9

Miscellaneous sensors

This chapter presents a sampling of capacitive sensor designs for a variety of miscellaneous transducers. Just about any measurement task can be handled by converting the variable to be measured into mechanical displacement of capacitor electrodes; Jones [1973] points out that an excellent thermometer could be built by capacitively sensing the change in size of a brass block with temperature.

9.1 PRESSURE SENSORS

Capacitive pressure transducers are generally built with spacing-change sensors, governed by the usual equation

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad 9.1$$

When the plates are parallel and displaced by Δd, the change in capacitance ΔC is

$$\frac{\Delta C}{\Delta d} = -\varepsilon_0 \varepsilon_r \frac{A}{d^2} \qquad 9.2$$

Hence as dimensions are scaled to submillimeter silicon size, the capacitance scales linearly, but the percent change in capacitance with displacement does not change. Capacitive pressure sensors are displacing piezoresistive pressure sensors because of lower power requirements, less temperature dependence, and lower drift.

9.1.1 Differential pressure transducer

A typical differential pressure transducer construction is shown in Figure 9.1.

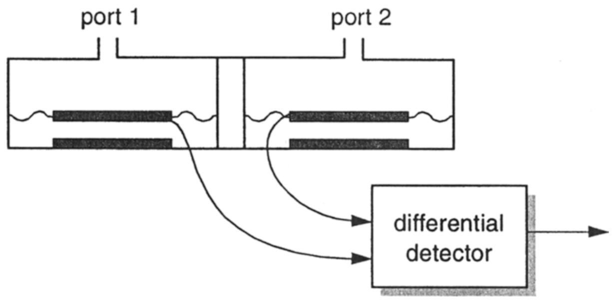

Figure 9.1 Differential pressure transducer

9.1.2 Absolute pressure sensors

A medical implant pressure sensor constructed with discrete components [Puers, 1993] has been developed by a pacemaker company for automatic defibrillation, and is optimized for small size, low power consumption, and high sensitivity (Figure 9.2).

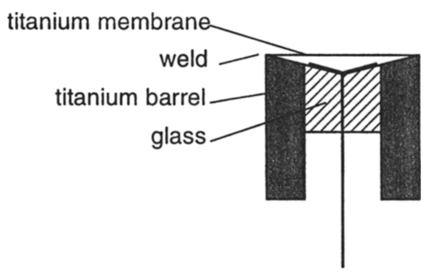

Figure 9.2 Pressure transducers

A titanium barrel is filled with a glass cylinder and sputtered with a gold layer to form the fixed electrode, and a thin titanium diaphragm is welded to the periphery to form the movable electrode. The total capacitance is 1.5 pF.

An alternate construction method [Puers, 1993, p. 96] is to use a flexible silicone rubber dielectric to support the moving plate. This technique has been applied to force transducers as well as pressure transducers, and has the advantage of a sensitivity improvement due to the dielectric constant increase which compensates for its lower compliance compared to air.

9.1.3 Silicon pressure sensors

Silicon based capacitive pressure sensors have these advantages over alternate construction methods:

- Silicon has excellent elastic properties and excellent stability
- Capacitance conversion is a stable and noise-free conversion method well-matched to IC fabrication processes and batch technology
- Capacitive sensors have been fabricated with a gap of 1 μm, for a very acceptable 8.85 pF/mm^2 electrode capacitance

A review of pressure sensors fabricated on silicon shown in Appendix 1 [Puers, 1993, pp. 97–104] covers 25 different devices from many different laboratories, with dimensions down to 0.4 × 0.5 mm and capacitances on the order of 0.3–25 pF. Accelerometers are also listed, with sizes down to 0.3 × 0.1 mm and capacitance down to 0.004 pF. The earlier devices listed use primarily oscillator circuits for demodulation, with a later trend to switched capacitor CMOS with one device using NMOS; synchronous demodulators are beginning to appear in later circuits.

Linearity

Performance of silicon pressure sensors without adding linearity compensation is good. A nonlinearity is caused by the nonparallel deflection of the moving plate, which may form a dome shape when displaced, as the gap is of micron dimensions for sensitivity the nonlinearity can be significant. Adding a guard ring (the Kelvin guard) to the smaller of the two electrodes and reducing its area to 36% of the diaphragm area decreases sensitivity but improves linearity to 1.5% [Artyomovet et al., 1991], with a pressure-induced capacitance change of 2.5×.

Another approach is to stiffen the center section of the moving diaphragm with a boss [Schnatz et al., 1992, p .79] (Figure 9.3).

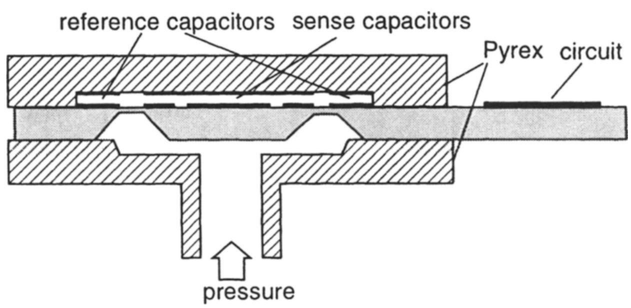

Figure 9.3 Bossed diaphragm

The demodulation circuit for the sensor above places the capacitor in the feedback path of the input op amp to linearize it, as discussed in Chapter 4, adds the central boss as shown to ensure that the plates are parallel, and includes a bandgap temperature compensation for temperature effects, primarily due to the different temperature coefficients of silicon and Pyrex glass. Two reference and two sense capacitors and a differential CMOS switched-capacitance amplifier were used for a very accurate 0.3% nonlinearity over an input pressure range of 0 –30 kPa and temperature dependence of 13% p-p over the range –60 to +140°C.

