6

Proximity detectors

Proximity detectors sense the presence of nearby targets, usually without requiring any contact or wiring to the target or any particular target material properties. Various sensors are available for proximity detection and measurement, including capacitive, inductive, optical, ultrasonic, and magnetic sensors. These detectors are used for many industrial applications and they are available with a variety of analog and digital outputs.

6.1 APPLICATIONS

Typical applications of proximity sensors include [Soloman et al., 1994]:

Motion detection	Detection of rotating motion Zero-speed indication Speed regulation
Motion control	Shaft travel limiting Movement indication Valve open/closed Conveyer system control Transfer lines Assembly line control Packaging machine control
Process control	Automatic filling Product selection Machine control Fault condition indication Broken tool indication

	Product present Bottle fill level Product count
Sequence control	Verification and counting Product selection Return loop control Product count
Liquid level detection	Tube high-low liquid level Overflow limit Dry tank
Material level control	Low level limit Overflow limit Material present

6.2 TECHNOLOGY

Proximity sensors are used as inputs for industrial control systems. Sensors for this application are available with many different outputs to connect to different control systems, including two- and three-wire AC, two-, three-, and four-wire DC, normally open and normally closed switches, TTL logic level, AC/DC, and several four-wire analog output versions including linear 4–20 mA current and 0–5 V voltage output versions. A two-wire analog variable-resistance interface (NAMUR) is often used; these devices are small and easy to wire in a system. NAMUR sensors are calibrated to sink 1.55 mA with a nominal 8.2 V DC supply at the nominal sensing range.

Proximity switches can replace mechanical limit switches for difficult environments. Different versions are used to detect ferrous and nonferrous materials, including glass, cardboard, and plastics. LED lamps are often provided for a visual indication of output state.

6.2.1 Inductive sensors

Inductive sensors generate a local magnetic field at a 2 kHz–500 kHz frequency and detect ferrous materials as an increase in flux for constant excitation, or conductive nonferrous metals are detected as a decrease in flux due to their shielding effect or due to induced lossy eddy currents. Detection range is a function of the size of the magnetic system and is in the range of 1 mm–100 mm; for most industrial sensors the maximum detection range is about the same as the diameter of the magnetic coil. Inductive sensors are rugged, cheap, and reliable, but cannot detect dielectric materials. The range and field topology is similar to capacitive sensors with the limited range similarly due to the inability to focus the magnetic field in air. More power is needed for inductive sensors than capacitive sensors.

6.2.2 Magnetic sensors

Magnetic sensors are similar to inductive sensors, except a DC magnetic field generated by a permanent magnet is used instead of the AC field.

As pickup coils are sensitive only to AC magnetic flux, a Hall effect device which is sensitive to DC magnetic fields is often used. The Hall effect, discovered by Mr. E. F. Hall in 1879, is created in a conductive sheet. With a linear current flowing in one axis, a linear field-dependent voltage is measured in the other axis when a magnetic field is induced through the sheet. Silicon implementations are usually packaged in a plastic transistor case with built-in linear amplifier; output sensitivity is 0.25–2 mV/G with a 25 kHz bandwidth. Some versions are available from vendors such as Allegro Microsystems in Worcester, MA, with Schmitt trigger outputs and high current drivers. A drawback of commercially available Hall sensors is the large and poorly controlled offset voltage which is compensated by the use of AC coupling or computer calibration strategies.

Another magnetic sensor with response to DC uses a saturable high permeability material. Permalloy, for example, has a very high permeability of 100,000 or more, a rectangular hysteresis loop, and low saturation flux density, and can be biased to switch states in response to low level DC magnetic fields.

A switching response is also available with a magnet-actuated reed relay, but sensitivity is not as good.

6.2.3 Optical sensors

Many different types of optical sensors are available, from simple slotted optical gate types to reflective sensors. For very accurate long-range object distance measurement, a coherent laser beam can be bounced off a reflective target, and optical interference effects used to measure position differences by counting interference cycles, with one cycle representing 680 nm for red laser light. At the extreme in complexity, a tunable laser can be used to provide an absolute distance capability as well as the differential distance capability.

Optical sensors can be focused, and they can be very accurate, but often need lenses and special target preparation.

6.2.4 Ultrasonic sensors

Ultrasonic sensors radiate a short ultrasonic pulse in the 20 kHz–500 kHz range. The pulse bounces off a local object and the echo is detected, often by the transducer which launched the pulse. Operation depends on the transmission of air and the sonic reflectivity of the target, which is a function of the orientation and material of its surfaces. Ultrasonics is quite useful in sea water, which attenuates E and H fields but transmits sound well. Soft materials such as cloth and foam do not reflect well.

