Accelerometer Design and Applications

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ANALOG DEVICES

Objectives

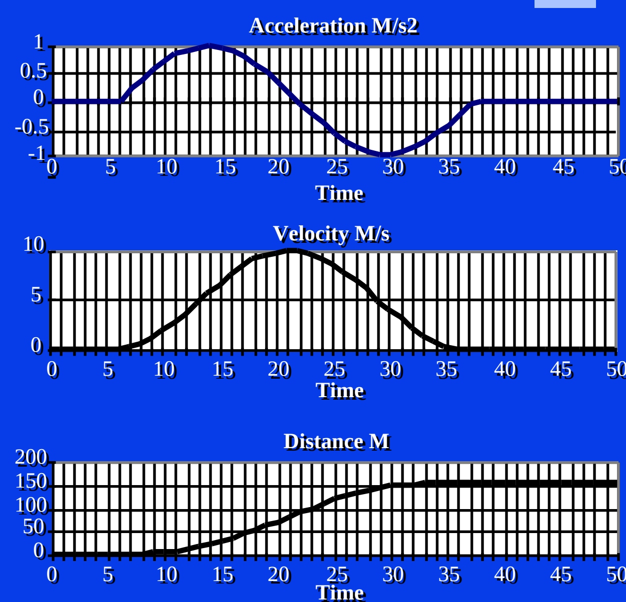
- What can I do with an accelerometer?
- Why consider an accelerometer?
- Product technology overview
- Performance requirements for various applications
- Accelerometers from the Point of View of Signal Conditioning and Data Acquisition
  - Inertial
  - Vibration
  - Tilt

What can I do with an accelerometer?

- Inertial measurement of velocity and position
  - Acceleration single integrated for velocity
  - Acceleration double integrated for position
- Vibration and shock measurement
  - Measuring vibration for machine health
  - Motion and shock detection
- Measurement of gravity to determine orientation
  - Tilt and inclination
  - Position in 2 and 3 dimensional space
  - Can only be done with accelerometers that have DC response

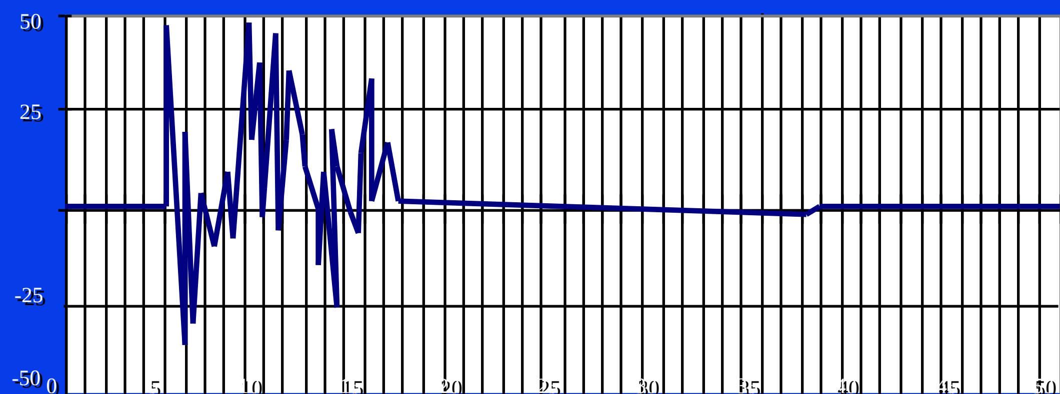
Inertial measurement

- Non-contact method to measure acceleration, velocity, and distance traveled
- Velocity is the integral of Acceleration
- Distance is the integral of Velocity (double integral of acceleration)



Inertial sensing for Airbag Crash Detection

- Single accelerometer replaces 3 to 5 ‘g’ switches
- Signature analysis of acceleration, velocity and distance profile is used to distinguish a crash from a non-crash event.

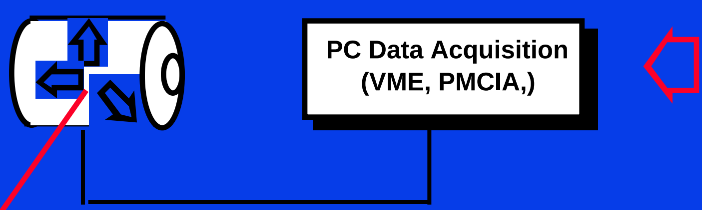


Using accelerometers in machine condition monitoring

- Monitor and predict the health and condition of moving machinery
  - Predict failure before incurring expensive unplanned downtime
  - Increase time between preventative maintenance cycles
  - Improve product reliability and safety
  - Gain competitive advantage
- Accelerometers monitor the vibration level.
  - Analysis of acceleration, velocity, and displacement
  - Time domain and frequency domain analysis
  - Detect out of balance, bearing failure, bushing failure etc.

Using accelerometers in machine condition monitoring

- XL150/250 Capable of machine health measurements for motors, pumps, compressors
  - Preconditioned Analog output eliminates need for charge amplifier
  - Scale factor insensitive to temperature, 10mg resolution
  - Multi-axis sensor reduces cost, simplifies packaging
  - XL105 will increase BW to 10kHz and increase SNR



Triaxial Accelerometer
Xl150+XL250
50g FS with 10mg resolution

Data Analysis
-Acceleration
-Velocity
-Displacement

Data analyzed in:
Time Domain
Frequency Domain

Tilt sensing example

- Pitch and Roll Sensing
  - Requires one accelerometer for each axis
  - Compass Correction
  - Machine position
  - Computer input devices
- 3D Orientation in Space
  - Requires three accelerometers, X,Y, Z
- 6 Degree of Freedom Sensing
  - Requires 3 accelerometers and 3 gyros

