Sensors and Transducers

E80 Spring 2015
Erik Spjut

What Motors Will You Fly?

- Motor Lottery/Draft at 9:35 AM on Tuesday, 10 MAR 2015.
- List on http://www.eng.hmc.edu/NewE80/RocketLaunchLab.html#Motors
- Those with * require an extra-long motor mount and MUST be reinforced with a layer of fiberglass.

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Scientific & Engineering Measurements

- Scientific Measurements
  - What you measure *with* a rocket.
  - What are examples?
- Engineering Measurements
  - What you measure *about* a rocket.
  - What are examples?

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Experimental Measurements

- Mass
- Force
- Acceleration
- Velocity
- Position
- Displacement
- Orientation
- Vibration
- EM Intensity
  - Radio
  - Microwave
  - IR
  - Visible
  - UV
  - X-ray
  - Gamma

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Experimental Measurements II

- Temperature
- Pressure
- Flow Rate
- Composition
  - Partial Pressure
  - Humidity
  - Mass fraction
  - Mole fraction
  - pH
- Phases
  - Aerosols
  - Suspensions
  - Microstructure
- Sound
- Images
- Video

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Experimental Measurements III

- Electrical
  - Voltage
  - Charge
  - Current
  - Resistance
  - Inductance
  - Capacitance
  - Power
- Time
- Frequency
- Phase
- Angular
  - Position
  - Velocity
  - Acceleration

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Digikey's List of Sensors

- Accelerometers (1069 items)
- Accessories (3933 items)
- Amplifiers (312 items)
- Capacitive Touch Sensors, Proximity Sensor ICs (569 items)
- Color Sensors (126 items)
- Current Transducers (1555 items)
- Dust Sensors (17 items)
- Encoders (4286 items)
- Flex Sensors (3 items)
- Float, Level Sensors (533 items)
- Flow Sensors (177 items)
- Force Sensors (76 items)
- Gas Sensors (69 items)
- Gyroscopes (246 items)
- Image Sensors, Camera (354 items)
- Inclinometers (44 items)
- IrDA Transceiver Modules (294 items)
- LVDT Transducers (Linear Variable Differential Transformer) (153 items)
- Magnetic Sensors - Compass, Magnetic Field (Modules) (23 items)
- Magnetic Sensors - Hall Effect, Digital Switch, Linear, Compass (ICs) (3023 items)
- Magnetic Sensors - Position, Proximity, Speed (Modules) (3641 items)
- Magnets (101 items)
- Moisture Sensors, Humidity (354 items)
- Motion Sensors, Detectors (282 items)
- Multifunction (80 items)
- Optical Sensors - Ambient Light, IR, UV Sensors (639 items)
- Optical Sensors - Distance Measuring (45 items)
- Optical Sensors - Mouse (117 items)
- Optical Sensors - Photo Detectors - CdS Cells (48 items)
- Optical Sensors - Photo Detectors - Logic Output (131 items)
- Optical Sensors - Photo Detectors - Remote Receiver (1139 items)
- Optical Sensors - Photodiodes (990 items)
- Optical Sensors - Photoelectric, Industrial (11099 items)
- Optical Sensors - Photointerrupters - Slot Type - Logic Output (1078 items)
- Optical Sensors - Photointerrupters - Slot Type - Transistor Output (1164 items)
- Optical Sensors - Phototransistors (781 items)
- Optical Sensors - Reflective - Analog Output (325 items)
- Optical Sensors - Reflective - Logic Output (130 items)
- Position Sensors - Angle, Linear Position Measuring (1213 items)
- Pressure Sensors, Transducers (26694 items)
- Proximity Sensors (3759 items)
- Proximity/Occupancy Sensors - Finished Units (236 items)
- RTD (Resistance Temperature Detector) (60 items)
- Shock Sensors (18 items)
- Solar Cells (85 items)
- Specialized Sensors (359 items)
- Strain Gages (21 items)
- Temperature Regulators (3803 items)
- Temperature Sensors, Transducers (1031 items)
- Temperature Switches (719 items)
- Thermistors - NTC (4972 items)
- Thermistors - PTC (1253 items)
- Thermocouple, Temperature Probe (399 items)
- Tilt Sensors (54 items)
- Ultrasonic Receivers, Transmitters (77 items)
- Vibration Sensors (35 items)

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What Spec's Do We Care About?

