Gapsense product comparison

Gapsense comparo.doc

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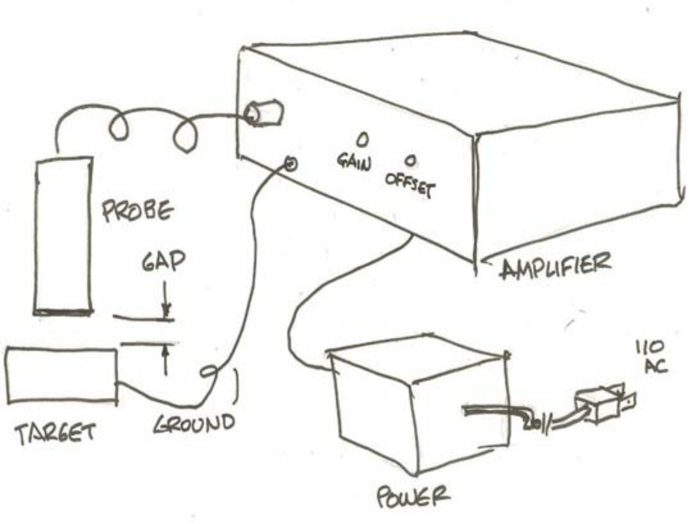
Introduction

Very precise position sensors are available from several companies. These sensors can be considerably less expensive ($1-2k) and more accurate than laser techniques (see http://www.capacitance-sensors.com/capacitive_sensor_tutorial.htm). They handle target-to-sensor gaps from microns to centimeters, signal bandwidths can be over 10kHz, and with two sensors you can handle non-contact thickness measurements.

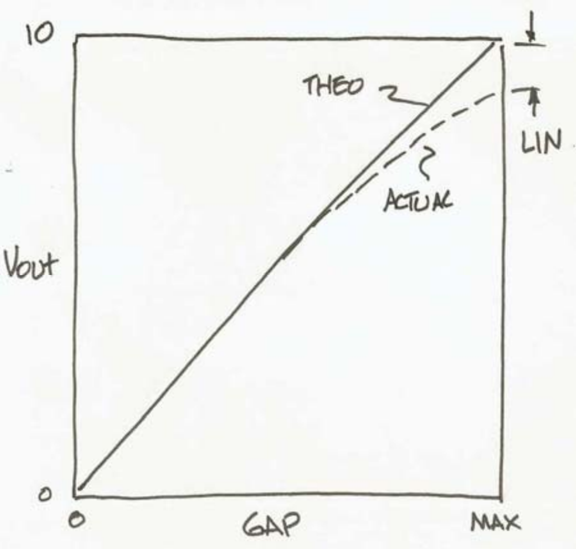
The instrumentation is an "amplifier" card in a rack for multichannel or in a small enclosure for single channels. It is usually powered by a remote 110/220VAC power "brick" with +/-15V out. Some low-powered models use 5VDC.



The amplifier accepts a coax or triax cable to the sensor, with often a fixed 1m cable length. Some manufacturers allow extension cables to 10m without recalibration. Shorter cables are less noisy due to the lower signal-to-guard capacitance. Some manufacturers offer active probes, or an active preamp in the cable, for long cable runs but limited temperature range.

The typical sensor is a stainless steel triaxial cylinder with an inner signal conductor, shielded by a driven guard, with an outside grounded shield. The diameter of the exposed sensor disk is in the 1-5mm range and the maximum gap ranges from 0.1 to 0.66x this active disk diameter.

Resolution with small gaps and low bandwidths can be spectacular: with a very accurate 2mm diameter sensor, an 0.1mm gap, and a 1Hz bandwidth, it's down to 0.05nm. Blue light's wavelength is 380nm, and a water molecule is 0.1nm diameter.



Uncorrected linearity can be 2-5%. One source of nonlinearity is the non-zero input capacitance looking into the cable. As the sensor capacitance can be ~0.1pF, for uncorrected 1% linearity the input capacitance must be <0.0001pF.

Another source of nonlinearity is the imperfect electric field due to the finite size of the guard ring. If the guard ring was large, about five times the sensor disk, this nonlinearity would be <1ppm, but with the much-smaller guard used by most manufacturers, electric-field nonlinearity is a few percent for large gaps, <0.5% for small gaps.