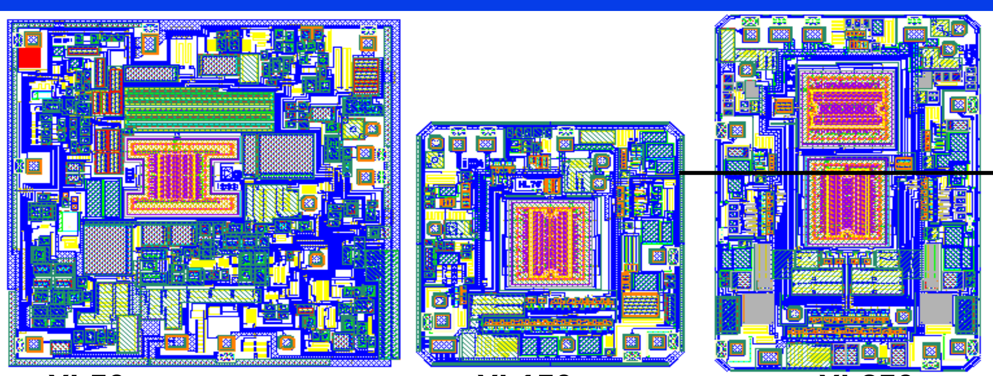
Why should I consider using an accelerometer?

- A variety of new devices and technologies are on the market
- Prices have gone down dramatically
- Cost/Performance ratio is improving

What is a Micromachine? ADI's implementation

- Surface Micromachined Mechanical Element
  - Combination of springs, masses, motion sensing and actuation cells
- BiMOS Circuitry for On-Board Signal Conditioning
  - Oscillators and Demodulators
  - Amplifiers and Filters
  - Self Test Circuitry
- All On a Single I.C. Chip
  - Fabricated in a Standard I.C. Wafer Fab
  - Uses Standard IC Photo Lithographic, Etch and Implant Technologies
  - Packaged Using Specially Developed Techniques to Protect Moving Parts
  - Highly Reliable, Low Cost Solution to Motion Sensors

Die size and cost per axis is decreasing



XL50 Original

XL150 New

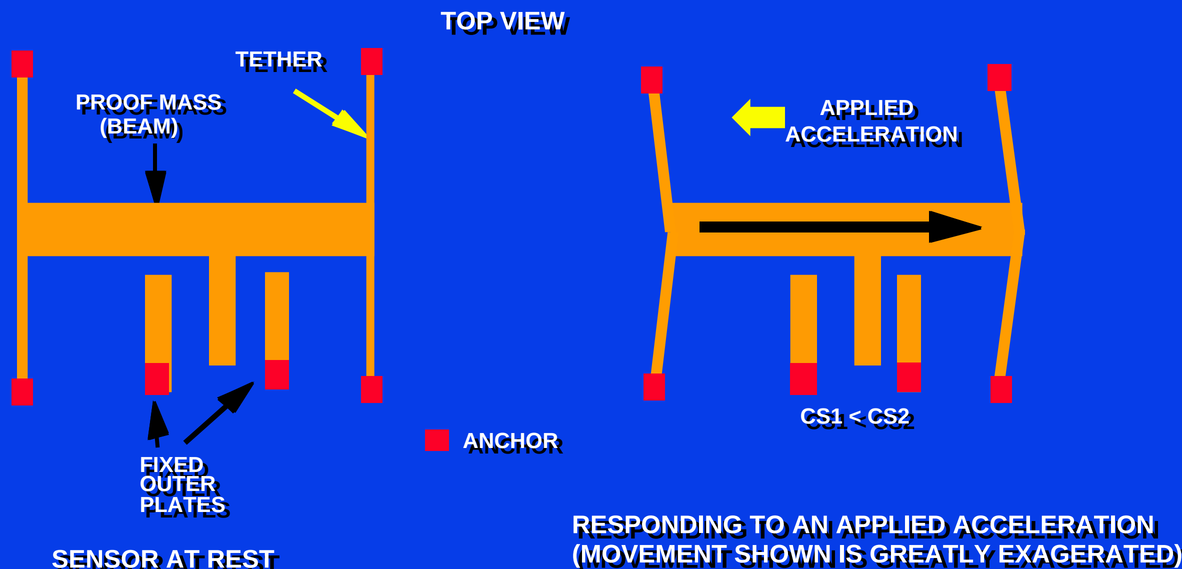
XL250 2 Channel New

New technology reduces the cost of sensing

- Micromachining uses standard integrated processing techniques
- Leverages existing technology base
- Benefits of batch processing
- Uses standard IC packages
- Easy to handle and integrate with other IC devices
- Some devices now have PWM outputs that can interface to a microcontroller / DSP without an A to D converter