- Quantity Measured
- Range or Span
- Accuracy
- Precision
- Noise
- Linearity
- Speed of Response
- Voltage Requirements
- Current Requirements
- Output Impedance
- Mounting Requirements

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Example – Altimeter

- Measure Absolute Pressure and Calculate Altitude
  - What range of pressures do we need?
  - What accuracy do we expect?

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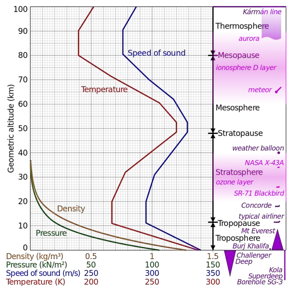
Calculate Altitude from Pressure



US Standard Atmosphere

http://en.wikipedia.org/wiki/File:Comparison_US_standard_atmosphere_1962.svg

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For the Troposphere

$$h = \frac{T_0}{-\left(\frac{dT}{dh}\right)} \cdot \left[1 - \left(\frac{P}{P_0}\right)^{\frac{-\left(\frac{dT}{dh}\right)R}{gM}}\right]$$

where

- h = geopotential altitude (above sea level) (in meters)
- P_0 = standard atmosphere pressure = 101325Pa
- T_0 = 288.15K (+15°C)
- dT/dh = –0.0065 K/m: thermal gradient or standard temperature lapse rate
- R = 8.31432 Nm/mol K (Current NIST value 8.3144621)
- g = 9.80665 m/s²
- M = 0.0289644 kg/mol

From 1976 US Standard Atmosphere

How Does Pressure Vary With Height?

Alt. (m)	Alt. (ft)	Alt. (mi)	P (Pa)	dP/dh (Pa/m)
0	0	0.000	101325	-12.01
200	656	0.124	98945	-11.78
400	1312	0.249	96610	-11.56
600	1969	0.373	94321	-11.34
800	2625	0.497	92076	-11.12
1000	3281	0.621	89874	-10.90
1200	3937	0.746	87715	-10.69
1400	4593	0.870	85598	-10.48
1600	5249	0.994	83522	-10.27
1800	5906	1.118	81488	-10.07
2000	6562	1.243	79494	-9.87
2200	7218	1.367	77540	-9.67
2400	7874	1.491	75624	-9.48
2600	8530	1.616	73747	-9.29

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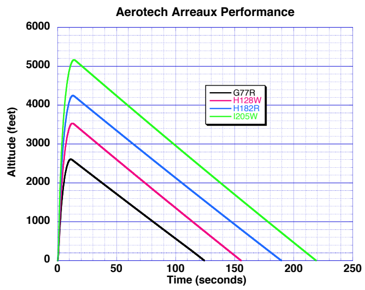
Calculate Flight Height



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Assume 1 Mile AGL Max Alt

- Lucerne Valley at 3000 ft MSL, Claremont 1200 ft
- P_{ground} = 90 kPa
- P_{apogee} = 74 kPa
- Span = ΔP = 16 kPa
- Need to allow for Barometric Pressure Changes +7% to –13%
- $P_{\max}$ = MAX(104 kPa, 97 kPa)
- $P_{\min}$ = 64 kPa

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MPXA6115AC7U

Operating Characteristics

Table 1. Operating Characteristics (V_S = 5.0 Vdc, T_A = 25°C unless otherwise noted, P1 > P2)