A third source of nonlinearity is mechanical imperfection like tilt, curvature, surface roughness, or small target size.

Optional linearity correction to 0.02-1% is done with analog or digital circuits.

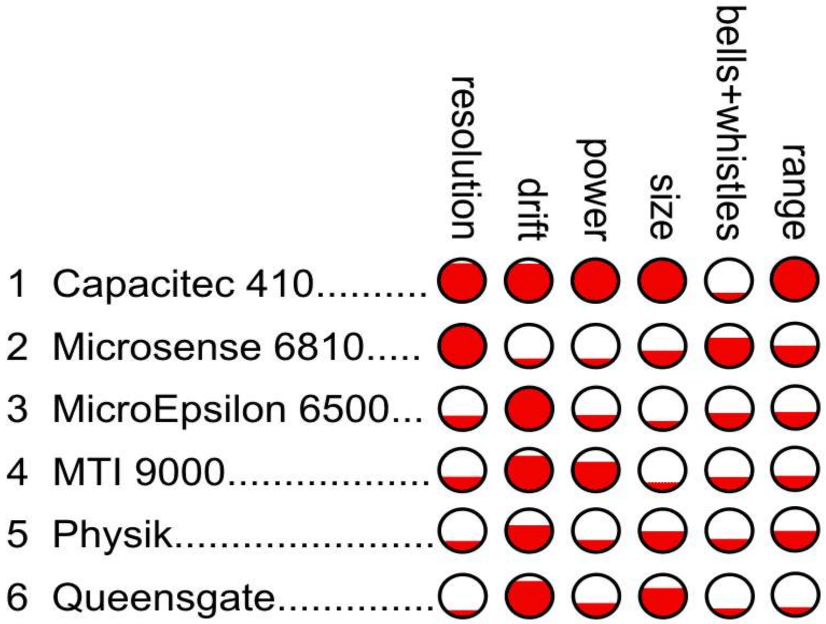
Most models have gain and offset adjustments from the front panel. All models are undamaged if the sensor touches the target, or if the guard is grounded. Amplifier damage with electrostatic discharge (ESD) is infrequent but possible; few manufacturers list this important spec.

Temperature drift in the amplifier can be 20-400ppm/degC. Drift in the sensor is usually worse, although Invar and ceramic sensors are available from some manufacturers with drift comparable to electronic drift. In any case, proper kinematic mounting with stable materials is required.

The dielectric constant of air changes with temperature, pressure, and humidity, but the total error in a typical lab environment is <50ppm with a 5degC temperature change, a 10% relative humidity change, and an 0.05atm pressure change (*Capacitive Sensors*, Larry K. Baxter, p. 73). This is less than the typical 50ppm change in 5degC with the most accurate amplifier (below). An air-dielectric reference capacitor would fix this not-too-significant issue, but no manufacturer seems to do this.

Signal output is most often a 0-10V DC signal. Digital outputs are available.

Comparison results



The comparison results (detail below) rank Capacitec #1, with solid performance in the most critical parameters, best range, and excellent stability with different cable lengths. Microsense takes the resolution award, and Micro Epsilon the drift award. Physik has an accurate probe assortment.