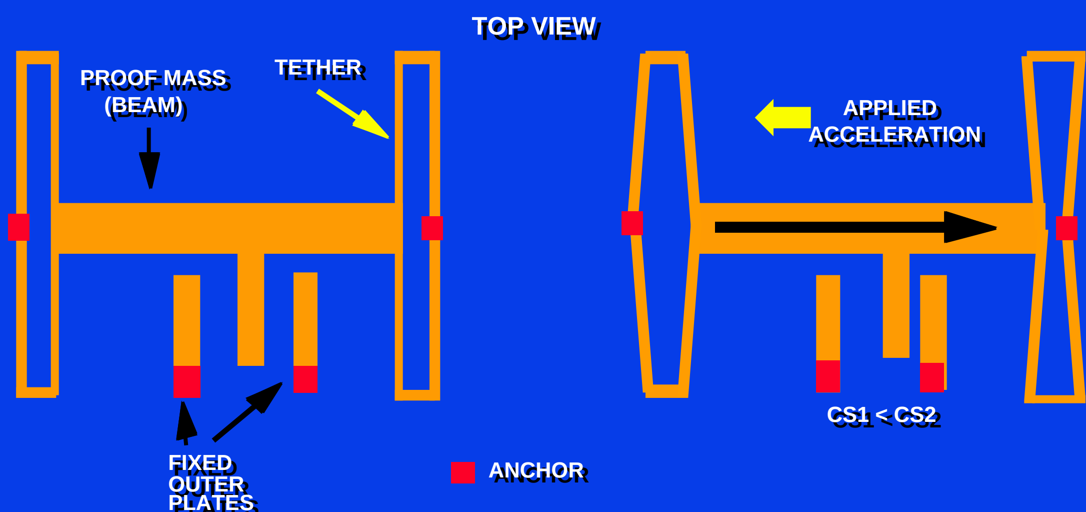
Sensor operation

- Sensor Forms Differential Capacitor



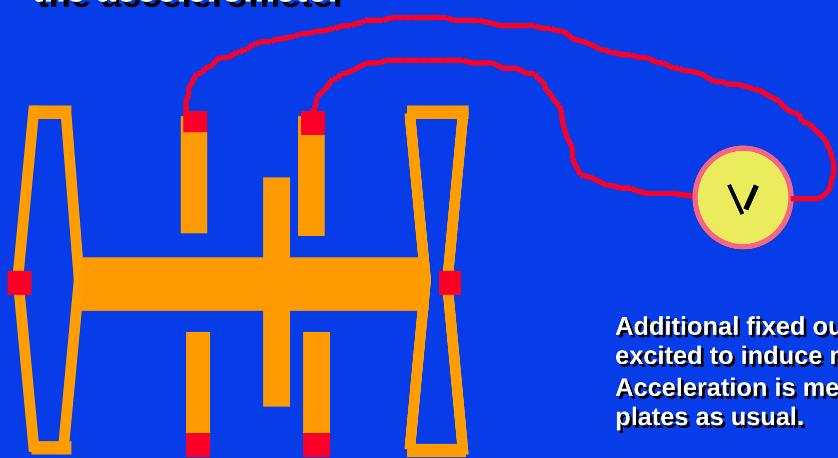
Sensor operation; ADI's implementation

- **Folded tethers have more consistent spring constants, leading to better part to part consistency**



Self test operation

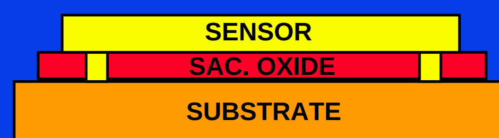
- Extra fixed outer plates may be added which when exited, force the proof mass to move. So you can electronically test the accelerometer



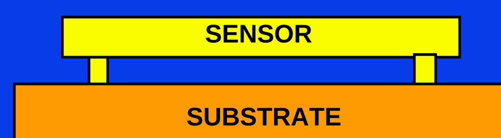
Additional fixed outer plates are electrically excited to induce movement of the proof mass. Acceleration is measured by the standard fixed plates as usual.

Surface Micromachining

- Selective Etching
  - Standard IC Photolithographic Processes
  - 1.6µm Thick Sacrificial Oxide Layer
  - Deposited 2.0µm Polysilicon Layer



- Resulting in 3 Dimensional Structure
  - Suspended Above Substrate
  - Free to Move in 3 Dimensions



- Surrounding Silicon for Integrated Circuits
  - BiMOS-2 with 3µm Design Rules

Interesting facts

- 0.1μgrams Proof Mass
- 0.1pF per Side for the Differential Capacitor
- 20aF (10^{-18}f) Smallest Detectable Capacitance Change
- Total Capacitance Change for Full-scale is 10fF
- 1.3μm Gaps Between Capacitor Plates
- 0.2Å Minimum Detectable Beam Deflection (one tenth of an Atomic diameter)
- 1.6 μm Between the Suspended Beam and Substrate
- 10 to 22kHz Resonant Frequency of Beam

Design focus

- Tilt and Inertial
  - DC Accuracy
  - Null Drift with time and temperature
  - mg Resolution
- Vibration and shock
  - Dynamic Range 1ug to 100g
  - Bandwidth
  - Amplitude Stability
- Common Issues in Data Acquisition
  - Bandwidth
  - Resolution
  - Accuracy

Choosing an appropriate technology

- Will you be measuring an AC phenomenon like vibration, or a DC phenomenon like gravity or constant acceleration?
- What is the maximum g range you expect?
- What is the smallest signal you need to detect?
- What is the maximum frequency required?
- What level of stability is required for the null and sensitivity of the accelerometer?
- What about size and power consumption?
- Will you mount to a circuit board ?

Comparison of approaches to acceleration sensing

- **Piezo-film (Vibration, shock)**
  - Inexpensive
  - AC Response only
  - Sense many things besides motion (sound, temperature, pressure)
- **Electromechanical Servo (Tilt, Inertial)**
  - DC accurate, low frequency only
  - Tend to be fragile
  - Expensive