9.2 3 cm LINEAR TRANSDUCER

A linear transducer with multiple sine-cosine plates on 41 μm (0.0016 in) centers was designed to replace diffraction grating and laser interferometer measurement systems at lower cost [Kosel et al., 1981] for precision positioning uses like semiconductor step-and-repeat imaging. An air bearing support is used for zero friction. The electrode design is similar to the 6 in caliper (Chapter 15) except a factor of 60 smaller, with 0.5 μm etched aluminum electrode fingers on a 6.3 mm glass substrate and a protective overcoat of 1 μm photoresist. The transducer has these characteristics:

- Position uncertainty of 4 nm
- 3 cm effective linear range
- Operating frequency 870 kHz
- Plate separation 15–23 μm
- Transducer capacitance 10 pF

The position uncertainty is due to resistor thermal noise, and was improved by tuning the detector circuits to the operating frequency with a Q of 30.

Kosel presents an analysis of the coupling efficiency of the gaps, with computer simulations which show that the coupling of about 10% in air deteriorates to 3% with glass substrate, but improves to 16% with a dielectric (resist) layer over the electrode-glass layers. A formula is derived for the output voltage of the transducer as a function of electrode finger dimensions, gap size, and linear displacement. With this electrode geometry, showing only one of the two short gratings (Figure 9.4)

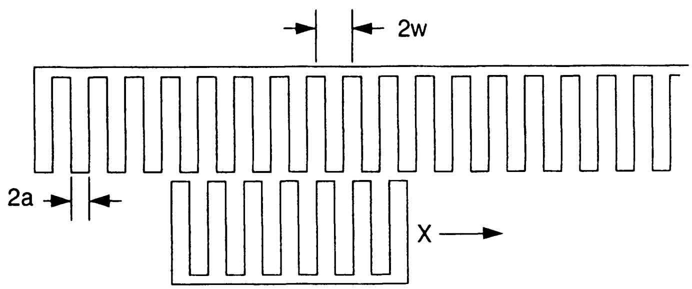

Figure 9.4 3 cm linear transducer [© 1981 Institute of Electrical and Electronics Engineers]

and approximating the finger dimensions with these values

$$w = 20\ \mu\text{m}$$
$$a = 10\ \mu\text{m}$$
$$d = 19\ \mu\text{m} = \text{gap width}$$

the formula for output voltage as a function of linear displacement is

$$V_j = \frac{\ln\left[\dfrac{\left(\cosh\left(\dfrac{\pi \cdot d_i}{2 \cdot w}\right)\right)^2 - \left(\sin\left(\dfrac{\pi \cdot X_j}{2 \cdot w}\right)\right)^2}{\left(\cosh\left(\dfrac{\pi \cdot d_i}{2 \cdot w}\right)\right)^2 - \cos\left(\dfrac{\pi \cdot X_j}{2 \cdot w}\right)}\right]}{\ln\left[4 \cdot \left(\dfrac{w}{\pi \cdot a}\right)^2 \cdot \left(\sinh\left(\dfrac{\pi \cdot d_i}{w}\right)\right)^2 + \left(\sin\left(\dfrac{\pi \cdot X_j}{w}\right)\right)^2\right]}$$

And a numerical evaluation for output voltage vs. linear displacement X, for two different gaps of 10 and 20 μm, is shown in Figure 9.5.

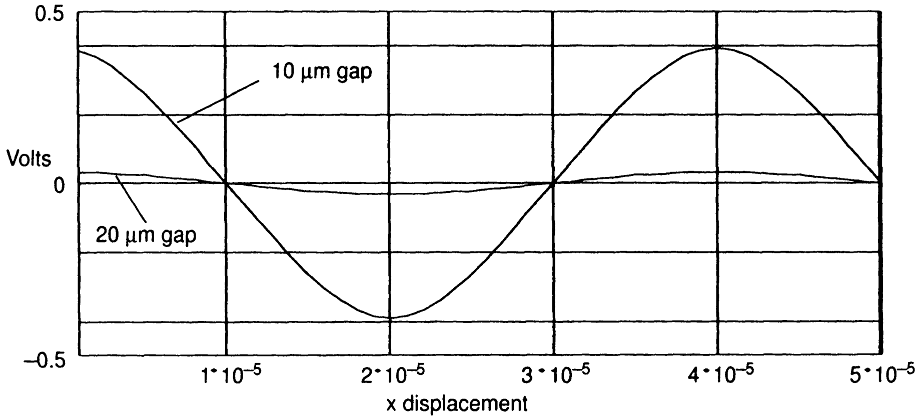

Figure 9.5 3 cm linear transducer output vs. displacement
[© 1981 Institute of Electrical and Electronics Engineers]

The extreme sensitivity of this system to gap width is shown in Figure 9.6.

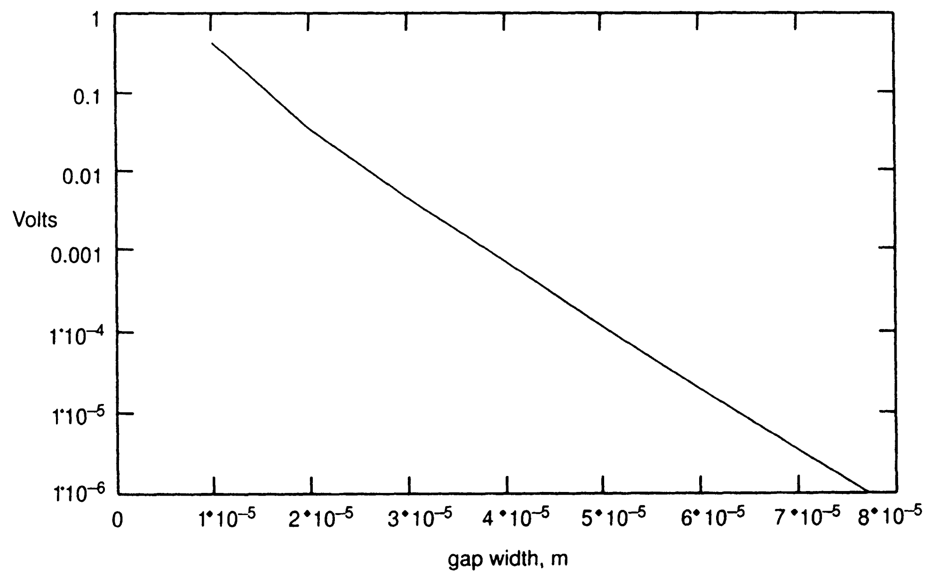

Figure 9.6 3 cm linear transducer output vs. gap width

This graph shows the typical rapid falloff of signal with spacing and the need to keep gap size smaller than electrode size for good performance. The design challenge for this transducer is to keep the gap very well controlled so that the output voltage is not modulated, or include a reference level so that the amplitude modulation due to gap change can be compensated. Increasing electrode size for higher depth of modulation would ease the gap tolerance requirement, and the reduction in sensitivity due to the increased pitch should be compensated by the increased modulation depth.