Comparison listing

Company	Model	Size	in^3	Lin %	Out	Pwr	Pwr, W	Res nm[1]	Range[2] **probe no.**, dia/near/far	BW	Drift ppm/C	Notes
MicroSense microsense.net Was ADE, KLA-Tencor	4810	7x4x 1.5	42	0.1	+/-10 dig	+/-15 200mA	6	21	**2805** 8/0.5/1.5	1k-100k	200	Triax; Active probe available.
	6810/ 6501	7x4.3x 1.6	47	0.25	+/-10			0.4	**2805** 8/0.5/1.5	1k-100k	200	0.25nm/5kHz/50um
Capacitec Ayer, MA capacitec.com	410XSC	2x3	4	0.2-1	0-10	+/-15 or +5	1.2	0.9	**HPC-150** 9.5/0/2.5	232-6k	50	Coax probe cable, sig and guard, 20V p-p drive
	4100SL	~4x4x1	16	0.2			?	0.9	**HPC-150** 9.5/0/2.5	5k		
Fogale												no data available
Micro Epsilon micro-epsilon.com	6300	7x4x1.3	36	0.2	0-10	+/-15 150mA	4.5	8	**CS08** 8/0/0.8	8k	100	11ppm/C (sensor). Zero and gain adj.
	6500	4x1.3 x14	72	0.05	0-10	110 AC	?	7	**CS08** 8/0/0.8	8.5k	10	FS 0.2-20mm available.
MTI Inst. Albany, NY mtiinstruments.com	micro	6x2.4x.5	72	0.02	+10	+/-15 100m	3	10	**ASP-20-PCR** 8/0/0.5	0-5k	60	10ppm res, 0.02% accurate Resolution given is p-p(!)
	9000	9x6x2	108		0-10 +/-5	110AC	?	10	**ASP-20-PCR** 8/0/0.5	5k	30	2 channel
Physik Instrumente PI-USA.us	E582	4.1x3x 1.6	20	0.1	+/-10	+/-15 125m	3.75	78	**D-510.100** 20/0.25/.75	6k	80	resolution=0.001 % of measurement range(RMS)
Queensgate nanopositioning.com	NS2000		5	0.02	+/-5	+/-15 70m	2	24	**NXA** 10/.025/.075	5k	50	2 or 10pF, 2m cable adj. Gain, lin not compensated
	SPNS 1100	2.7x2.3 x1.2	12	0.08	+/-10	+/-15 150m	4.5	24		35k		2 or 10pF, “single point”

1 Resolution normalized to 1mm active-area diameter, 1mm spacing, 100pF cable capacitance (about 1m), 20V p-p drive signal, 1nV/rootHz preamp noise.

2 Range is with a typical cylindrical probe, overall probe diameter/smallest gap/largest gap in mm, using mfgr's largest spec'd gap for this probe. Linearity may be worse than listed in the Lin column with the largest gaps. For more range, use a larger probe diameter if possible.

Size and power

A small low-power unit with excellent precision is available from Capacitec. Queensgate sells a small unit with higher (4.5W) power. Power isn't a critical spec, but multichannel enclosures can get warm, causing temperature drift.

Linearity

The nonlinearity has two sources:

1) If the capacitance looking into the sensor cable is not zero. This circuit nonlinearity can change with temperature and is difficult to compensate. This is <0.1% with well designed amplifiers.
2) Geometric nonlinearity due to bending of field lines if the guard ring is not large enough, or the target is too small. As most manufacturers use similar guard rings, the intrinsic geometric nonlinearity is similar, ranging from <0.1% for small gaps to 5% for large gaps, and the uncorrected linearity is similar.

Both of these effects decrease with small gaps relative to active area. As most manufacturers sell similar linearity correction circuits, the corrected linearity is also similar. The compensation circuits must be calibrated to sensor and gap and often cable length.

All manufacturers use the same driven-guard-ring probe design for best linearity.

It's difficult to get an apples-to-apples comparison of linearity from manufacturer to manufacturer, so this spec did not make it to the comparison chart.

Resolution

Resolution is a critical specification . Better resolution (lower noise) allows a smaller probe diameter, so accurate parallelism is not as important, or allows larger gaps. But it's difficult to compare resolution apples-to-apples between gapsense manufacturers.

Resolution would be infinite (well, except for vibration and Brownian motion) if the electronics were noiseless. But the typical preamp may have a noise of, say, 5nV RMS in a 1Hz bandwidth. In an ideal 10V system, that's only 0.0005 parts per million, or with an 0.1mm gap, 0.00005nm resolution. Not bad. But in our non-ideal world, this spectacular performance is heavily attenuated by unwanted capacitance.

Noise comes from the input preamp. Signal-to-noise ratio is the sensor voltage (at max gap) divided by this preamp noise (at max or nominal gap). Resolution is the max gap divided by this signal-to-noise ratio.

Any gapsense product's output noise varies approximately as Cg/Cx, where Cg is the cable capacitance between signal and coax shield and Cx is the gap capacitance. With a long cable (say, 4m) and a large gap (say, 0.1pF), Cg/Cx can be 400pF/0.1pF, so the small 5nV preamp noise is multiplied by 4000, for a resolution with the gap above of 0.2nm.