Comparison of approaches to acceleration sensing

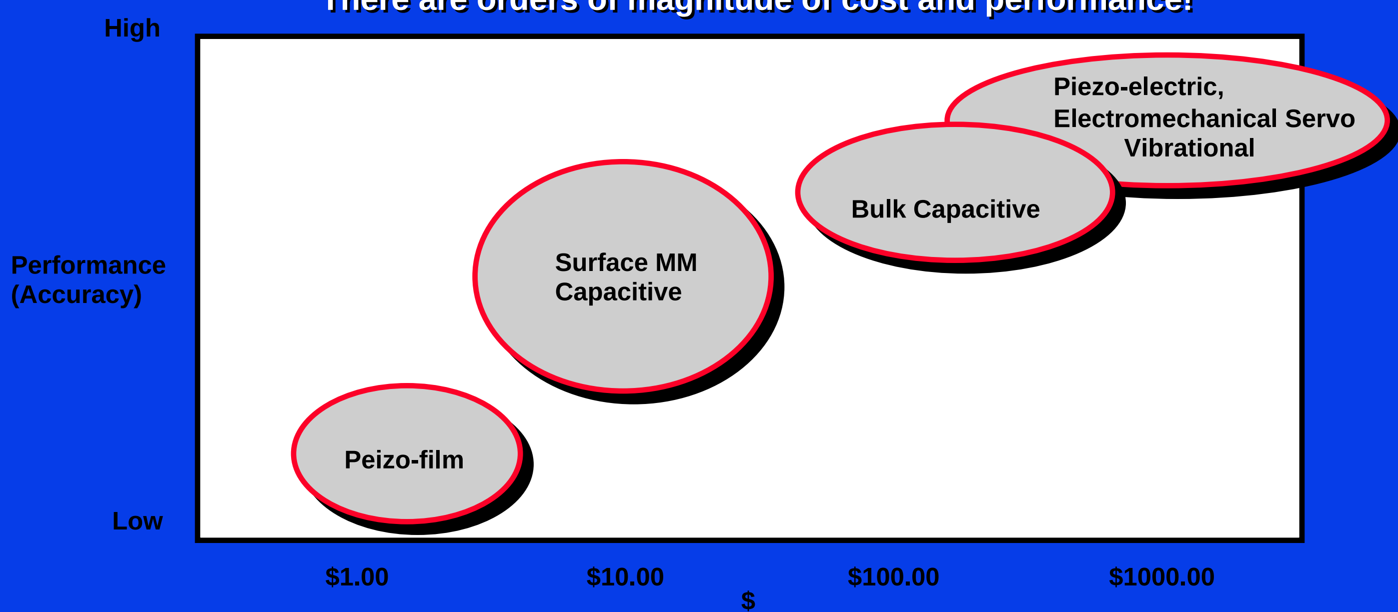
- Piezoelectric (Vibration, Shock)
  - Wide-dynamic range
  - AC Response only
  - Can be expensive, depending on the package
- Liquid tilt sensors (Tilt)
  - DC response
  - Inexpensive
  - Fragile
  - “Slosh” problems

Comparison of approaches to acceleration sensing

- Bulk Micromachined Piezo Resistive (Tilt, Vibration, Inertial)
  - DC Response
  - Difficult to trim, poor temperature performance
  - Can be expensive
- Bulk Micromachined Capacitive (Tilt, Vibration, Inertial)
  - DC Response
  - Good DC accuracy, low noise
  - Expensive
- Surface Micromachined Capacitive (Tilt, Vibration, Inertial)
  - DC Response
  - Standard IC form factors
  - Inexpensive

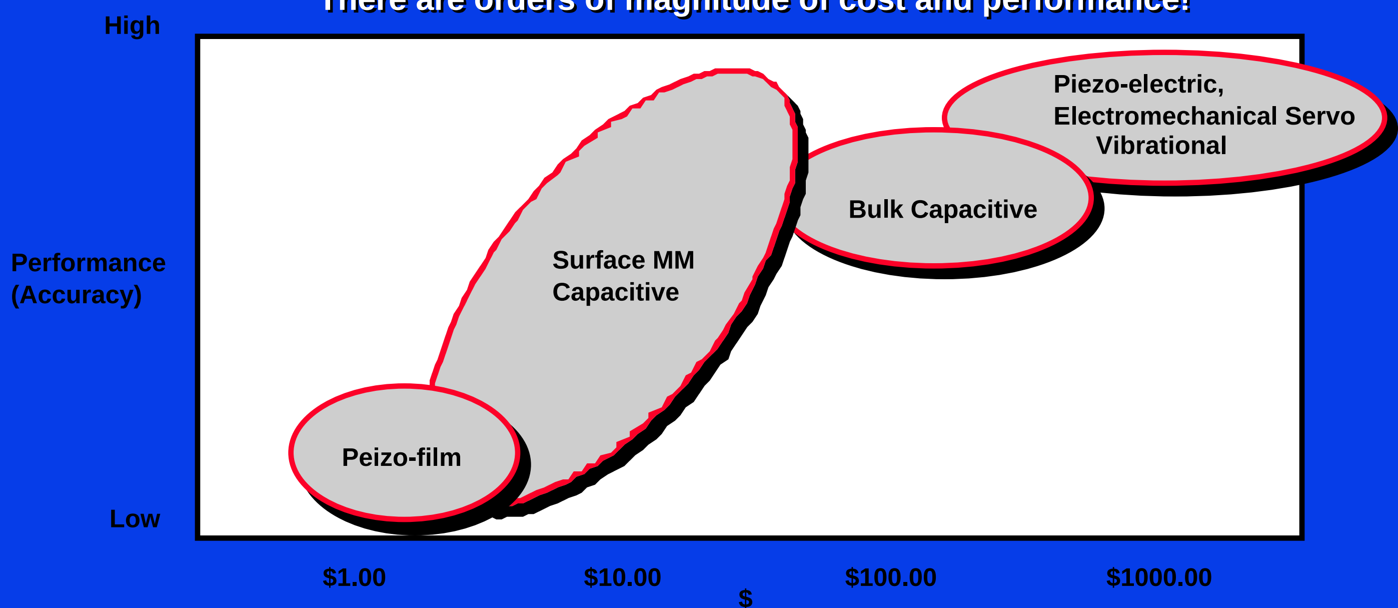
Comparison of various technologies

There are orders of magnitude of cost and performance!



Future roadmap

There are orders of magnitude of cost and performance!



