

ADXL105: A Lower Noise, Wider Bandwidth Accelerometer Rivals Performance of More Expensive Sensors

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INTRODUCTION

Surface micromachining has been used to make reliable accelerometers in large quantities at very low cost, but with modest performance, for the airbag and consumer products industry (*Analog Dialogue* 27-2 (1993), *A-D* 30-4 (1996), *A-D* 33-1 (1999)). The accuracy and noise limitations for more-sophisticated applications are due to the tiny signals involved, given the small size of surface-micromachined structures.

However, recent advances in circuit architectures and beam structures used in integrated micro-electromechanical systems have resulted in order-of-magnitude improvements in resolution and accuracy. The recently introduced ADXL105 accelerometer has a $225\text{-}\mu\text{g}/\sqrt{\text{Hz}}$ noise floor, 10-kHz bandwidth, and an on-board temperature sensor, which can be used for calibrating against temperature effects. In comparison, the ADXL50, the first Analog Devices accelerometer, had a noise floor of $6500\text{ }\mu\text{g}/\sqrt{\text{Hz}}$. A $65\text{-}\mu\text{g}/\sqrt{\text{Hz}}$ version has also been demonstrated on ADI's new $3\text{-}\mu\text{m}$ polysilicon process. The ADXL105 is initially targeted at machine health and tactical guidance & control applications, as well as a number of new automotive applications.

The ADXL105, a near ideal kind of vibration sensor, eliminates significant problems with existing vibration sensors, such as piezoelectric and bulk capacitive sensors. Primary benefits derive from much lower cost, stable sensitivity as a function of frequency and temperature, ruggedness, and ease of use. Besides machine health and condition monitoring, it is particularly well suited for noise and vibration cancellation applications.

Structurally, the ADXL105 is the first of a new generation of precision surface-micromachined devices that attempts to push the performance envelope using a $2\text{-}\mu\text{m}$ -thick polysilicon process. The device is fabricated on a process that combines the surface-micromachined differential-capacitance sensor and the electronic signal conditioning circuitry on a single IC chip. The sensor itself is $0.5\text{ mm} \times 0.4\text{ mm}$ and $2\text{-}\mu\text{m}$ -thick, with $1\text{-}\mu\text{m}$ feature size and a mass of only 0.5 micrograms. The deflection due to a 1-g acceleration is 1 nanometer ($E\text{-}9\text{ m}$), or about 0.07% of the gap width, and the minimum resolvable deflection is about 210 femtometers ($E\text{-}15\text{ m}$), or 0.002 Angstrom units, at a noise level of $225\text{ }\mu\text{g}/\sqrt{\text{Hz}}$ and 1-Hz bandwidth.

With a source capacitance in the neighborhood of 150 femtofarads (i.e., 0.15 pF), and orders-of-magnitude smaller differential capacitance changes (100 attofarads ($E\text{-}18\text{ F}$) for a 1-g acceleration

and 23 zeptofarads ($E\text{-}21\text{ F}$) resolution, the signal output of these devices could be easily lost in the presence of parasitic capacitance or noise.

The ability to provide on-chip signal conditioning is what allows the minute signals to be read with minimal interference. A synchronous demodulation technique ("ac bridge") is used to increase noise immunity and improve signal to noise. A square-wave carrier drives the sensor, and the modulated signal produced by the change in differential capacitance is amplified and synchronously demodulated, minimizing noise and boosting the signal-to-noise ratio.

The limitations on size and mass of the structural beam place a weighty constraint on the performance of these devices. To make a precision accelerometer, it is helpful to have as much mass as possible and a large output signal from the sensor. But both parameters are limited by the size of the sensor element, which in turn is limited by the ability to control the curvature, or out-of-plane deviation of the structure due to internal polysilicon stress. Limits on size (hence mass) set a lower noise limit on the sensor, because the Brownian noise floor of the device, which is imposed by gas molecules bouncing off the beam, is inversely proportional to the mass of the sensor. Signal to noise is of course limited by the size of the signal, (related to spring stiffness, mass of the sensor, and source capacitance), as well as the noise floor set by the front-end circuitry.