Sound velocity in air is about 344 m/s, but it is affected by several factors [Eshbach, p. 1092]:

Temperature	+ 0.18%/ °C
Relative humidity	+ 0.4% from 0 to 20% RH
Pressure	little effect below 50 atm
Frequency	- 0.243% for 41 kHz to 1.5 MHz

Some ultrasonic sensors can be adjusted to detect objects only between a preset maximum and minimum range [Turck, p. E4]. As the sound is easily focused, maximum range is higher than inductive and capacitive sensors; maximum range for industrial control units is 6–8 m, while security applications make use of longer range units, with up to 15 m range.

6.3 CAPACITIVE PROXIMITY DETECTORS

Proximity sensing is a simple and effective application of capacitive sensors. Capacitive proximity sensors are used for many applications in plant control, and generally are supplied as a small (1 × 5 cm) cylinder with a pair of electrodes on one end and wire leads on the other. The usual output is a contact closure or TTL-level pulse when an object comes within detection range, about 1 cm. A small amount of hysteresis is added to guarantee dither-free output.

Capacitive proximity sensors are noncontact, can detect small objects, and work with either conducting or insulating objects, such as an unprepared surface of a mechanism or a moving conveyerized object. Similar sized conductive objects are all detected at the same range, but detection of insulating objects depends on a lossy dielectric or a dielectric constant sufficiently different from unity; different insulators are detected at different ranges depending on these parameters and on excitation frequency.

Commercial capacitive proximity sensors specify detection ranges of up to 40 mm for a 34 mm diameter cylinder. One manufacturer [Turck] lists cylinder-style capacitive proximity sensors with diameters between 25 and 80 mm with detection distance approximately proportional to diameter. Several other mechanical configurations are available such as rectangular form factors intended for bolt-in replacements for mechanical limit switches. The output is either a switched AC or DC voltage, analog signals, or a contact closure, as for inductive sensors. Two concentric electrodes are used on the end face, as shown in Figure 6.1.

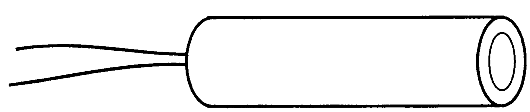

Figure 6.1 Cylindrical capacitive proximity detector

The active face of capacitive proximity sensors is composed of two concentric metal rings. In one manufacturer's implementation the mutual capacitance between the rings appears as the capacitive feedback element of a high frequency Colpitts oscillator. With no object present, the oscillator is tuned to a point just below oscillation; as a target approaches, the coupling between electrodes increases and the circuit oscillates. The oscillator output feeds a switch or an analog amplitude measurement circuit which generates the digital or analog output voltage.

Dielectric materials are effective at actuating the sensor, with effectiveness increasing with increasing dielectric constant. Conductive materials have a different detection range if they are connected to earth ground; the capacitance of the target to ground produces a decrease in coupling but an increased capacitance to ground. A 40 mm diameter model, the CP40 from Turck, lists these specifications (see Table 6.1).

Table 6.1 CP40 capacitive sensor

Nominal sensing range	20 mm
Max. switching frequency	100 Hz
Input voltage	10–65 VDC
Output contacts	1 NO, 1 NC
Sensing range	
Metal	40 mm
Water	40 mm
PVC	20 mm
Wood (varies with RH)	20–32 mm
Cardboard	8 mm
Glass	12 mm

Turck also lists the dielectric constants shown in Table 6.2.

Table 6.2 Dielectric constants

Material	Dielectric constant	Material	Dielectric constant
Acetone	19.5	Ethylene glycol	38.7
Acrylic resin	2.7–4.5	Fired ash	1.5–1.7
Air	1.000264	Flour	1.5–1.7
Alcohol	25.8	Freon R22, 502	6.11
Ammonia	15–25	Gasoline	2.2
Aniline	6.9	Glass	3.7–10
Aqueous solution	50–80	Glycerine	47
Bakelite	3.6	Hard paper	4.5
Benzene	2.3	Marble	8.0–8.5
Cable sealing compound	2.5	Melamine resin	4.7–10.2
Carbon dioxide	1.000985	Mica	5.7–6.7
Carbon tetrachloride	2.2	Nitrobenzene	36
Celluloid	3.0	Nylon	4–5
Cement powder	4.0	Oil saturated paper	4.0
Cereal	3–5	Paraffin	1.9–2.5
Chlorine liquid	2.0	Paper	1.6–2.6
Ebonite	2.7–2.9	Perspex	3.2–3.5
Epoxy resin	2.5–6.0	Petroleum	2.0–2.2
Ethanol	24	Phenol resin	4–12