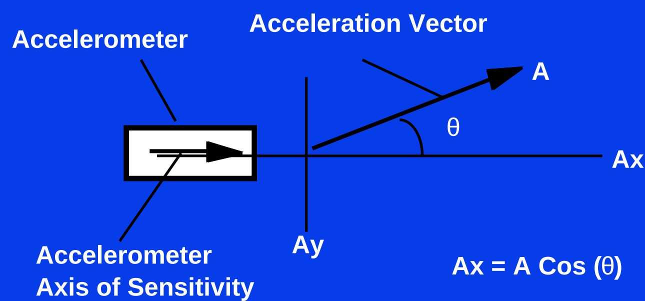
Overview: Specifications

- Zero g offset (i.e. voltage output at 0g)
  – May vary from sensor to sensor
  – Can be trimed out at system level using the Earth's gravity as reference input
- Sensitivity (i.e. voltage output per g)
  – May vary from sensor to sensor
  – Can be adjusted at system level using the Earth's gravity as reference input
- Noise
  – Noise determines the minimum resolution of the sensor
  – Noise floor can be lowered by restricting bandwidth if the noise is Gaussian

Overview: Specifications

- Temperature Range
- Bias drift with temperature
  - How does the zero g output change with temperature
  - Can be trimmed out at system level by several methods
- Sensitivity drift with temperature
  - How does the output per g change with temperature
  - Difficult to trim out at system level
- Bandwidth
- Power consumption
  - Can power cycling be used to minimize power consumption

Acceleration is a Vector



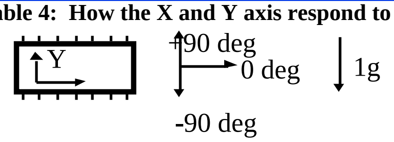
- The accelerometer has an axis of sensitivity
- An acceleration has a direction and a magnitude relative to the accelerometer axis of sensitivity (or other reference frame).

Acceleration is a vector

theta	% of signal appearing at output	Output in g's for a 1g applied acceleration
0	100.00%	1.0000
1	99.98%	0.9998
2	99.94%	0.9994
3	99.86%	0.9986
4	99.76%	0.9976
5	99.62%	0.9962
10	98.48%	0.9848
20	93.97%	0.9397
30	86.60%	0.8660
45	70.71%	0.7071
60	50.00%	0.5000
75	25.88%	0.2588
85	8.72%	0.0872
86	6.98%	0.0698
87	5.23%	0.0523
88	3.49%	0.0349
89	1.75%	0.0175
90	0.00%	0.0000

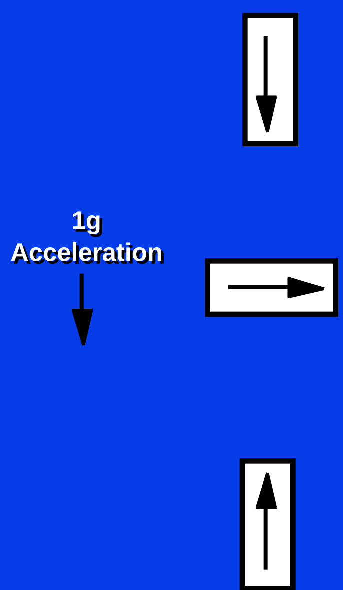
How the accelerometer output changes with tilt

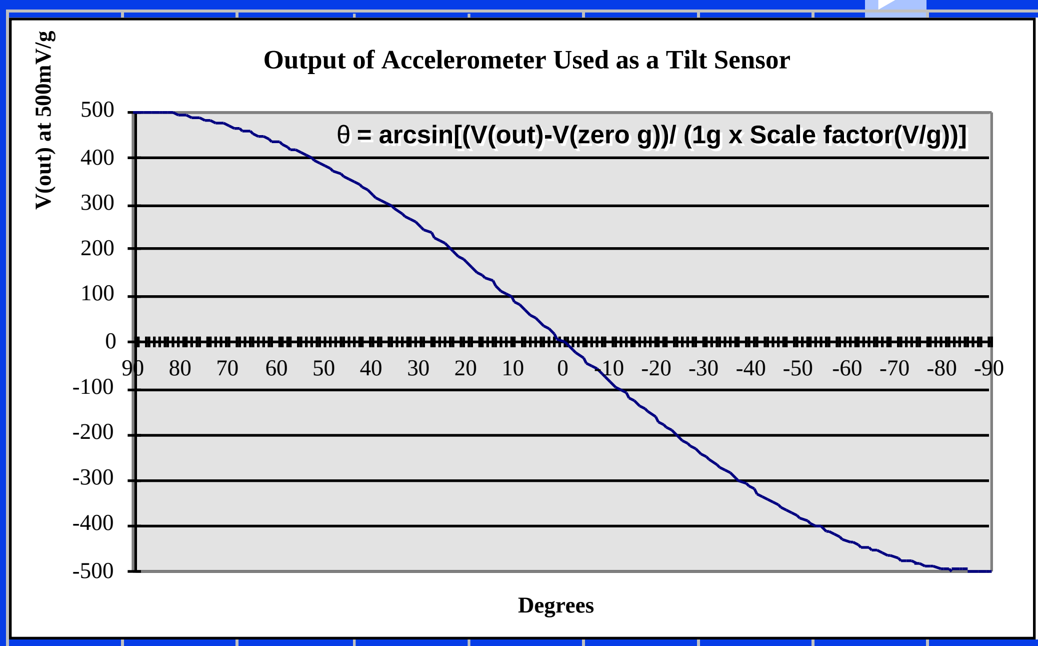
Table 4: How the X and Y axis respond to changes in tilt



X axis Orientation to Horizon (deg)	X Output		Y Output (g)	
	X Output (g)	**Delta per Degree of Tilt (mg)**	**Y Output (g)**	**Delta per Degree of Tilt (mg)**
-90	-1.000	-0.2	0.000	17.5
-75	-0.966	4.4	0.259	16.9
-60	-0.866	8.6	0.500	15.2
-45	-0.707	12.2	0.707	12.4
-30	-0.500	15.0	0.866	8.9
-15	-0.259	16.8	0.966	4.7
0	0.000	17.5	1.000	0.2
15	0.259	16.9	0.966	-4.4
30	0.500	15.2	0.866	-8.6
45	0.707	12.4	0.707	-12.2
60	0.866	8.9	0.500	-15.0
75	0.966	4.7	0.259	-16.8
90	1.000	0.2	0.000	-17.5

How a “DC” accelerometer responds to tilt





Data acquisition: Tilt

- How does it work
  - Accelerometer measures the static gravity field
  - Acceleration of $9.8 m/s^2 = 1g$
  - Changing the tilt (along the sensitive axis) changes acceleration vector
  - θ = arcsin[(V(out)-V(zero g))/ (1g x Scale factor(V/g))]
- Important Specifications
  - Since gravity is static (DC), absolute accuracy is important
    - Drift of zero g bias affects how accurately you can measure tilt
    - Low hysteresis & repeatability are important
  - High resolution is important as 1 degree of tilt is 17mg
    - Noise level is the chief determinant of resolution