9.3 LINEAR MULTIPLATE MOTION SENSOR

A prototype sensor was built by Zhu, Spronck, and Heerens [Zhu et al., 1991] with the following specifications:

Coarse plate pitch .... 2 mm
Fine plate spacing .... 250 μm
Substrate construction.......... PC board on steel backing
Electrode capacitance .... 0.75 pF
Resolution .... 1 μm
Stability..................... <1 μm
Measurement speed............ 500 mm/s
Linearity .... 50 μm

The sensor was designed to be capable of a measurement range of a few meters, to be insensitive to misalignment, dirt, and electromagnetic disturbances, and to be manufacturable at low cost.

A novel technique is used for measuring position. The fine grid electrode configuration with 250 μm pitch opposes a coarse grid of plates with 2 mm pitch with a small air gap of 250 μm (Figure 9.7).

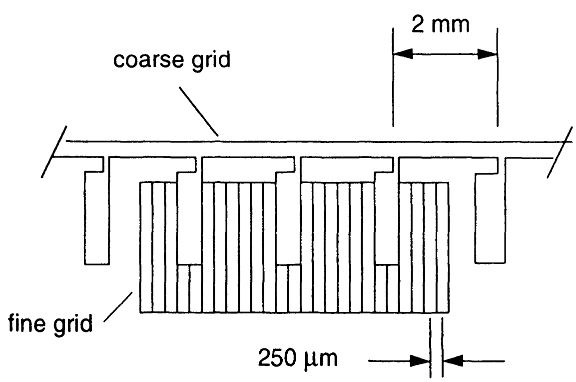

Figure 9.7 Linear multiplate sensor electrodes [Reprinted from *Sensors and Actuators*, A25–27, Zhu et al., "A Simple Capacitance Displacement Sensor," p. 266, 1991, with kind permission from Elsevier Science S.A., Lausanne, Switzerland]

The fine plates are connected together in groups of 8, plate 1 is connected to plates 9 and 17, etc., plate 2 is connected to plates 10 and 18, etc., so that their signals will average out small irregularities and will sum together for more signal amplitude. The fine plates are scanned with a clock at an adequately high frequency for the anticipated fastest translation speed. A block diagram of the electronics shows the scanning method (Figure 9.8).

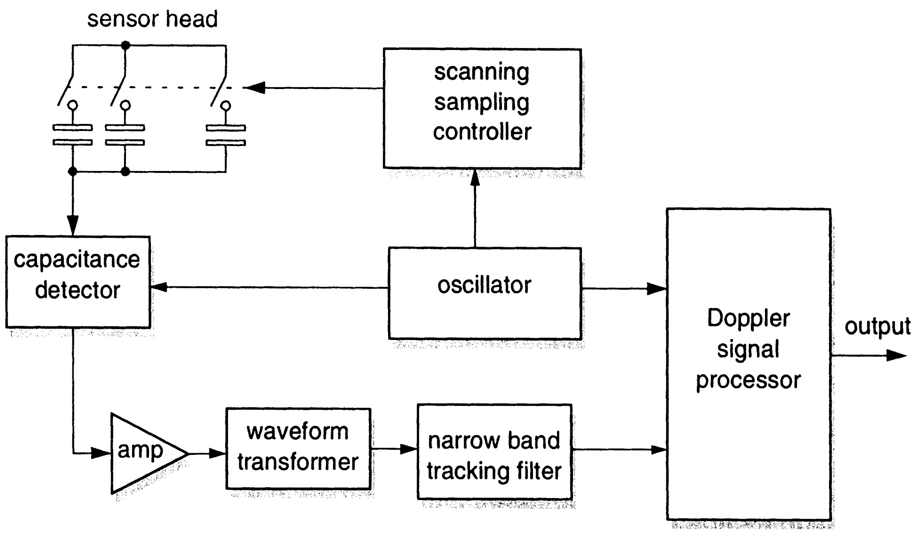

Figure 9.8 Linear multiplate sensor block diagram [Reprinted from *Sensors and Actuators*, A25–27, Zhu et al., "A Simple Capacitance Displacement Sensor," p. 268, 1991, with kind permission from Elsevier Science S.A., Lausanne, Switzerland]

As the electrode air gap is about the same as the pitch of the fine plates, the fine plates will exhibit a capacitance which is a defocused image of the coarse plates (Figure 9.9).