Table 6.2 Dielectric constants *Continued*

Material	Dielectric constant	Material	Dielectric constant
Polyacetal	3.6–3.7	Shell lime	1.2
Polyamide	5.0	Silicon varnish	2.8–3.3
Polyester resin	2.8–8.1	Soybean oil	2.9–3.5
Polyethylene	2.3	Styrene resin	2.3–3.4
Polypropylene	2.0–2.3	Sugar	3.0
Polystyrene	3.0	Sulfur	3.4
Polyvinyl chloride resin	2.8–3.1	Teflon	2.0
Porcelain	3.5–4	Toluene	2.3
Powdered milk	3.5–4	Transformer oil	2.2
Pressboard	3.7	Turpentine oil	2.2
Quartz glass	3.7	Urea resin	5-8
Rubber	2.5–3.5	Vaseline	2.2–2.9
Salt	6.0	Water	80
Sand	3–5	Wood, dry	2-7
Shellac	2.5–4.7	Wood, wet	10–30

6.3.1 Limits of proximity detection

Single or dual electrodes

Either a single or a dual electrode structure can be used for proximity detectors. A single electrode produces dielectric flux lines which terminate on the surrounding building structure or on the surface of the earth, and single electrodes can have higher values of detection distance relative to electrode size than dipole electrodes. A hazard is that the earth or building ground potential is available to AC-powered instruments only as the third wire in the power cable, and that connection is usually contaminated by noise, but the use of a high carrier frequency usually successfully avoids this noise component.

The dipole electrode pair is simpler and works as well for low ratios of electrode size to detection distance. Dipole geometry is used in commercially available capacitive proximity sensors.

Earth ground

Capacitive proximity detectors may need to function in environments which are corrupted with extraneous electric fields. One cause of extraneous fields in industrial environments is due to high impedance ground connections.

The "earth ground" in textbooks is a perfectly conducting infinite plane. In real life, earth is not particularly conductive, with a resistivity of 500 Ω-cm or more [Morrison, p. 138]. Sand and gravel can have bulk resistivity of 10 kΩ-cm or more, and a 1 in diameter rod driven to a 10 ft depth can have a resistance of 30 – 50 Ω. Treatment with magnesium sulphate will reduce resistance [Fink et al., pp. 19–52].

Current flow in the earth is due to lightning strikes, power transmission lines, and also earth return currents in power distribution systems. Lightning strikes generate by far the largest earth currents; maximum current can exceed 20,000 A. Power transmission line earth currents are restricted to the area immediately beneath the lines and will not trouble most installations.

Earth current returns from power distribution will be a factor in any industrial situation. The power distribution inside a building is set up so that the "hot" AC connection is made through a black wire, in the U.S., and the return current is nominally through the white wire. Conductive equipment enclosures are earthed through the service neutral, the third (green) wire for three-wire connections. The service neutral is unfused, and it has two functions: to provide a return path for small mA-level leakage currents to the equipment enclosures to return to earth ground for safety, and to provide a return for the much larger fault current which flows if a hot wire is shorted to an enclosure. The fault current then results in a blown fuse instead of a dangerous potential on the enclosure.

Leakage currents to the service neutral result from motor or power transformer insulation leakage and from charging current due to small primary-side capacitors used for EMI control. The service neutral potential in an industrial building relative to earth ground is determined by the sum of these mA-level leakage currents flowing through the service neutral ohmic resistance multiplied by the resistance of the local connection to earth. This potential is usually in the 1–15 V range.

6.3.2 Maximum detection range

It is interesting to calculate the approximate detection range of a carefully designed capacitive proximity detector.

From "Monopole proximity detector, parametric plot, log" (Figure 2.40), the falloff in capacitance with 16 mm diameter electrodes is at a rate of 1 decade / 18 mm of spacing. The capacitance at 1 mm target distance is

$$C_1 = \pi r^2 \cdot \frac{\varepsilon_0}{d} = 1.78 \quad \text{pF} \tag{6.1}$$

For this geometry

$$C = 1.78 \cdot 10^{-d/0.018} \quad \text{pF, m} \tag{6.2}$$

The theoretical limit of detectable capacitance variation from "Limiting displacement of three-plate micrometer," Section 12.2.1, is 3×10^{-22} F for a detection limit of 0.176 m, using a narrow 1 Hz bandwidth. Most proximity detectors have a motion detection bandwidth of 100 Hz; for a 100 Hz bandwidth the theoretic limit degrades to 0.158 m.

The limit of experimentally verified capacitive detection with high voltage (100 V rms) excitation [Jones and Richards, 1973] is 0.05 aF, 0.05×10^{-18} F. Substituting this value for C and solving for d, we have

$$d = 0.018 \log \frac{1.75 \cdot 10^{-12}}{0.05 \cdot 10^{-18}} = 0.136 \quad \text{m} \tag{6.3}$$

That limit is, not unexpectedly, difficult to achieve in practice because of the several effects discussed as follows.