Data acquisition: Inertial

- How does it work
  - Integrate acceleration once for velocity, twice for distance
  - Relative measurement from an initial position
  - Distance = 1/2 AT^2
- Important Specifications
  - Bias stability: any offset is integrated as an acceleration
  - Noise and resolution; Small signals must be measured
  - Similar to tilt, but need 10X or better accuracy
- Gravity and orientation effects on acceleration
  - A tilt will look like an acceleration and thus a change in position
  - A rotation will change the accelerometer axis of sensitivity
  - Gyroscopes are needed to determine tilt Vs acceleration

Practical inertial applications

- Most problems will require 6 degrees of Freedom
  - 3 Axes of lateral acceleration
  - 3 Axes of rotation
- Attempt to constrain the degrees of freedom
  - Constrain acceleration or rotation axes
  - Allows fewer sensors to be used
  - Simplifies mathematics
- Try to take advantage of the constraints of the mechanical system
  - I.e. cars can only pitch or roll a few degrees

Practical inertial applications

- Attempt to limit time between absolute updates
  - Attempt to have periodic absolute position updates
  - Reduce dead reckoning time to a minimum
  - Combine absolute and relative position sensors
    - Example: Magnetics, encoders, LED's etc.
- Use signature analysis
  - Look at the spectral response of one or more axis to make a very educated guess as to what the mechanical system is doing

Designing for tilt sensing

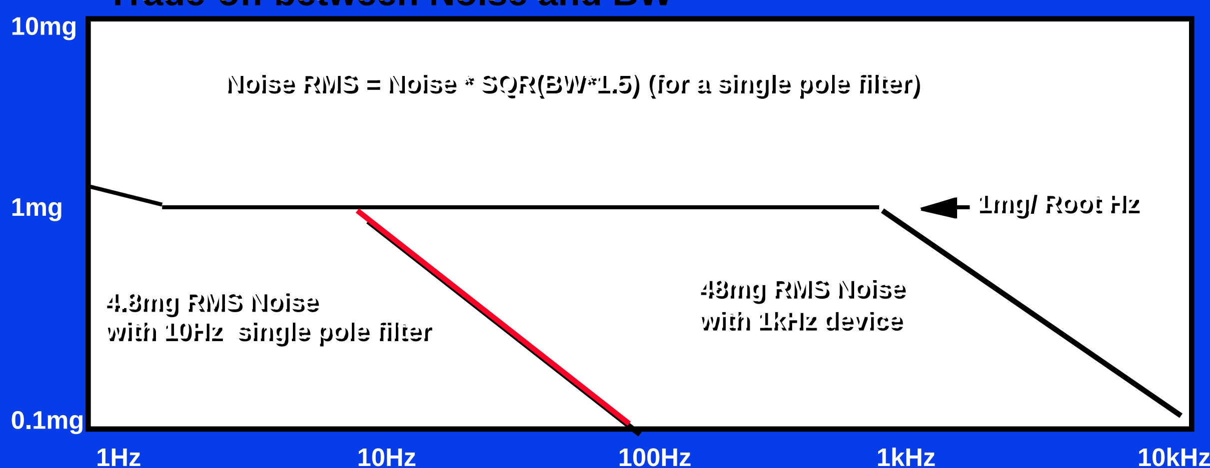
- How can I digitize my signal and achieve the BW, resolution and accuracy required?
- What are my requirements?
  - Resolution defined by bits, mg or degrees
  - BW defined in Hz
  - Accuracy in bits, mg or degrees
- What are the limitations
  - Accelerometer resolution and noise
  - Accelerometer short term and long term stability
  - Accelerometer Sensitivity
  - A/D converter bits

Resolution limited by accelerometer ‘noise’

- Short Term <1s
  - Dominated by 1/f and broadband noise
  - Noise trades off with BW
- Long Term > minutes to hours
  - Dominated by temperature changes due to bias drift with temperature (can be corrected at system level)
  - Hysteresis (non-repeatability) generated by temperature, shock or vibration
  - Often affected by packaging technology, or device technology

Noise in micro-machined accelerometers

- White noise characteristic defined by mg/ $\sqrt{Hz}$
- Noise rolls off with accelerometer BW
- Trade-off between Noise and BW



Resolution is generally limited by noise

- Given a 500ug/Rt Hz Accelerometer, what is the resolution Vs. bandwidth trade-off?

BW(Hz)	RMS Noise	P-P Estimate (4x)	Degree of Uncertainty
1Hz	0.5mg	2.0mg	0.1 degree
10Hz	1.6mg	6.3mg	0.4 degree
100Hz	5.0mg	20mg	1.2 degree

- Use a peak to peak estimation; measurement is absolute
- Be sure to account for an additional filtering due to averaging. Example 100hz averaged to 1hz will give 1 Hz noise

RMS noise Vs. peak to peak noise

- Noise is Gaussian in distribution and described statistically
- Peak to Peak Noise can only be estimated from statistics

Nominal Peak-to Peak Value	% of Time that Noise Will Exceed Nominal Peak-to Peak Value
2.0 x rms	32%
4.0 x rms	4.6%
6.0 x rms	0.27%
8.0 x rms	0.006%

A/D converter resolution

- Given a 5V reference and a 500mV/g accelerometer

A/D Bits	Resolution	g's per bit	Degrees/bit
8 Bits	19.5mV/bit	39mg	2.3
10 Bits	4.88mV/bit	10mg	0.6
12 Bits	1.22mV/bit	2.4mg	0.14