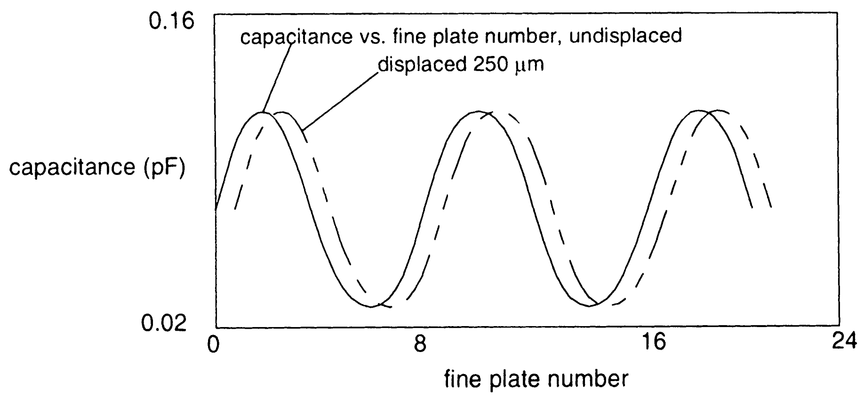

Figure 9.9 Capacitance of fine plates [Reprinted from *Sensors and Actuators*, A25–27, Zhu et al., "A Simple Capacitance Displacement Sensor," p. 268, 1991, with kind permission from Elsevier Science S.A., Lausanne, Switzerland]

The output of the fine plate scanner is an AC signal which varies in phase as shown above, directly as the relative position of the two sets of plates, so that a displacement of 250 μm causes the capacitance-vs.-electrode-number curve to move by one electrode. The scanner continuously scans through the 24 fine electrodes, so the scanner output is an AC signal which can be compared in phase to the oscillator output to determine mechanical displacement. The small capacitance changes, a fraction of a pF, mean that the usual guarding precautions need to be exercised, and the preamp needs to be very close to the electrodes.

The frequency shift of the AC signal is proportional to the velocity of the motion, similar to Doppler frequency shift. A variety of techniques are available to convert a frequency shift into position by measuring phase; the graphic tablet of Chapter 19 shows an example.

This sensor illustrates a novel method of position detection. It is a hybrid of two techniques which have been described, the tracking method and the sine-cosine method, and should offer similar performance, with the additional complexity of the sampling circuits compensated by less-critical analog circuits.

9.4 MOTOR COMMUTATOR

DC brushless motors are increasingly used to replace AC motors, steppers, and brush-type motors, as they have superior efficiency, long life, smooth torque delivery, and high speed operation. DC brushless motors reverse the construction of a DC brush motor, with wire coils outside and a permanent magnet rotor inside. The inherent cost of the motor is lower than brush motor cost, but as brushless motors are not built in large quantity as a standard part, the actual cost will be higher for quantities of under 100K/yr. Total system cost may be higher due to the more complex drive electronics needed.

DC brushless motors have performance similar to brush motors, with a slightly higher efficiency as the brush voltage drop is not a factor. Also, the small brush friction component of brush motors is eliminated. Brushless motors use a variety of commutators to do the function of the segmented commutator of the brush motor; this section is a proposal for the use of capacitive transducers for brushless motor commutation. Most of the circuits and systems shown in this book have been built in production or at least prototype form, but this idea has not been tested.

9.4.1 Commutation

Where commutation of DC brush motors is handled by the brushes, commutation for brushless motors is done by external electronic switches controlled by rotor position. Two or more poles can be used, with more complexity but higher torque for the higher pole count. The normal setup uses a three-phase winding and a two- or four-pole magnet, with three Hall effect devices which sense rotor position magnetically and actuate the proper coil winding switches.

9.4.2 Ripple torque

The motor designer can choose between designing the magnetic structure for a linear torque vs. position relationship which may have a large switching transient, or a sinusoidal torque vs. angle with more ripple but less commutation difficulty. For linear torque designs, the torque transient at commutation may be greater, as the normal Hall effect device is inaccurate enough to produce considerable error in commutation angle. This presents no problems at high speed, as inertia keeps speed reasonably constant, but in low speed servos this effect can cause jitter.

Transient torque and ripple are reduced with sinusoidal torque-vs.-angle motors and "soft" commutation which uses linear amplifiers instead of switches, with a more accurate rotor position sensor replacing the Hall effect devices. The best performance uses an absolute position encoder and linear amplifiers, and determines the best commutation angle by powering the windings with DC and measuring the rotor angle.

Capacitive sensors are preferable for high performance applications to Hall effect sensors, as they are considerably more accurate and less expensive, and can be easily integrated onto the PC board normally used to support the winding.

Brushless motors, as with brush motors, can be built either in disk or cylindrical geometry. Disk construction is used for head drives in VCRs and platter drives in computer hard disk drives. These motors are usually built on a printed circuit board substrate, and use Hall effect, back EMF sensing, or magnetic coupling to sense motor speed for commutation. The Hall effect commutators are not particularly accurate, and would not provide smooth, accurate, linear commutation signals for smooth motion, and other magnetic commutators do not work at slow speed.

Brushless motors with disk construction and a capacitive rotor position commutator (Figure 9.10) can be used at slow speed; they will have accurate, linear commutation and this technology can be used for a high performance assemble-it-yourself motor. This configuration is quiet and smooth, and ripple torque is easily compensated with a table lookup in microcomputer systems.

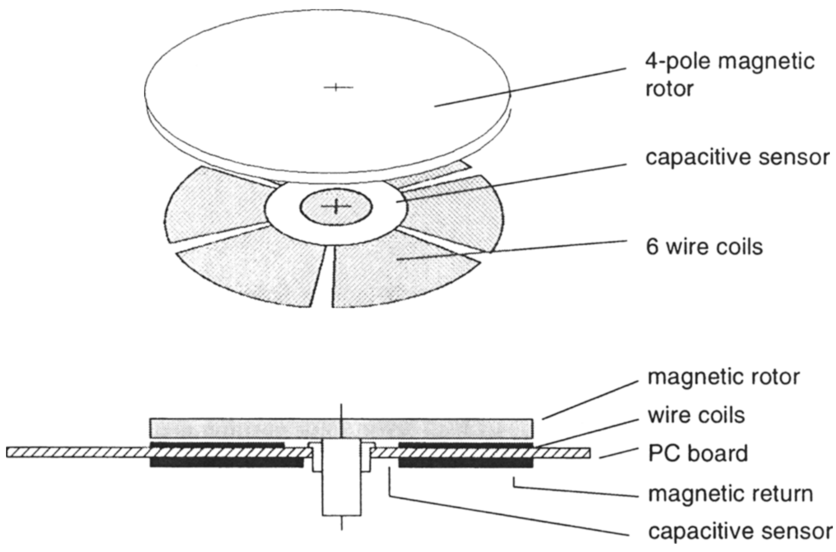

Figure 9.10 Brushless motor with capacitive position sense

The capacitive position sensor does double duty for both motor commutation and shaft position measurement. It uses a conducting pattern on the rotor which may be a metalized paper or plastic label. A typical electrode pattern which can be used directly for linear commutation is shown in Figure 9.11.