But this is at 1Hz. Noise varies as the square root of output bandwidth, so at a more useful 1kHz bandwidth, resolution is further degraded by sqrt(1000) to 6nm.

Few manufacturers specify preamp noise. Instead, they specify resolution, bandwidth, gap size, and sensor diameter. To get apples vs. apples, we must normalize to a particular bandwidth, gap size, and sensor diameter. We've chosen to normalize to a 1Hz bandwidth, 20V p-p drive, a 1mm dia. probe, and a 1mm gap. The number in the chart's Res column is the computed performance with this setup, ignoring the fringing effects of a finite guard ring, and should measure the preamp equivalent input noise.

The normalization equation multiplies sensor diameter squared, 1/gap squared, cable capacitance, and square root of bandwidth.

Range

Most manufacturers (Queensgate, Microsense, Physik, MTI) do not allow small gaps. To measure a 1mm gap change, you position the target 1mm from the sensor face (the "standoff" distance) and measure from 0.5 to 1.5mm. This sacrifices resolution, as an 0-1mm gap has higher capacitance, but it helps with tilt nonlinearity.

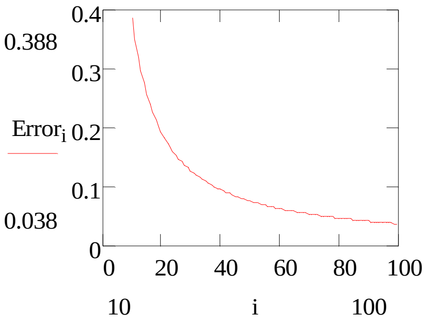
Others (Capacitec, MicroEpsilon) can work down to a minimum gap typically only a few percent of maximum gap.

Tilt

It's very difficult to design the mechanics to keep the sensor exactly parallel, and to minimize sensor and target flatness, roughness, etc. Usually the limit to accuracy is in the precision of mechanical design and fabrication. The mechanical precision is less important with large gaps.

The graph shows the measurement error as a percent of gap for a 1 deg. tilt, 2mm dia. sensor, and spacing from 0.1 to 1mm. Increasing the gap decreases the effect of tilt.

But resolution is proportional to the gap squared, so a low-noise amplifier should be chosen so a large gap can be used.



Calibration

Most models let you adjust span and offset with potentiometer adjustment. Most require recalibration for different cable lengths. Some (Capacitec) allow a cable change from, say, 1m to 10m with a small <0.2% change in output that does not require recalibration; for most models the sensor can be replaced with <0.5% change.

Virtual ground

Aa target ground isn't needed if the capacitive coupling of target to local ground is considerably larger than the capacitive coupling of the target to the active sensor area + guard area of the probe. This works, unless there's local electric fields with frequencies near the sensor carrier. This can happen with nearby high-power equipment, motor brush noise, fluorescent lamp electronic ballasts, AM radio transmitters etc.

Two manufacturers, MTI and Micro Epsilon, show a setup where two out-of-phase sensors look at an ungrounded target. This neatly lowers the target's carrier pickup to a theoretical zero, but only if the gaps are identical, the sensor mounting is identical, and there is no other electric field coupling to the target. It does not seem too useful except in carefully-shielded environments..

Temperature drift

Best competitive temp drift spec: MTI, 30ppm/degC and MicroEpsilon, 10ppm (amplifier only). But usually the mechanics is the tall pole. The temperature drift of stainless steel is 8-20um/m/degC, translating into about 10ppm for a gap-length steel section or 1000 ppm for the more common 100x gap length section. As it varies with steel type and steel heat treatment, compensating with similar structures is only partially successful. Invar has a much lower tempco, but is expensive and has much larger aging changes than steel.

Aging drift, creep

“Standard meter bars...were found to change by...2ppm in 52 years” [Baxter, *op. cit.* p. 211-213].

Stay away from aluminum for precision, and steel is more stable if you bake out stress at 100-200degC for a week. Metals creep under stress, especially at high temperature; better for hard alloys.

For insulators, diamond is best but tends to be a little pricey, many ceramics are quite stable and have half the tempco of steel.

Tech notes

http://www.capacitance-sensors.com/capacitive_sensor_tutorial.htm