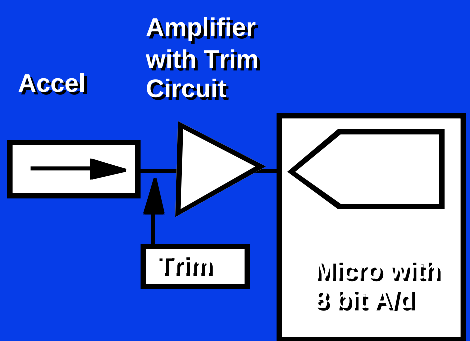
- Accelerometer offsets can limit resolution
  - Accelerometer signal can be amplified, but initial zero g offset is also amplified.
  - Low cost accelerometers have initial offset equal to full scale.
  - HW offset trimming is required even for moderate amplification

Digital trickery

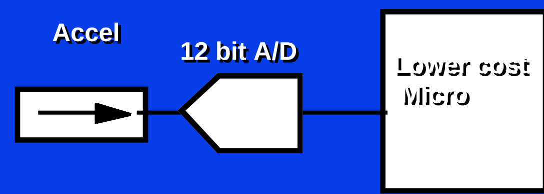
- A to D converter resolution may be increased by using digital signal processing techniques
  - Oversampling is a simple way to improve resolution at the expense of bandwidth
- Digital filters are very effective in very low speed, very high resolution applications
- Zero g bias offsets and scale errors are easy to deal with digitally
  - Calibrations can be automated
- Zero g bias shift over temperature can be eliminated at system level without temperature sensing in some cases

Some possible designs

- Trade-off noise and BW to achieve resolution
- Trade A/D converter bits Vs cost, and trimming



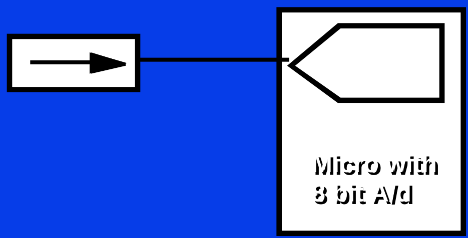
Amplifier allows use of lower resolution A/D, but requires trim resistor circuit to trim out offset of the accelerometer



More expensive A/D but trims are done in software. Possibility to use cheaper microcontroller

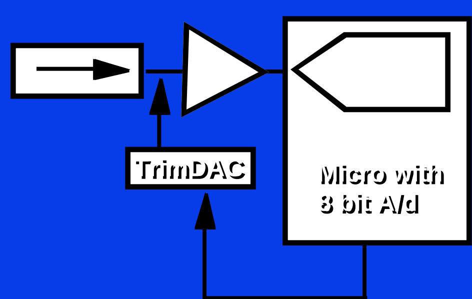
Some possible designs

- Using oversampling, resolution of an 8 bit converter can usually be increased to 10 bits or more
  - 16 averaged samples required for 2 bits of resolution improvement
  - Bandwidth is reduced proportionately (by a factor of 16 in this example)



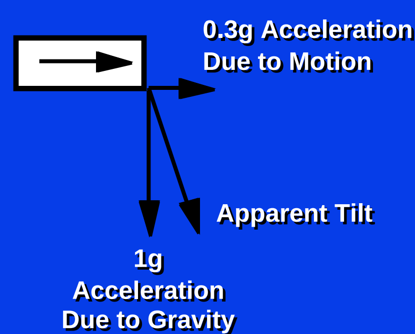
More digital trickery

- A TrimDAC may be used (controlled by the microcontroller) to trim for zero g offset.



Pitfalls: Acceleration interferes with tilt signal

- Both gravity and motion produce accelerations
- Accelerometer (or any tilt sensor) can't tell the difference between motion and tilt
  - However 2 accelerometers cleverly arranged (or a gyroscope) can. (Note: lots of digital trickery may be required)



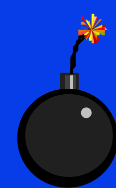
Solutions to the problem of bias stability

Correcting for temperature drift and long term stability

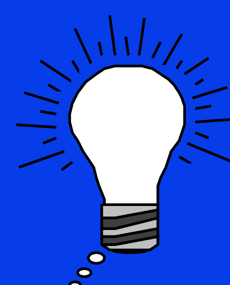
- Buy an expensive sensor ($100 +)
- Use a microcontroller with a temperature sensor
- Use an Analog correction circuit
- Use a temperature controlled crystal oven
- Allow a user recalibration
- Be very clever in your application

Correcting for temperature drift and long term stability

- Buy an expensive sensor
  - End product too expensive leading to bankruptcy and personal humiliation



- Use a microcontroller and temperature sensor
  - Zero g bias drift can be measured over temperature and compensated for by the microcontroller
  - Temperature induced effects are relatively linear so they are easy to handle using either a look-up table or a mathematical solution

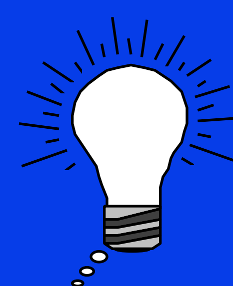


Correcting for temperature drift and long term stability

- Use an analog correction circuit
  - I.e. add a temperature controlled gain stage with an op-amp and a thermistor
  - Hard to match response for sensor to sensor variance
- Use a temperature controlled crystal oven
  - Holds the accelerometer at a constant temp, so drift due to temp doesn't exist
  - Crystal oven may consume a lot of power (500 mA)

Correcting for temperature drift and long term stability

- Allow a user recalibration
  - Let the user hit a “reset button” from time to time when the accelerometer is experiencing zero g
- Be very clever in your application
  - Does your application really need to be DC coupled (i.e. do you need to measure tilt)? If not you should AC couple the accelerometer, via a capacitor, to your signal conditioning stage to eliminate bias drift
  - Use software to detect very low speed, long term, zero changes



Using accelerometers as tilt sensors

Advantages

- Accelerometers have faster response and settling than traditional liquid tilt sensors, up to 100hz response
- No “slosh” or leaking problems associated with liquid tilt sensors
- Sensor + Signal conditioning on a single chip in an IC form factor