This pattern can be 2 cm or less in diameter. Three shaded rectangular pickup plates are shown, each of which can feed a high impedance amplifier and a linear motor drive amplifier. The rotor plate can be connected to capacitively coupled rings to handle drive voltages without need for wire connection. This pattern will generate three-phase sine waves for a brushless motor drive (Figure 9.12). Rounded trapezoidal shapes would be used if the motor magnetic structure were more linear.

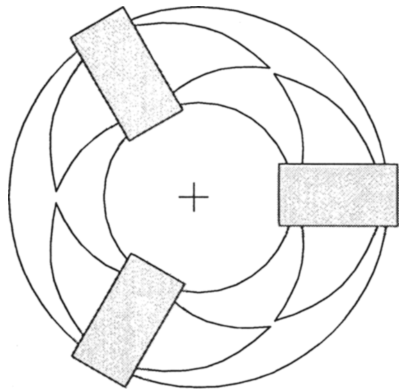

Figure 9.11 Brushless motor position sensor

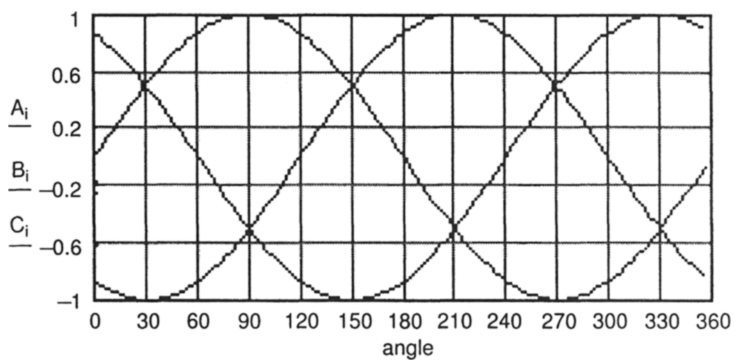

Figure 9.12 Brushless motor drive waveform

These outputs can also be converted to an angle for shaft position measurement as shown in Figure 21.2. One efficiency-increasing possibility is to generate a PWM signal from the sensor clock which is applied to the motor coils instead of a linear voltage.

9.5 WATER/OIL MIXTURE PROBE

Accurate measurement of the percentage of water in oil is extremely important for operators of off-shore oil drilling rigs and for refineries. Capacitive probes have been used for this purpose since 1982, but early units were unstable and temperature dependent. The principle behind these probes is to measure the dielectric constant of oil and of water separately at the operating temperature of the sensor and then to measure the dielectric constant of the mixture. A change in the relative volume of the two components produces a linear change in the measured dielectric constant.

9.5.1 Simple probe

A simple water/oil probe that does not work well is shown in Figure 9.13. This probe will have several problems.

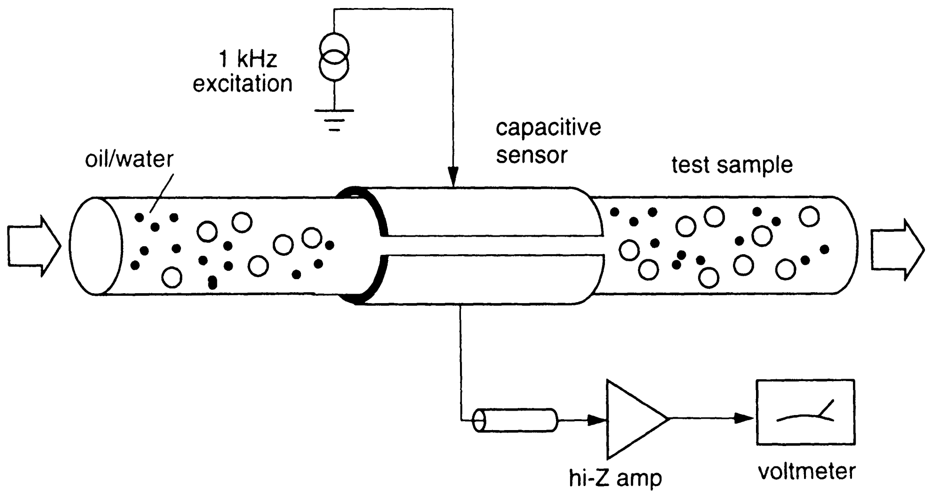

Figure 9.13 Simple oil/water probe

Parasitic capacitance

The probe capacitance will be on the order of 1–10 pF. This will be swamped by capacitance from the back side of the pickup plate and coax capacitance at 50 pF/m. As coax capacitance will have a respectable temperature coefficient, this probe's accuracy may be limited to 30% or so with temperature variation.

Temperature dependence of dielectric constant

The dielectric constant and loss tangent of water is shown in Figure 10.4, and the temperature dependence of these parameters is shown in Figure 10.5. Extrapolating these figures shows that water will be represented as a temperature-dependent resistor at the excitation frequency of 1 kHz, with a high temperature coefficient. This effect, also, will severely limit the performance of the simple probe.

9.5.2 Improved probe

Van der Linden [1988] describes an improved version of an oil-water probe which can measure concentrations of water from 100–1000 ppm with a resolution of 10 ppm (Figure 9.14). The exact capacitance can be calculated as described by Heerens et al. [1986].