Characteristic	Symbol	Min	Typ	Max	Unit
Pressure Range	P_{OP}	15	—	115	kPa
Supply Voltage[1]	V_S	4.75	5.0	5.25	Vdc
Supply Current	I_o	—	6.0	10	mAdc
Minimum Pressure Offset[2] (0 to 85°C) @ V_S = 5.0 Volts	V_{off}	0.133	0.200	0.268	Vdc
Full Scale Output[3] (0 to 85°C) @ V_S = 5.0 Volts	V_{FSO}	4.633	4.700	4.768	Vdc
Full Scale Span[4] (0 to 85°C) @ V_S = 5.0 Volts	V_{FSS}	4.433	4.500	4.568	Vdc
Accuracy[5] (0 to 85°C)	—	—	—	±1.5	$\%V_{FSS}$
Sensitivity	V/P	—	45.0	—	mV/kPa
Response Time[6]	t_R	—	1.0	—	ms
Warm-Up Time[7]	—	—	20	—	ms
Offset Stability[8]	—	—	±0.25	—	$\%V_{FSS}$

From Freescale Data Sheet

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Nominal Values

- $V @ P_{\mathrm{min}}$= 0.200 V + (64 kPa – 15 kPa)•0.045 V/kPa = 2.41 V
- $V @ P_{\mathrm{max}}$ = 0.200 + (104 kPa – 15 kPa)•0.045 V/kPa = 4.21 V
- Accuracy (Uncalibrated) ±1.5% V_{FS} = ±1.5%•4.7 V = ±0.071 V = ±1.57 kPa = ±157 m
- $t_{\mathrm{R10\%\text{-}90\%}}$ = 1.0 ms, $\tau = t_{\mathrm{R10\%\text{-}90\%}}/\ln(9)$ = 0.46 ms

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Output Impedance

- Can drive circuit with 0.5 mA at 4.7 V
- Impedance of driven circuit = V/I = 4.7 V/0.0005 A = 9400 Ω.
- Actual output impedance determined empirically. How?

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Choices on Conditioning

- Data Logger
  - 0 V to 3.3 V
  - Input Impedance ~2200 Ω
  - 16 bit, 1 LSB = 3.3 V/2^{16} = 50 μV

1. Change gain so V_{max} = 3.3 V
   - 1 LSB = 50 μV = 0.16 m = 6 in
2. Change gain and offset so V_{min} = 0 V & V_{max} = 3.3 V
   - 1 LSB = 50 μV = 0.06 m = 2.4 in

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Signal Conditioning

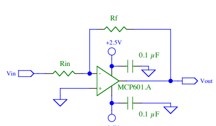
- Does it need a buffer amp? How would you know?
- How do you change the gain?
- How do you change the gain and offset?
- What about aliasing?

Single-Sided Circuits

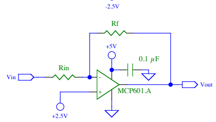
(Will visit again under Flight Hardware)

- Data logger expects 0 V to 3.3 V signals
- Classical op-amp circuit power ±15 V
- Low-voltage op-amp circuit power
  - ±1.4 V to ±3 V
  - 0-to-2.8 V to 0-to-6 V
- Signal offset
- Reference offset
- Virtual ground

Inverting Amps

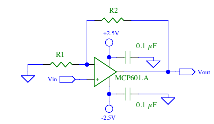


$$V_{out} = -\left(\frac{R_f}{R_{in}}\right)V_{in}$$

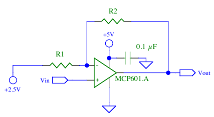


$$V_{out} = -\left(\frac{R_f}{R_{in}}\right)V_{in} + 2.5\left(1 + \frac{R_f}{R_{in}}\right)$$

Non-Inverting Amps



$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right) V_{in}$$



$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right) V_{in} - 2.5\left(\frac{R_f}{R_{in}}\right)$$

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Can You do Single Sided for:

- Differential Amplifier?
- Integrator?
- Transimpedance Amplifier?
- Sallen-Key Filter?
- Bipolar sensor like piezoelectric vibration?