Spring stiffness limits capacitance change, hence the magnitude of the electrical output. Although more-flexible springs allow greater travel of the mass under acceleration, with a corresponding increase in the delta capacitance read by the circuit, there is a direct trade-off between the flexibility of the springs and the robustness of the structure to shock and overload. If sensors are insufficiently stiff, their elements can touch, and the resulting stiction (static friction) produces a failure through irreversible physical latching.

The design goal of the ADXL105 was to improve the robustness of the sensor, and at the same time achieve an approximately $5\times$ improvement in performance over existing products built in the process; this would improve the suitability of the devices for machine health and tactical inertial applications.

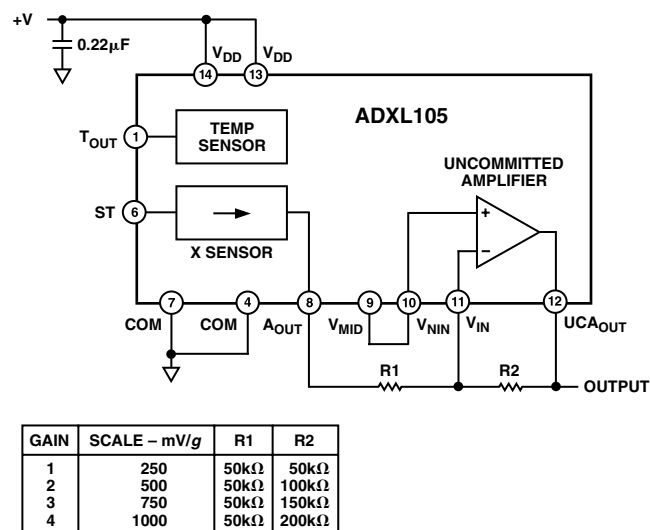


Figure 1. ADXL105 and typical application circuit.

To improve the robustness, and meet a target specification of 10-kHz bandwidth, a stiffer beam was selected. Supplanting a beam with a 12-kHz resonance, the new design has a 16-kHz resonant frequency, representing a 2.5× improvement in stiffness. In addition, the beam has a new suspension with increased Z-axis (beam to substrate) stiffness. While robustness was improved, the changes in fact increased the difficulty of meeting the design goal, as the stiffer beam reduced the signal coming from the sensor. This called for improvements in electrical design.

An especial effort was made to reduce or eliminate all sources of inaccuracy due to the electronics. Thus care was taken to use low drift amplifier designs and to track down error sources that were not important to airbag or consumer electronic designs, but would compromise an inertial or vibration sensor.

The front-end circuitry of the ADXL105 was designed using familiar precision design techniques to reduce the noise floor. Drive current and input FET size were increased to minimize noise and parasitic loading. Die size and current consumption were compromised somewhat in favor of performance. A special two-stage amplifier design was used that split up the gain segments to optimize the noise and drift components.

The increased performance produced by electrical and mechanical design improvements has answered two frequent criticisms of surface micromachined devices for precision measurement: that they have limited frequency response and that their noise floor is too high and hence resolution is too low. The table below compares the ADXL105 with other low-g ADI accelerometers.

Specifications	ADXL105	ADXL202	ADXL05	ADXL50
Range	$\pm 5 g$	$\pm 2 g$	$\pm 5 g$	$\pm 50 g$
Noise ($\mu g/\sqrt{Hz}$)	225	500	500	6500
Bandwidth (kHz)	10	5	5	6
Supply Current (mA)	2	0.6	10	10
Number of Axes	1	2	1	1
Output Type	Analog	Analog/ Digital	Analog	Analog

Beyond these specifications, there are other favorable characteristics of the surface micromachined approach that result in a sensor that rivals or exceeds the performance of existing (and considerably more expensive) sensors employing other technologies.