Disadvantages

- Acceleration signals may interfere with tilt signal, (problem for all tilt sensors)
- Currently available low cost devices difficult to use for sub 1 degree resolution (except for very low speed applications)

Data acquisition:
Vibration and shock

- How does it work
  - Acceleration used to measure vibration in x, y or z axis
  - Often analyzed in frequency domain as acceleration, velocity or distance (FFT or spectrum analysis)

- Important specifications
  - Bandwidth (minimum and maximum)
  - Dynamic Range (noise limited)
  - Amplitude Stability (Sensitivity changes with temperature, time)

Characteristics of vibration

- For rotating equipment
  - Acceleration and velocity of a vibration are the result of displacements with time.
  - Peak velocity is proportional to displacement and frequency

    $Vpeak = 2\Pi f*(\text{peak displacement})$

  - Peak acceleration is proportional to displacement and frequency squared

    $Apeak = 4*(\Pi\hat{}2)*(f\hat{}2)*(\text{peak displacement})$

  - Energy is proportional to frequency and amplitude

Characteristics of vibration

Examples

- **Fan Motor**
  - 30 Hz (1800 RPM) with a displacement of 1mm peak
  - Velocity = 0.2m/s
  - Acceleration = 35.5 m/s^2 = 3.62g peak
- **Turbine**
  - 10,000 Hz with a displacement of 0.0001mm peak
  - Velocity = 0.006m/s
  - Acceleration = 394m/s^2 = 40g

Characteristics of vibration

- Notice how high frequencies combined with small displacements cause large acceleration
- Even low energy inputs applied to an absolutely fixed accelerometer can cause very large acceleration (this is common to all accelerometers)
- Many applications can tolerate a small amount of “cushioning” of the accelerometer to protect it from damage due to exposure to very large acceleration (cushioning acts as a low pass filter)

Special techniques to recover signal from noise

Example:

Detect a 10mg signal at 1khz using an accelerometer with a 1mg/Root Hz noise floor.

Noise (rms) = 1mg/root Hz * sqr(1000) = 32mg rms

= 128mg p-p

recall that 4.6% of the time the peak to peak noise will exceed 128mg

What if we add a bandpass filter?

- Use a 10 Hz bandpass filter

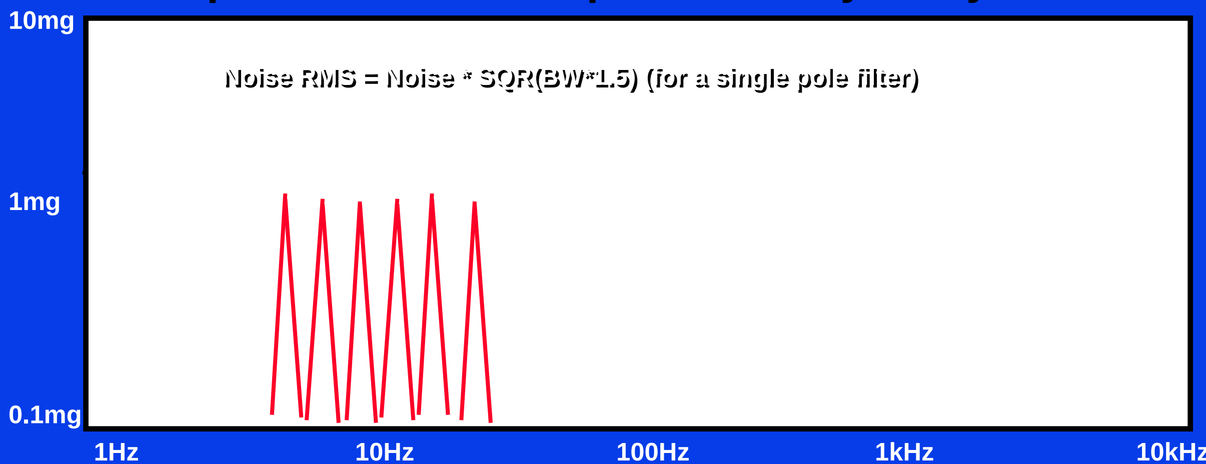
Noise (rms) = 1mg/root hz * sqr(10) = 3.2mg rms

= 12.8mg p-p

But how do we look at multiple frequencies?

Use an FFT to recover signals from noise

- An FFT is essentially a series of narrow band pass filters.
- Low speed FFTs can be performed by many 8-bit micros



Pro's and Con's of Micromachined Sensor

- Advantages
  - Low cost (can even be made "disposable")
  - FFTs can be used to increase the performance
  - Will work for many machine health applications
  - On board signal conditioning. No charge amplifiers required
- Disadvantages
  - Performance still below that of more expensive sensors
  - May not be available in industrial hardened packages

Calibration methods

- Shaker with reference device
  - An AC test that can be done at various frequencies
  - Required a calibrated reference device
  - Can test to higher g levels than 1g
  - Fixturing can be an issue for higher g levels
- Gravity Test
  - Test sensor at +1g and -1g to calibrate offset and sensitivity using Earth's gravity
  - No need to calibrate the reference!
  - Fairly insensitive to alignment errors
  - Only works for DC sensors
  - Will not test the full scale of a high g device.

Calibration methods

- Gravity test method
  - Rotate the accelerometer at least 180° normal to the axis of sensitivity
  - Look for the minimum and maximum values
  - Zero g output = (maxout+minout)/2
  - Scale = (maxout-minout)/2 Volts per g
- Calibration can be performed by the system microcontroller
- Easy fixture construction
- Dual axis accelerometers can calibrate both axis by extending the rotation to at least 360°

Summary

- New accelerometers open the door for new applications in tilt, inertial and vibration
  - Low cost
  - High level of integration: Multiple sensors, + signal conditioning
- Clever design can allow use of a less accurate, but less expensive sensor
  - Using microcontrollers for calibration and algorithms
  - Using signal analysis to improve noise levels
  - Taking new approaches to traditional problems