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Example – Gas Sensor

- MQ-2 CH_4 Gas Sensor (Digikey, Parallax, or Pololu)

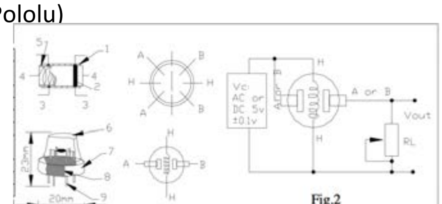

Fig. 1 Fig.2

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Other Specs

SPECIFICATIONS

A. Standard work condition

Symbol	Parameter name	Technical condition
V_C	Circuit voltage	5V±0.1
V_H	Heating voltage	5V±0.1
R_L	Load resistance	can adjust
R_H	Heater resistance	33Ω ± 5%
P_H	Heating consumption	less than 800mw

C. Sensitivity characteristic

Symbol	Parameter name	Technical parameter	Remarks
Rs	Sensing Resistance	3KΩ-30KΩ (1000ppm iso-butane)	Detecting concentration scope: 200ppm-5000ppm LPG and propane
α (3000/1000) isobutane	Concentration Slope rate	≤0.6	300ppm-5000ppm butane
Standard Detecting Condition	Temp: 20℃±2℃ Vc:5V±0.1 Humidity: 65%±5% Vh: 5V±0.1		5000ppm-20000ppm methane 300ppm-5000ppm H_2
Preheat time	Over 24 hour		100ppm-2000ppm Alcohol

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Sensitivity

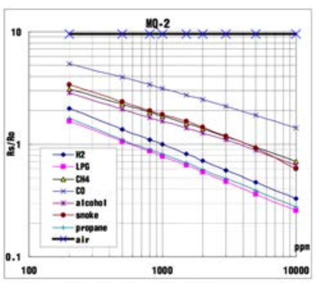

Fig.2 sensitivity characteristics of the MQ-2

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Power Calculations

- 5 V @ 800 mW = 160 mA.
- 5 V @ 33 Ω = 150 mA.
- Standard 9 V battery is ~250 mAh
  - Would last about 1 ½ hours
  - Separate battery for sensor and system.

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Signal Conditioning

- Must get air to sensor.
- Resistance changes with gas concentration.
- Designed to work in voltage divider.
- Need R in range of approx. 3 kΩ to 30 kΩ.
- Need buffer amp.
- What is time constant?
- http://www.parallax.com/catalog/sensors/gas for more info

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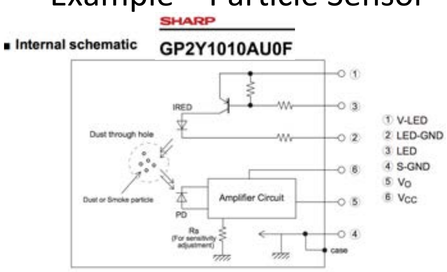
Example – Particle Sensor



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Driving & Reading Circuits

Fig. 1 Input Condition for LED Input Terminal

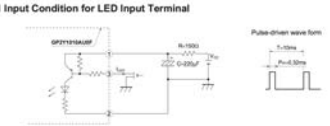
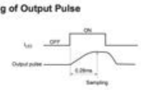


Fig. 2 Sampling Timing of Output Pulse



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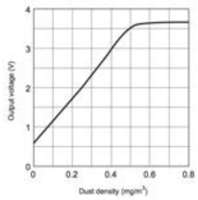
Output & Caution

Fig. 3 Output Voltage vs. Dust Density



10 Vibration influence
The sensor may change its value under mechanical oscillation. Before usage, please make sure that the device works normally in the application.

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Driving Circuit

intersil ICM7555,

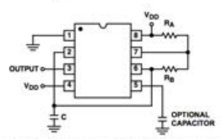

FIGURE 2B. ALTERNATE ASTABLE CONFIGURATION

The timer can also be connected as shown in Figure 2B. In this circuit, the frequency is:

$$f = 1.44/(R_A + 2R_B)C \quad \text{(EQ. 2)}$$

The duty cycle is controlled by the values of R_A and R_B, by the equation:

$$D = (R_A + R_B)/(R_A + 2R_B) \quad \text{(EQ. 3)}$$

D must be ≥ 0.5

See http://www.physics.udel.edu/~nowak/phys645/555%20timer%20lab_files/555%20timer%20lab.pdf for alternate duty cycle control

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Reading Circuit

- Pulse Width 0.32 ms
- Minimum 1 point
- Best 10 points
- Sample rate = 10/0.32 ms = 31.25 kSPS

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Could You Do Better?