Dielectric constant of air

One limit to the maximum detection distance is due to the change of the dielectric constant ε_r of air. At extreme distances, target movement is indistinguishable from ε_r variations. This section calculates the effect of environmental variations on maximum detection distance.

The dielectric constant of air changes slightly with pressure, temperature, and humidity. At standard temperature and pressure, the dielectric constant changes with temperature as 2×10^{-6}/°C for dry air, increasing to 7×10^{-6}/°C for moist air. At 20°C, the dielectric constant change with relative humidity is 7×10^{-5} for an RH change from 40 to 90%. A change of pressure of 1 atm changes the dielectric constant by 10^{-4}. Over a distance of a few tens of meters and a time span of a few hours, the expected variation of these parameters might be typically as shown in Table 6.3.

Table 6.3 Change in dielectric constant of air

	Change	Coefficient	Effect
Temperature	5 °C	5 ppm / °C	25 ppm
Relative humidity	10%	1.4 ppm / %RH	14 ppm
Pressure	0.05 atm	100 ppm / atm	5 ppm
Total			44 ppm

The total of the atmospheric variations above will cause the 1.78 pF capacitor of eq. 2.13 to change by 44 ppm, or by 7.8×10^{-5} pF. Using this new value for C and recalculating the limit of detection of the 16 mm circular plate proximity detector (eq. 6.3) we arrive at

$$L = 0.08 \quad \text{m}$$

so the maximum detection distance has been cut down by a factor of 20 by these environmental effects. A bridge circuit which uses an airgap capacitor as a reference will compensate for these atmospheric variations, but becomes sensitive to temperature and RH gradients, and constructing an air-spaced capacitor with less than 44 ppm drift is not a simple project.

Local motion

Another limit to the sensitivity of proximity detectors is the effect of small movements of local objects which change the mutual capacitance between the measuring electrodes. This motion may be temperature-induced. The temperature coefficient of aluminum, brass, and steel is in the range of 10–20 ppm/ °C. Depending on the orientation of nearby conductors relative to the measurement electrodes, the effect of a nearby conductor moving only a few μm could considerably decrease detection distance.

Focusing field lines

Sensitivity is also limited by the inability to focus capacitance. The field lines can be controlled locally by use of guarding and shielding electrodes, but once in free space, they spread uncontrollably in response to Poisson's law. Wave-propagated signals like light, sound, or electromagnetic radiation can be accurately focused at considerable distance, but that advantage is not available in capacitive sensors; hence a nearby moving object such as a machine operator may drastically limit the usable maximum distance of a proximity detector. Some improvement in performance is available by positioning grounds appropriately; if the sensor is detecting moving dielectric objects on a conveyer belt, say, the best electrode setup is with the two detection plates on either side of the belt. If that is not possible, with both electrodes on one side, a ground on the other improves field focus by a factor of two or three.

Experimental circuit

An experimental capacitive proximity sensor was built to verify the theoretical limiting range calculated above; it is detailed in Chapter 17.

6.3.3 Proximity sensing equivalent circuit

The proximity sensor electrodes are shown in Figure 6.2.

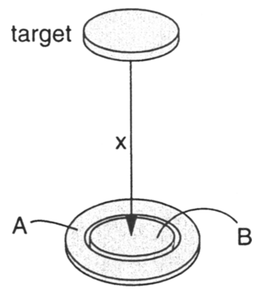

Figure 6.2 Proximity sensor electrodes

A simplified block diagram (Figure 6.3) of the standard two-electrode proximity detector shows the effect of the various capacitances.

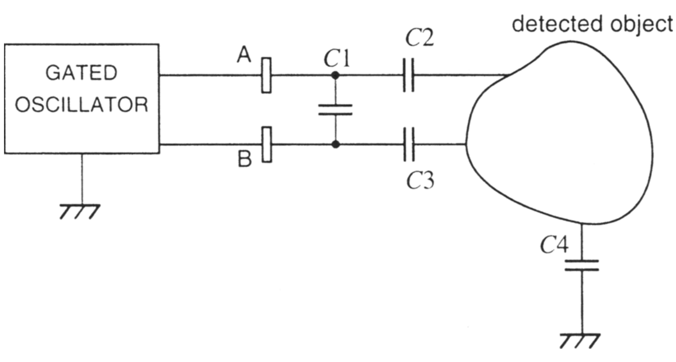

Figure 6.3 Proximity sensor block diagram

The gated oscillator is commonly used for proximity detectors, but it does not have as good a performance as a synchronous detector in noisy environments. The equivalent circuit, for a synchronous detector implementation with electrode A excited, is illustrated in Figure 6.4.