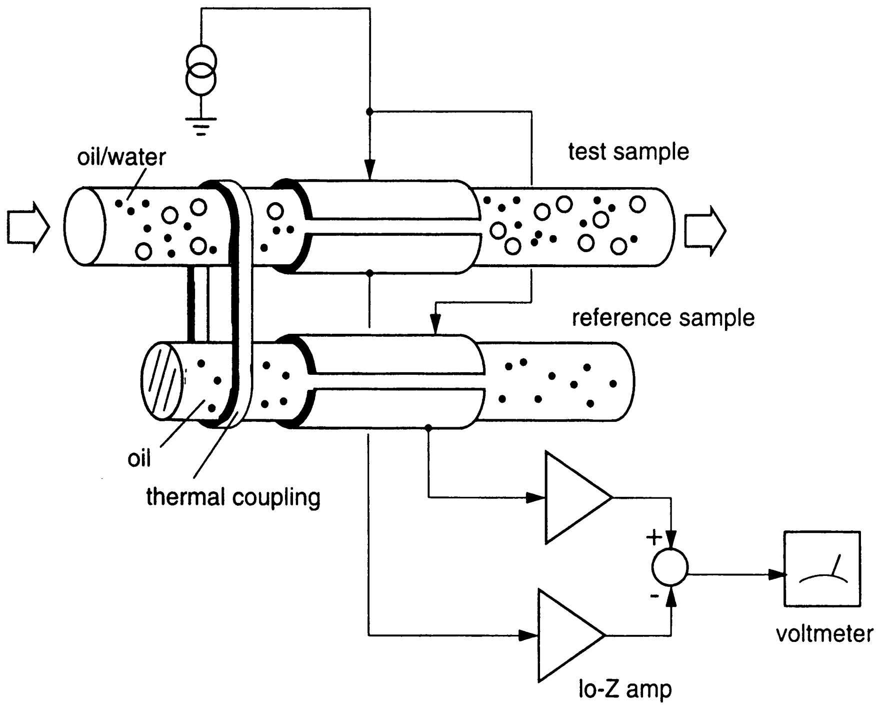

Figure 9.14 Improved oil-water probe

Parasitic capacitance

The guarding principles discussed in Chapters 2 and 3 are used to eliminate the effects of parasitic capacitance. If a low-Z amplifier is used, the coax shield can be grounded without adding coaxial cable capacitance to the measurement and the back side of the pickup electrode can be shielded with ground, so only the cell capacitance will contribute to the signal. The ground shield should be spaced as much as possible, as pickup electrode coupling to this ground decreases signal to noise ratio as seen in Chapter 12.

Temperature dependence

The temperature dependence can be reduced considerably with this two-probe circuit, one measuring the liquid under test and the other measuring a reference liquid. In this case, where small concentrations of water are expected, the reference liquid is 100% oil. Couple the test and reference probes closely for thermal matching (Figure 9.15).

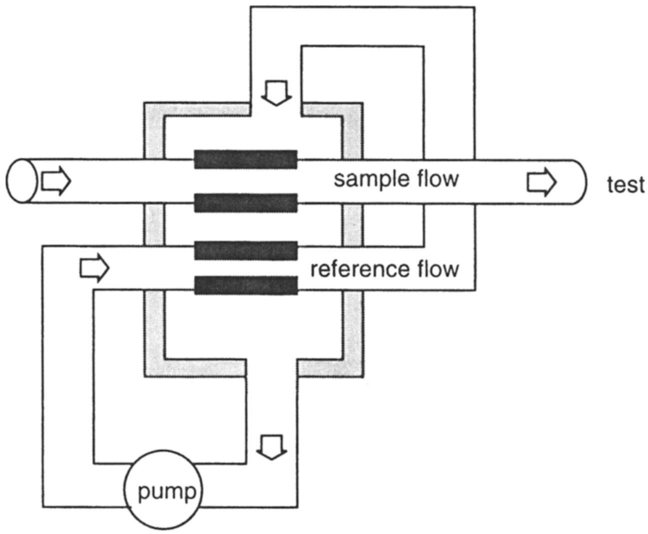

Figure 9.15 Thermal coupling of test and reference cells

9.6 TOUCH SWITCH

A very simple (one resistor) but reliable switch can be built for finger activation if a microcomputer with a comparator input is available (Figure 9.16). Plate *b* can be a 2 cm square copper pattern on the top of a printed circuit board. Plates *a* and *c* are on the bottom side, and with 0.062" glass-epoxy printed circuit board, will couple with about 6 pF to the top plate. A 5 V pulse on plate *a* is coupled through plate *b* to sensor *c*, and can be detected by a microcomputer such as the 80C552, a version of the 8051 made by Philips, with a comparator input. The received signal will be about a volt; when the top plate is touched by a finger, the coupling drops and the received signal drops to 0.1 V or so. A plastic actuator can replace the human finger for keyswitch applications; the actuator can be nonconducting and increase coupling by its dielectric constant, or decrease coupling if it is conductive.

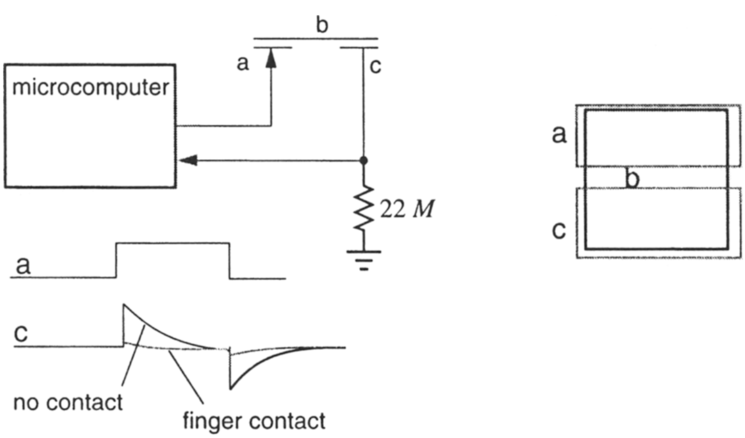

Figure 9.16 Finger-touch switch

9.7 KEYPAD

The techniques of two-plate proximity sensing can be extended to a multiplexed keypad. As the different keys can have different capacitances due to interconnection capacitance variation, the received signal comparator threshold is adapted to the key capacitance using a calibration sweep through the keys during power-up when no key is touched.