- IRED and Driver
- Photodiode & Reading Circuit
- Mechanical & Optical Chamber
- Start at http://en.wikipedia.org/wiki/Particle_counter for more information

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Example – Humidity Sensor

- Check out Digikey
  - http://www.digikey.com/product-search/en?FV=fff4001e%2Cfff80274&mnonly=0&newproducts=0&ColumnSort=1000011&page=1&stock=0&pbfree=0&rohs=0&quantity=1&ptm=0&fid=0&pageSize=25
- Digital, I^2C – 18 s response time
- Capacitive – 15 s, 5 s response time
- Linear Voltage – 5 s response time

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Digital, I^2C

- Need microcontroller, e.g., Arduino Pro Mini 328 - 3.3V/8MHz <Sparkfun>
- Power separately from data logger
- Must synchronize
- Must program

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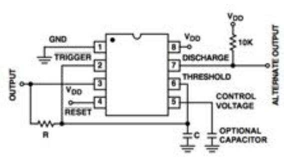
Capacitive

- How do you measure capacitance?
  - Put in a timer circuit
  - Put in an integrator
  - Put in a voltage divider

In a Timer Circuit

intersil ICM7555,



$$f = \frac{1}{1.4\ RC} \qquad \text{(EQ. 1)}$$

HS1101LF (Capacitive)

HS1101LF – Relative Humidity Sensor

measurement SPECIALTIES™

ELECTRICAL CHARACTERISTICS OF HUMIDITY SENSOR

(Ta=25℃, measurement frequency @10kHz / 1V unless otherwise noted)

Characteristics	Symbol	Min	Typ	Max	Unit
Humidity Measuring Range	RH	1		99	%RH
Supply Voltage	Vs			10	V
Nominal capacitance @55%RH (1)	C	177	180	183	pF
Temperature coefficient	T_{cc}		-0.01		pF/℃
Average Sensitivity from 33% to 75%RH	ΔC/%RH		0.31		pF/%RH
Leakage Current (Vcc=5V)	I			1	nA
Recovery time after 150 hours of condensation	tr		10		s
Humidity Hysteresis				+/-1	%RH
Long term stability	T		+/-0.5		%RH/yr
Time Constant (at 63% of signal, still air) 33%RH to 80%RH	ta		3	5	s
Deviation to typical response curve (10% RH to 90%RH)			+/-2		%RH

(1) Tighter specification available on request

TYPICAL PERFORMANCE CURVES

POLYNOMIAL RESPONSE OF HS1101LF

$C\ (pF) = C@55\ \% * (3.903\ 10^{-8} * RH^3 - 8.294\ 10^{-6} * RH^2 + 2.188\ 10^{-3} * RH + 0.898)$

TYPICAL RESPONSE LOOK-UP TABLE (POLYNOMIAL REFERENCE CURVE) @ 10KHZ / 1V

RH (%)	0	5	10	15	20	25	30	35	40	45	50
Cp (pF)	161.6	163.6	165.4	167.2	169.0	170.7	172.3	173.9	175.5	177.0	178.5
RH (%)	55	60	65	70	75	80	85	90	95	100	
Cp (pF)	180	181.4	182.9	184.3	185.7	187.2	188.6	190.1	191.6	193.1	

REVERSE POLYNOMIAL RESPONSE OF HS1101LF

$RH\ (\%) = -3.4656\ 10^{+3} * X^3 + 1.0732\ 10^{+4} * X^2 - 1.0457\ 10^{+4} * X + 3.2459\ 10^{+3})$

With X=C(read) / C@55%RH

MEASUREMENT FREQUENCY INFLUENCE

In this data sheet, all capacitance measurements are done @ 10 kHz / 1Volt. However, the sensor can operate without restriction from 5 kHz to 300 kHz.