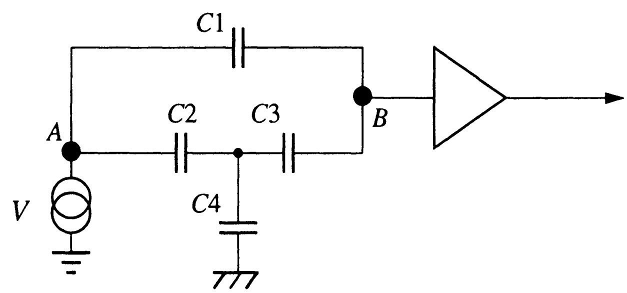

Figure 6.4 Proximity detector equivalent circuit

The synchronous detector and the keyed oscillator circuit can both be analyzed using this equivalent circuit.

The capacitances to be detected, $C2$ and $C3$, are contaminated by stray capacitance $C1$ and $C4$. As target distance increases, $C2$ and $C3$ become much smaller than $C1$, and the additional shunting effect of $C4$ further decreases the signal so that the change in signal with target movement may become a tiny fraction of a percent. Three possible capacitive proximity detector targets may be considered.

Metallic, floating

The equivalent circuit of the floating metallic target is shown in eq. 2.13. $C2$ and $C3$ decrease by about a decade for every sense-plate-diameter increment of target motion.

Metallic, grounded

If the target is a conductive grounded object $C4$ is a short circuit and $C1$ will decrease as the target approaches due to the shielding effect; the change in $C1$ is the measured variable, or a circuit which measures $C2$, the capacitance to ground, can be used.

Dielectric

With a dielectric target $C4$ can be considered open and the values of $C2$ and $C3$ are modulated by the target's proximity. $C1$ increases as a dielectric target approaches due to the increase in permittivity.

6.3.4 Stray fields

Stray electrostatic or electromagnetic fields can interfere with capacitive proximity detection in two ways: by saturating the input amplifier or by being mistaken for the exciting signal.

Input amplifier saturation

An ambient electric field can result from capacitive coupling to a 60 Hz power signal or from the electric field associated with electromagnetic radiation from an RF transmitter. The ambient field may saturate the input amplifier by driving the output to the power rails and the detector will be blocked. Regulatory bodies specify that electronic equipment should not exhibit degraded performance in the presence of a 3 or 10 V/m maximum electric field.

Amplifier saturation is normally not a serious problem, except in very strenuous industrial environments, but it may be avoided by preceding the amplifier with a bandpass filter circuit tuned to the excitation frequency (Figure 6.5).

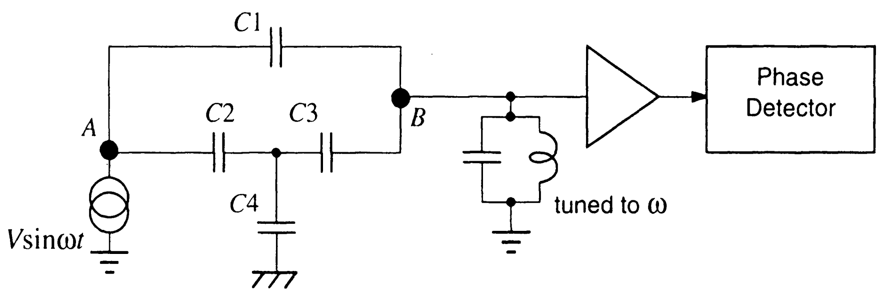

Figure 6.5 Tuned-input proximity detector circuit

Capacitively coupled in-band noise

If, for example, a 20 kHz excitation frequency is used and a local 60 Hz power signal with an irregular waveform is capacitively coupled to the sense electrodes, the 333rd harmonic of 60 Hz is within 20 Hz of the excitation frequency. If the proximity detector's circuits cannot reject this signal, the maximum detection range will be considerably reduced. A resonant circuit or a bandpass filter can help, but a high Q is difficult to achieve and may require tuning. A synchronous detector (below) replaces the bandpass filter with a lowpass filter. This is a very good trade as a 10 Hz lowpass filter is easy to build while a 10 Hz bandpass filter around a 20 kHz carrier is difficult.

Shielding

A metallic shield almost completely attenuates stray E-fields, but proximity detectors cannot usually be completely shielded. Partial shields may help reject local fields.

6.3.5 Phase detectors

Several effective phase detector circuit configurations can be used to virtually eliminate the effects of coupled in-band noise.

Synchronous phase detector

As the detection circuit is in the same enclosure as the transmitter, the detector knows the exact frequency and approximate phase of the signal to be detected. The phase is known exactly if the equivalent circuit is purely capacitive, but in practice resistive elements such as amplifier input impedance will contribute a small phase shift, usually in the range of 10–20°. This phase shift can often be ignored or compensated, and a synchronous detector used (Figure 6.6).