For example, the amplitude vs. frequency response of the micromachined sensor is nearly ideal given that its dynamic behavior results from shape and dimensions that are tightly controlled by the integrated-circuit micromachining process. Combining this with well-designed and linear electronics results in a very flat amplitude vs. frequency response. This characteristic is extremely valuable in vibration measurement, which requires very accurate and repeatable measurement of amplitude for machine condition monitoring or vibration cancellation. In fact, when applying the device, poorly designed mounting can introduce far greater dynamic errors than those inherent in the device itself.

A desirable figure of merit for most piezoelectric sensors is that amplitude response at 1 kHz be within 5% of its 100-Hz value. The ADXL105 is easily within 1% at 1 kHz (Figure 2), and it typically has deviated only 2% from its 100-Hz value at 5 kHz. The 10-kHz single pole response of the ADXL105 also results in predictable phase response and low phase lag at 5 kHz, an important characteristic for noise and vibration cancellation schemes.

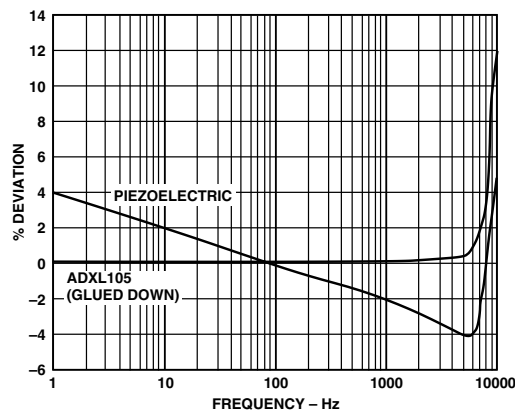


Figure 2. Amplitude response deviation.

In this type of sensor, as mentioned earlier, the motion of the beam in response to the force of acceleration is detected by a capacitive technique. The measured capacitance change ratio is nearly invariant with temperature, resulting in a sensitivity (V/g) that changes only $\pm 1\%$ over the -40 to $+85^\circ C$ industrial temperature range (Figure 3).

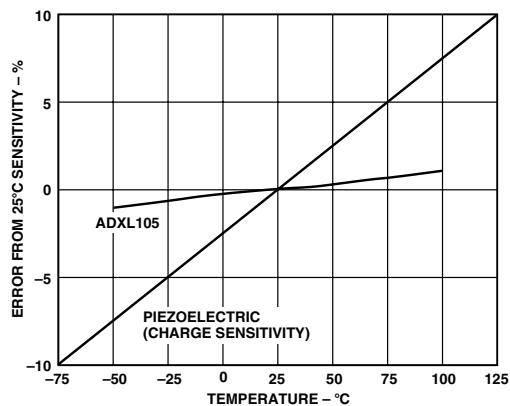


Figure 3. Sensitivity error as a function of temperature (uncompensated).

Finally, the noise characteristics of the ADXL105 are very different from those of the popular piezoelectric sensors commonly used for vibration. The synchronous demodulation scheme used to decode the amplified capacitive sensor output results in a noise spectral density that is essentially independent of frequency. This contrasts with the noise from a piezoelectric sensor, which increased substantially as the frequency decreases (Figure 4).

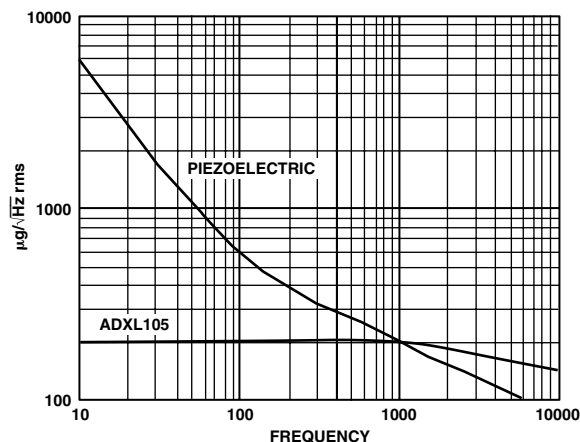


Figure 4. Noise floor comparison.