Kronos, Inc., of Waltham, MA, used a keypad of this type in a wall-mounted computerized time clock. The keypad was used only by the operator, so it was normally blacked out. The blackout construction used a transparent keypad with a transparent conductor, tin oxide, on 1/8 in thick polycarbonate plastic. Keys and sense electrodes were deposited in this pattern (Figure 9.17). A section view shows the construction (Figure 9.18).

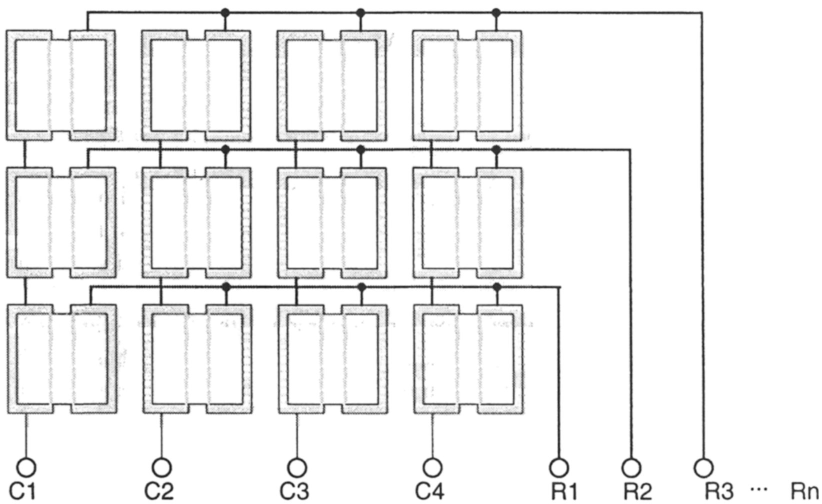

Figure 9.17 Keypad plate pattern

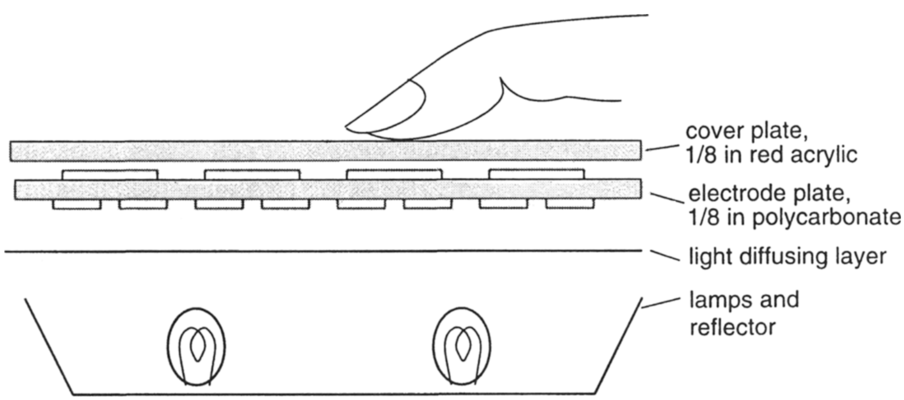

Figure 9.18 Keyboard construction

The column electrodes $C1$–$C4$ and the row electrodes $R1$–Rn are multiplexed using CMOS switches, type CD4051 (Figure 9.19).

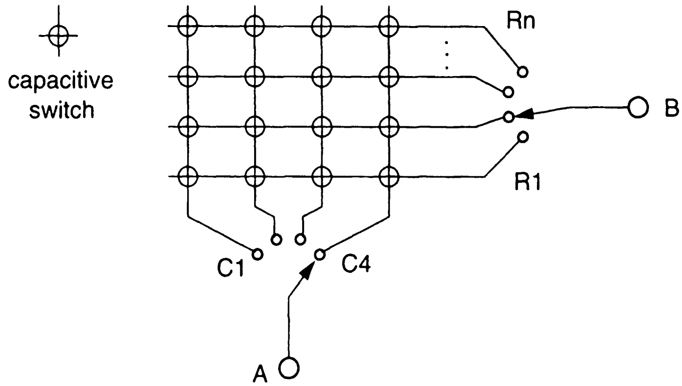

Figure 9.19 Keyboard multiplex

The control microcomputer sequences through each switch, measures its capacity using a technique similar to the single-switch circuit above, and compares it to the threshold value stored for that switch. As the stray capacity for this construction can be greater than the measured capacity, a reasonably accurate digital representation may be needed, perhaps 4 or 5 bits, to discriminate between the considerable variation of stray capacitance between the different switches. Alternately, the signal electrodes can be individually adjusted to add intentional stray capacitance which compensates for the variation. This adjustment will not be needed if signal capacity change is much larger than circuit and stray wiring capacity or guards are used to null out stray wiring capacitance and avoid the adjustment.

9.7.1 CMOS and ESD

Electrostatic discharge (ESD) must be correctly handled for keypads. The human body can be modeled as a capacitor to ground of 350 pF in series with a 1 kΩ resistor (rather a trivial representation of the complex human condition), and in dry climates up to 25 kV of charge on this equivalent capacitor can be discharged through the keypad. This may produce a circuit transient which is interpreted as a logic pulse or in extreme cases the discharge can destroy integrated circuits.

CMOS devices, like the older metal-gate CD4000 series or the newer silicon-gate HC4000 parts, are protected against ESD with this internal circuit (Figure 9.20).