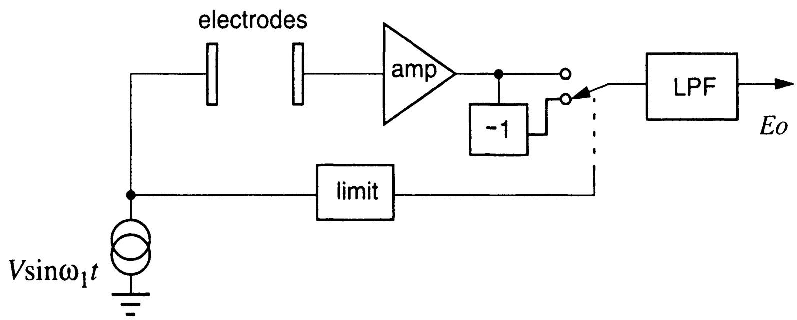

Figure 6.6 Synchronous phase detector

Here, the excitation voltage for the electrodes is also applied to a switch which chooses between the amplified signal electrode voltage and its negative. If phase shifts are small, the result at the LPF output is a DC representation of the magnitude of the electrode voltage at the switching frequency, with switch transients removed by the lowpass filter. The sinusoidal excitation signal, hard limited to a square wave, activates the switch, or a square wave signal feeds both switch and electrodes.

If the phase shifts in the two paths from excitation to multiplier are unequal, the performance degrades until, when the difference in phase shift becomes 90°, the circuit is completely inoperable. Phase shifts can be matched by adding a passive delay line to the control input, usually the shorter path, or by adding a second matched electrode-amplifier with reference capacitors for very accurate tracking.

Pseudorandom carrier

A fix for proximity circuits which need maximum performance in the presence of interfering spectral noise components is to use a pseudorandom excitation voltage, a two-level signal which changes phase in a predictably random way, which is applied to the sense plates and also to the demodulator. The maximal length shift register connection [Rhee, 1989, pp. 265–268] generates a repeating sequence of $2^n - 1$ binary outputs. For example, a 10 bit maximal length shift register outputs $2^{10} - 1$ or 1023 random-appearing binary symbols before repeating. The number of 1s and 0s is almost equal (it differs by 1) and the longest length of a repeated 0 or 1 symbol is $n - 1$. This pseudorandom number (PRN) code can be used directly as a carrier with, say, a 50 kHz clock and a 50 kHz/1023 repetition frequency, and gives good rejection of in-band spectral noise components. With a band-limited amplifier, performance would suffer because of the spectrum-broadening effect of a long run of adjacent 1s or 0s, but a simple digital phase modulator can be added to the PRN output to guarantee a maximum run length of two symbols. The added circuitry for a pseudorandom carrier is minimal; a 10 bit PRN is built with a 10-stage shift register and a quad exclusive-OR gate.

6.4 CAPACITIVE LIMIT SWITCHES

An important type of proximity detector is the limit switch which senses a moving vane and activates a switch closure. For the general case of proximity detector the target cannot be altered, but a limit switch can be designed to use a grounded, dielectric, or floating target, as the target is built as part of the switch. The limit switch should be accurate, inexpensive, and reliable. An example is the optical gate, where a light-emitting diode is paired with a phototransistor to detect any opaque object moved through its 2.5 mm gap.

A capacitive limit switch has several advantages over the optical gate, including much lower power dissipation, lower cost, and more stable operation (Figure 6.7).

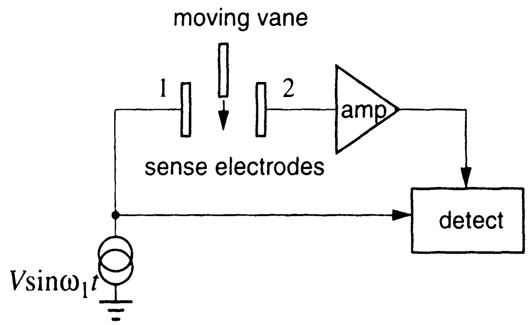

Figure 6.7 Limit switch block diagram

6.4.1 Vanes

The capacitive limit switch detects the difference in capacitive coupling between electrodes 1 and 2 caused by the movement of the vane. The vane may be grounded, and decrease capacitance; floating or dielectric, and increase capacitance; or it may be separately excited.

Grounded vane

To detect a grounded vane, the optimum electrode geometry maximizes coupling when the vane is not present (Figure 6.8).

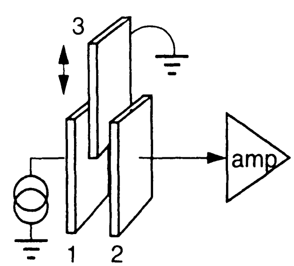

Figure 6.8 Grounded vane electrode geometry

With the grounded vane limit switch, the modulation depth can be very good, especially if the vane is larger than the electrodes; the minimum capacity can be 2–3% of the maximum capacity. The lateral position of the vane does not affect the measurement.