Displacement is an important characteristic to measure for low-speed equipment, such as large air conditioning fans. Excessive displacement is a sign of bearing wear and of a potential for mechanical failure. The vibration acceleration signal is integrated twice to compute displacement. The ADXL105 can measure acceleration all the way down to dc; piezoelectric sensors cannot. They lose sensitivity in the neighborhood of 1 Hz due to a low-frequency zero. The dc ability and excellent low-frequency noise characteristics of the ADXL105 enable the accurate measurement of vibration displacement at low frequencies.

Applications Issues in Vibration Measurement

The ADXL105 is significantly different from other vibration sensors in one final area: packaging. Most vibration sensors are in a packaged format, with stud or screw mounts, and a pigtail for electrical connections. The packages are hardened for industrial use, stainless steel is often used. The ADXL105 comes housed in a standard ceramic surface-mount IC package. For industrial applications, it must usually be repackaged and potted into a form appropriate for the target equipment and the type of acceleration measurement required. Analog Devices works with a number of 3rd party suppliers, who can provide the product in a variety of form factors.

As noted earlier, the near-ideal characteristics of the sensor can be compromised by careless mounting. When potting the accelerometer, it is important to consider the resonant frequencies of the IC package leads and the PC board it is mounted to. For example the leads of the surface mount package have a resonant frequency of about 7 kHz. This resonance could degrade accuracy in high-frequency vibration measurement. To solve the problem, the package should be glued to the PC board (if a PC board is used) in order to make a tight mechanical coupling from the sensor to the board. PC-board resonances typically occur at even lower frequencies and can be damped by potting the assembly in epoxy or using a thicker PC board.

Special Features for Inertial Measurements

Although the ADXL105 is optimized for vibration measurement, its dc accuracy is also improved over that of earlier ADI acceleration sensors. Special attention was paid to the design of the electronics to eliminate dc drift and noise sources that were ignored, or were simply not important in the applications the earlier products were used for. Particular attention was paid to the final output stage to lower the 1/f noise corner that limits stability at dc and low frequencies.

The accelerometer includes an 8-mV/°C on-board temperature sensor that measures the actual temperature of the IC die. For inertial applications, the accelerometer is mathematically modeled over temperature to eliminate static errors. The on-board temperature sensor is used both for initial calibrations of the sensor and as an input to the calibration model. The sensor was designed to be repeatable and accurate to reduce residuals in the modeling process.

Future Work

The ADXL105 has demonstrated that, despite inherent obstacles, it is possible to develop high-performance acceleration sensors on a 2- μm thick, surface-micromachine polysilicon process. An experimental version of the device, built on a 3- μm -thick polysilicon process, has demonstrated a $65\text{-}\mu\text{g}/\sqrt{\text{Hz}}$ noise floor, a 3 $\times$ improvement over the ADXL105. Concepts are now being developed to demonstrate a $25\text{-}\mu\text{g}/\sqrt{\text{Hz}}$ device, and to combine this increased resolution with wider ranges of $\pm 50\text{g}$, $\pm 100\text{g}$, and more. Other developments will focus on lower-stress packaging methods, which will enable better bias stability—an important requirement for tactical inertial applications.

Conclusions

The primary opportunity posed by the low cost and increasingly high performance of these devices is to enable new applications that weren't possible before. Although there is also a potential for replacing other means in existing applications, there is no reason to believe that designers who design or customers who purchase precision instruments will suddenly change to a new technology strictly on the basis of cost, as there are other important considerations in the precision instrumentation business.

However, there is a limitless opportunity to develop new or expanded uses of precision sensors. For example, the new technology may allow designers to instrument full-time monitoring of every machine, motor, pump or compressor that a manufacturer makes. New low cost, precision sensors with their fully signal conditioned output can reduce the cost of each point in a real-time monitoring system from \$1000 to under \$100. That kind of cost reduction makes feasible new uses for sensors that were not possible before. For example, a manufacturer of industrial equipment can now economically produce a "smart motor," which has high-efficiency drive electronics employing DSP for speed control, and accompany it by a low-cost machine-health conditioning module to increase energy efficiency, improve up time, reduce maintenance cost, and thus lower the end customer's total cost of ownership.