HS1101LF continued

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Timer Calc's

f	5.291	kHz	f@RHmin	5878	Hz
	5291	Hz	f@RHmax	4939	Hz
Cnom	180	pF	Δf/ΔRH	-9.58	Hz/%Rh
	1.8E-10	F	Min Frame	0.1044	s
R	750000	Ω	Min SR	11755	SPS
	750	kΩ	SR	58777	SPS
				58.78	kSPS

The sample rate will need to be twice the frequency and preferably 10X. The frame size needs to be the reciprocal of the frequency resolution

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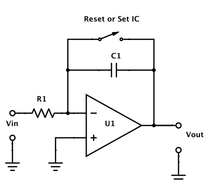
Integrator



$$V_{out}(t_1) = V_{in}(t_0) - \frac{1}{R_1 C_1} \int_{t_0}^{t_1} V_{in}(t)\,dt$$

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Issues

- Easiest input is constant voltage
  - Output is then a ramp
  - Calculate C from ramp slope or time to V_{set}.
  - Ramp up or down? Single-sided supply?
- How control reset switch?
  - Solid state switch
  - Signal generator
  - Comparator
- Are you just making an oscillator?

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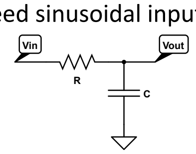
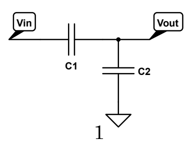
Voltage Divider

- Need sinusoidal input





$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{1 + jRC\omega}$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\frac{1}{j\omega C_2}}{\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}} = \frac{1}{1 + C_2 / C_1}$$

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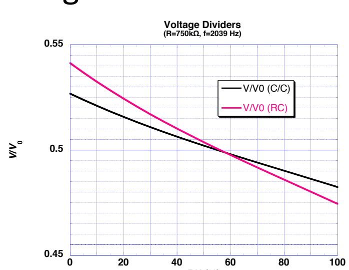
Voltage Divider Performance



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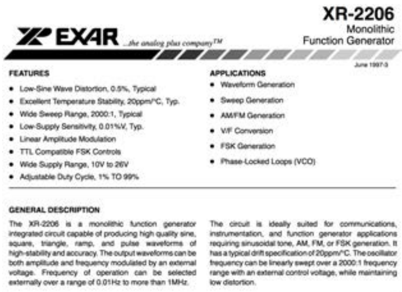
How Do You Generate a Sine Wave?


XR-2206
Monolithic
Function Generator

EXAR ...the analog plus company™

June 1997-3

FEATURES

- Low-Sine Wave Distortion, 0.5%, Typical
- Excellent Temperature Stability, 20ppm/°C, Typ.
- Wide Sweep Range, 2000:1, Typical
- Low-Supply Sensitivity, 0.01%V, Typ.
- Linear Amplitude Modulation
- TTL Compatible FSK Controls
- Wide Supply Range, 10V to 26V
- Adjustable Duty Cycle, 1% TO 99%

APPLICATIONS

- Waveform Generation
- Sweep Generation
- AM/FM Generation
- V/F Conversion
- FSK Generation
- Phase-Locked Loops (VCO)

GENERAL DESCRIPTION

The XR-2206 is a monolithic function generator integrated circuit capable of producing high quality sine, square, triangle, ramp, and pulse waveforms of high-stability and accuracy. The output waveforms can be both amplitude and frequency modulated by an external voltage. Frequency of operation can be selected externally over a range of 0.01Hz to more than 1MHz.

The circuit is ideally suited for communications, instrumentation, and function generator applications requiring sinusoidal tone, AM, FM, or FSK generation. It has a typical drift specification of 20ppm/°C. The oscillator frequency can be linearly swept over a 2000:1 frequency range with an external control voltage, while maintaining low distortion.

Available on eBay

What killed it?