Floating vane

With a floating vane, detection is best done with electrodes which have minimum capacity before the vane is introduced (Figure 6.9).

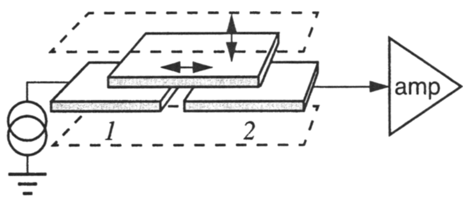

Figure 6.9 Floating vane electrode geometry

Floating vane modulation depth is not as good as grounded vane and, if detecting lateral movement, the vertical position of the vane considerably changes the capacity. Grounded shields installed at the position of the dotted lines will reduce stray capacity and increase modulation depth. These shields will minimize stray capacitance between electrodes 1 and 2, but not affect the coupled capacitance when the moving vane is in position. Motion in the vertical axis can also be detected.

Dielectric vane

The dielectric vane uses an electrode geometry similar to the grounded vane configuration, and the presence of the vane increases electrode capacitance proportional to the vane's dielectric constant and the percent of gap occupied.

Separately excited vane

If the vane can be connected to a high frequency AC source, the performance is improved considerably. In Figure 6.8, for example, this would be done by removing electrode 1 and attaching the exciting signal to electrode 3. Normally this is considered the last choice because of the inconvenience of the extra wire.

Summary of vane performance

A very approximate comparison of the performance of these different limit switch geometries is given in Table 6.4.

Table 6.4 Vane performance

Type	Modulation depth	Sensitivity to gap variation
Grounded vane	97%	low
Floating vane	60%	high
Excited vane	99%	low

6.4.2 Limit switch circuits

The challenge for limit switch circuit design is to reliably detect small changes of capacitance and be insensitive to board contamination and stray resistance or capacitance. For 1 cm square plates and a 2.5 mm gap the capacity is, from eq. 2.13, 0.35 pF, so the detector needs to resolve a change from an open gap at 0.35 pF to a grounded-vane capacitance of 0.05 pF or so. If the electrodes are connected with a 1 cm 0.015 in trace width on 1/16 in glass-epoxy with a ground plane on the opposite side, the PC trace will add a stray capacitance of 0.5 pF. The capacity of an IC pin adds about 4–10 pF to ground. A simple method is needed to detect a fraction of a pF in the presence of much larger strays; the guarding techniques used for the synchronous demodulator circuits would work well, but these circuits are more complex. One method is to use an AC reference.

AC reference

An AC reference, shown in Figure 6.10, is used rather than a DC threshold so that the detection threshold is at ground.

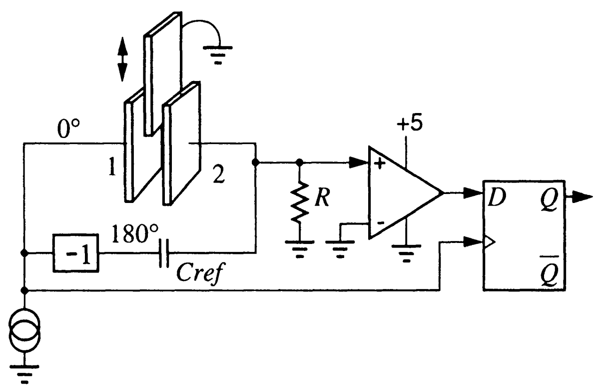

Figure 6.10 Limit switch, AC reference

The waveforms at the excitation terminals and the comparator input are as shown in Figure 6.11.

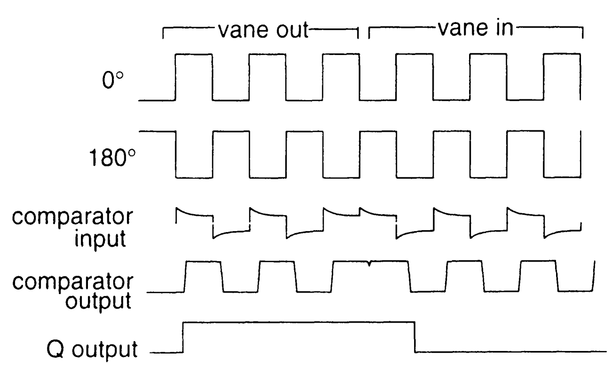

Figure 6.11 Limit switch, AC reference, waveforms

A 5 V 10–200 kHz logic signal can be used for the 0° clock, and a logic inverter generates the 180° clock. If the equivalent capacity between electrodes 1 and 2 varies from 0.05 to 0.35 pF as the vane is moved, *Cref*, the reference capacitor, is chosen to be halfway between the maximum and minimum value of the sense capacitor, or 0.2 pF. *R* is a large-value resistor, over 22 MΩ, and the comparator is a totem-pole-output CMOS type such as Texas Instruments' dual, the TLC3702. The TLC3702 works on a 5 V supply, the input common mode voltage range includes ground, and the input bias current is 5 pA at 25°C temperature.

