms after V_{DD} is applied to the ADXL202, C_X and C_Y are 2.471 V. That is within 28 mV (or 92 m*g*) of the steady state output in this case.

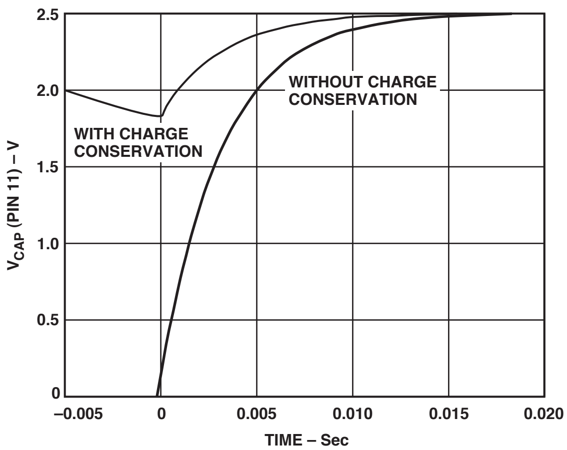

Figure 4. Voltage with and without Charge Conservation

Had charge conservation not been used, we would have had an error of 107 mV (or 342 m*g*) versus the steady state output after 10 ms. To get to within 92 m*g* of steady state output without charge conservation, we would have had to wait 14.1 ms after turn-on, resulting in an average current consumption of:

$$I_{AVG} = 600\ \mu A \times (14.1\, ms/27\ ms) = 313\ \mu A$$

a difference of 41%.

Had we lowered the supply voltage to 3.3 V, the average current consumed would be 146 µA with charge conservation and 207 µA without.

Note that the time required to arrive within 100 m*g* of the steady state response depends a great deal on the amount of droop, which is chiefly determined by the switch leakage.

Switch Selection

The performance of a charge conservation system depends greatly on the switch selected. The 74HC4016, and others like it, perform fairly well. However certain switches, such as the metal gate CMOS 4016 type, should be avoided because of their high ON resistance at supply voltages of 5 V or less. The 4066 and 74HC4066 should also be avoided because their internal architecture tends to discharge the filter capacitors when switched, precisely the opposite of what we wish to do.

There are many CMOS analog switches available that will work satisfactorily in this application. It is important to try out the switch you choose to see if its performance is adequate.

Using I/O Ports Instead of Switches

In minimal systems, the CMOS analog switch may be eliminated totally at the expense of some power consumption.

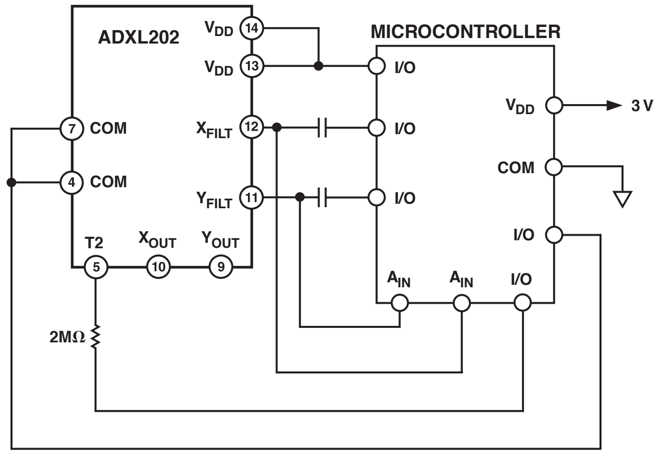

Figure 5. Using Microcontroller I/O

Rather than using CMOS analog switches to high side switch the capacitors (as shown in Figure 3), one can use the output ports of a microcontroller to low side switch the capacitors as shown in Figure 5. Here the bandwidth limiting capacitors, R_{SET}, and the ADXL202/ADXL210 are three-stated when no measurements are being made so as to remove any discharge path for C_X and C_Y. As the duty cycle outputs are not being used, we are free to choose a high value for R_{SET}, allowing us to save a few microamps.

Using I/O ports is usually a very low cost and compact solution since no additional components are required. However, it is generally lower performance than analog CMOS switches since microcontroller I/O ports are not optimized for low leakage. Figure 6 outlines a model of the nodes at the filter capacitors when both sides are connected to I/O ports that are in Three-State mode. The value of the “leakage” resistors depends on the construction of the given microcontroller. Obviously, the charged capacitor will discharge through the leakage resistors.

The performance of the system shown in Figure 5 is described in Table II. A Microchip Technology PIC16C73 was used. Different microcontrollers may yield different results because of differences in the I/O structure.

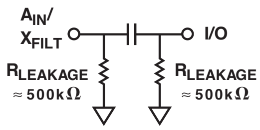

Figure 6. Model of Microcontroller Ports when in Three-State Mode

Table II. Peak-to-Peak Output Error vs. On Time for Figure 5 V_{DD} = 3.3 V, Sampling Rate = 36 Hz, and Bandwidth = 18 Hz

T_{ON}	T_{OFF}	I_{AVG}	Error
Infinity	0	400 μA	0 m*g*
11 ms	17 ms	157 μA	32 m*g*
9 ms	19 ms	128 μA	80 m*g*
7 ms	21 ms	100 μA	160 m*g*
5 ms	23 ms	87 μA	320 m*g*

If a slower (than 36 Hz) sampling rate could be tolerated, additional power savings can be realized by lengthening the T_{OFF} time. For example, a 10 Hz bandwidth (20 Hz sampling rate) system with a T_{ON} of 11 ms and a T_{OFF} of 39 ms would consume 87 μA while still settling to within 32 m*g* using the circuit shown in Figure 5.

Automatic Shut-Off Gas Valve Revisited

Looking back at the earlier low power design example, we can further reduce the power consumption by using the charge conservation techniques discussed here.

Using a circuit similar to Figure 5, but with C_X and C_Y 0.0022 μF, the settling time to 200 m*g* is approximately 430 μs plus 25 μs of A/D acquisition time. So the average current consumed is:

$$600\ \mu A = 455\ \mu s/25\ ms = 10.9\ \mu A$$

with a 5 V supply and only 7.3 μA with a 3 V supply (a 33% reduction in current consumption compared to the previous example).

Conclusion

While iMEMS accelerometers are inherently low power devices, several techniques are available to designers to lower their power consumption even further. Generally, lower power operation results in degraded noise performance. It is therefore important for the designer to understand the compromises they will be making in pursuing very low power operation. Current consumption of well under 100 μA is feasible in many low speed applications and even under 10 μA in some cases.

E03046-0-10/02(0)

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