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How Do You Generate a Sine Wave?

- http://www.valvewizard.co.uk/signalgenerator.pdf
- http://arduino.cc/en/Tutorial/DueSimpleWaveformGenerator
- http://www.analog.com/media/en/technical-documentation/data-sheets/AD9833.pdf

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Linear Voltage

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Table 1. Performance Specifications (At 3.3 Vdc supply and 25 °C [77 °F] unless otherwise noted.)

Parameter	Minimum	Typical	Maximum	Unit	Specific Note
Interchangeability (first order curve)					
0% RH to 10% RH, 90% RH to 100% RH	-7	–	7	% RH	–
11% RH to 89% RH	-3	–	3	% RH	
Accuracy (best fit straight line) 11% RH to 89% RH	-3	–	+3	% RH	4
Hysteresis	–	2	–	% RH	–
Repeatability	–	±0.5	–	% RH	–
Settling time	–	–	70	ms	–
Response time (1/e in slow moving air)	–	5	–	s	–
Stability (at 50% RH in 5 years)	–	±1.2	–	% RH	1
Voltage supply	2.7	–	5.5	Vdc	2
Current supply	–	200	500	µA	–
Voltage output (1st order curve fit)	$V_{OUT}=(V_{SUPPLY})(0.00636(\text{sensor RH}) + 0.1515)$, typical at 25 °C				
Temperature compensation	True RH = (Sensor RH)/(1.0546 – 0.00216T), T in °C				
Output voltage temp. coefficient at 50% RH, 3.3 V	–	-2	–	mV/°C	–
Operating temperature	-40[-40]	See Figure 2.	85[185]	°C[°F]	–
Operating humidity (HIH-5030)	0	See Figure 2.	100	% RH	3
Operating humidity (HIH-5031)	0	See Figure 2.	100	% RH	–
Storage temperature	-50[-58]	–	125[257]	°C [°F]	–
Storage humidity	See Figure 3.			% RH	3

Specific Notes:
1. Includes stress outside of recommended operating zone.
2. Device is tested at 3.3 Vdc and 25 °C.
3. Non-condensing environment. When liquid water falls on the humidity sensor die, output goes to a low rail condition indicating no humidity.
4. Total accuracy including interchangeability is ±3 %RH.

General Notes:
- Sensor is ratiometric to supply voltage.
- Extended exposure to ≥90 % RH causes a reversible shift of 3 % RH.
- Sensor is light sensitive. For best performance, shield sensor from bright light.

CAUTION

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Figure 4. Typical Output Voltage (BFSL) vs Relative Humidity (At 0 °C, 70 °C and 3.3 Vdc.)

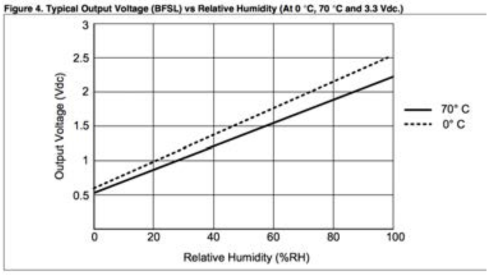

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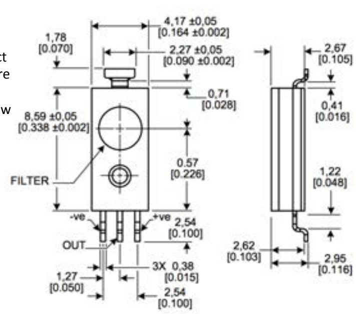
Figure 7. HIH-5031 Mounting Dimensions (For reference only. mm/[in])

The challenges are how and where to connect it, how and where to mount it, and how to get airflow over it.



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Where to look for sensors

- Digikey: http://www.digikey.com
- Mouser: http://www.mouser.com
- Arrow: http://www.arrow.com
- Sparkfun: https://www.sparkfun.com
- Pololu: https://www.pololu.com
- Parallax: http://www.parallax.com
- SGX Sensortech: http://sgx.cdistore.com

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