It is important with a single-supply comparator or amplifier not to exceed the common mode input range with a signal that goes more negative than ground; the usual specification is to limit negative excursions to less than 0.2 V. This is done automatically if stray capacitance is large, as the peak signal is lower than 0.4 V, but if the peak signal is higher than this, a dual power supply or an input bias voltage is needed. Also, the comparator needs to have a minimum delay which is greater than the latch's hold time to avoid a race condition.

As the logic signals can be shared with many switches, the parts to build a switch are just one or two discretes, a comparator, and a latch.

The redeeming virtue of this circuit is that shunt resistance and shunt capacitance strays across the comparator input do not affect the threshold voltage, just the gain. As the comparator has high gain, there is no change in operation with a stray 10 pF or 10 MΩ shunt impedance. If the comparator has nonzero input voltage offset, this is not exactly true; the 3702's 5 mV maximum offset will have a small effect, on detection threshold; adding an AC amplifier fixes it. With 10 pF stray, the signal swing across the comparator input is determined by the capacitive divider to be 5 × 0.2 / 10.2 or about 100 mV, so 5 mV offset change will change the threshold by 5%.

Simpler AC reference

If a microcomputer is available, the circuit can be further simplified. The 0°/180° square wave signals can be replaced by a single interrogation pulse (Figure 6.12).

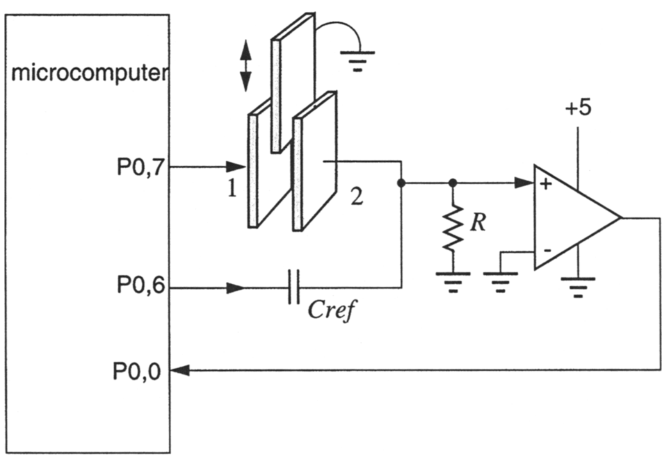

Figure 6.12 Limit switch, single pulse detector

With a microcomputer having an available general-purpose input-output port, this instruction sequence for an 8 bit microcomputer excites and reads the switch.

During power on initialization:

```
out     port0    40H
```

To read the switch:

```
out     port0    80H    ;switch both P0,7 and P0,6
nop                     ;delay by a time interval
nop                     ;longer than the comparator delay
in      port0,0         ;read the comparator; 1= vane out
out     port0    40H    ;reset excitation voltages
```

Noise rejection is handled by multiple reads and discarding a single reading in disagreement with its neighbors.

In Figure 6.13 port 0,7 outputs a positive-going edge at the same time as port 0,6 outputs a negative-going edge. If C_{12}, the coupling capacitance between electrodes 1 and 2, is greater than the reference capacitor, *Cref*, the comparator output will be a zero. *Cref* can be built as a printed circuit board capacitance so its characteristics track with C_{12}. Here, too, stray capacitance across the load resistor does not affect operation if the comparator input offset is small.

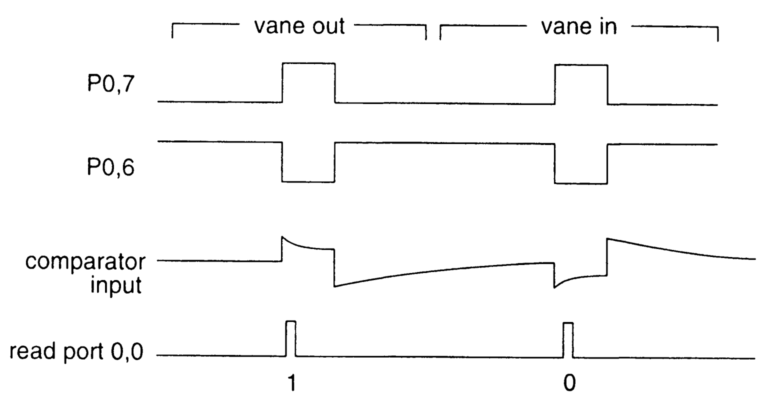

Figure 6.13 Limit switch, pulse reference, waveforms