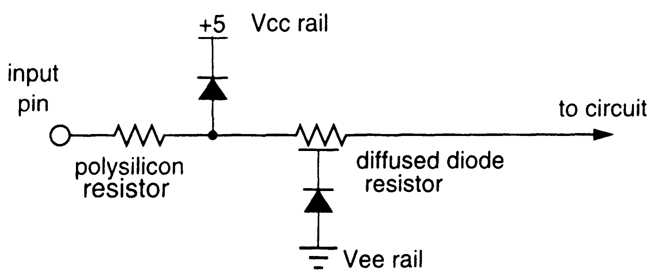

Figure 9.20 ESD protection circuit

The JEDEC-registered maximum voltage rating for CMOS input circuits is $-0.5 < Vin < Vcc + 0.5$, but some manufacturer's specifications are more forgiving, allowing the input voltage to swing as much as 1.5 V over the power rails. The diodes are rated at 20 mA, so ESD using the human body model must be limited to 20 mA continuous. For the short transients of ESD events, CMOS inputs can normally withstand 2.5 kV, still much less than could be expected from an actual discharge. Also, the channels of multiplexers (the analog switch terminals) are more sensitive than normal logic inputs. If the DC voltage on a multiplexer channel is more than a few tens of mV outside the power rails, internal parasitic bipolar transistor structures are turned on, excess power supply current is taken, and other multiplexer channels that are normally off in the same device begin to turn on.

Keyboards can have a protective conducting plate which absorbs an ESD discharge and conducts it to chassis ground, or a suitably thick plastic plate as in the design above prevents the discharge from occurring, as the dielectric strength of most plastics is in the 10–20 kV/mm range. Often, high current diodes such as the 1N4001 are used to shunt ESD discharges to the power rails in order to protect CMOS inputs from damage, but these diodes will not prevent a logic transient. Capacitive keypads have an advantage over other types, as a keypress can be sensed through a thick plastic material which prevents breakdown from occurring, even with a 40 kV charge. Because of the probability of an ESD discharge of producing a logic transient, software which handles capacitive sensor inputs should discriminate against short, less than 100 μs, logic glitches.

9.7.2 Keypad software

A keypad such as the above has some characteristics which may be handled in software.

Ghost keys

In any multiplexed keypad such as Figure 9.19 without sneak path protection, the key contact can conduct in either the normal direction or, when three or more keys are pressed simultaneously in a particular pattern, the contact conducts in the reverse direction, producing unexpected results. If three keys are simultaneously pressed with the keys forming three of the four vertices of a rectangle, the key at the fourth vertex may be read as being pressed also. This "ghost key" can be handled with mechanical keypads by use of a diode on each key to prevent reverse current flow, but on a capacitive keypad this is not an option. One option on a capacitive keypad is to take advantage of the lower capacity through three keys in series.

Ghost key prevention can be handled by software, however. The software must keep track of keypress history, and if three keys such as $R1$-$C1$, $R2$-$C1$, and $R1$-$C2$ are pressed and held, in that order, the software will also receive the ghost key $R2$-$C2$ and be unable to determine whether the third key pressed was $R1$-$C2$ or $R2$-$C2$. To resolve the ambiguity the software must detect that the number of keys pressed has increased from 2 to 4 and look for a rectangular pattern. If such a pattern is detected, the third keypress is not resolved until the first key is released; then the third keypress is known and is transmitted.

ESD transients

The short transient produced by an ESD event is handled in software by resampling each input after a millisecond or two to reject transients. Interrupt-driven software can handle ESD problems as well as switch bounce.

9.8 TOUCHPAD

The mouse serves personal computers well as an input pointing device, but it has not been as popular for portable computers, where a number of solutions have been tried. Recently, small capacitive touch pads integrated into laptop computers are becoming popular. Several manufacturers make these products, including Philips, Symbios/Scriptel, Synaptics, and Alps.

Synaptics' touch pad is smaller than a business card, with a smooth mylar surface. It handles cursor control by finger position, and also substitutes for mechanical mouse switches by interpreting a finger tap as a switch closure. The standard size is 50 × 66 mm, with smaller sizes available, and thickness is less than 5 mm. The resolution is better than 500 dots/in, so that fine cursor control is achieved by rocking the finger slightly. As the device is sensitive to the total finger capacity which will vary with pressure, a degree of z-axis pressure response is available, which could be used to modulate line width in a paint program or control scroll speed in a word processor.

Electrostatic discharge performance is good, with soft failures occurring at 15 kV and hard failures at 20–25 kV.

9.8.1 Sensing Technique

The sensing technique, an analog version of the keypad above, uses an x-y grid of wires etched on the upper two layers of a four-layer printed circuit board (Figure 9.20a).

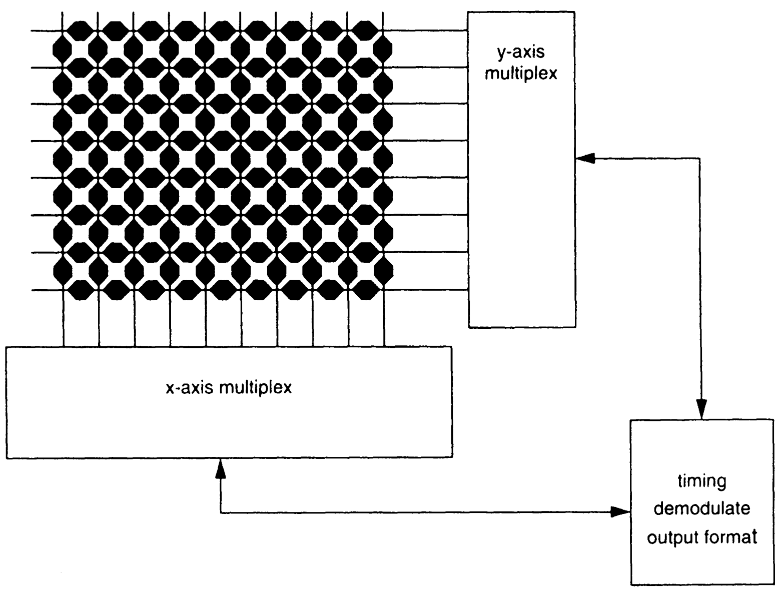

Figure 9.20a Example of the sensing technique

Capacitive coupling is improved by widening the traces, and finger capacitance is sensed as a decrease in coupling between adjacent electrodes caused by the shielding effect of the relatively high capacitance of the human body.

The electronics are surface-mount components on the bottom side of the board, including a mixed-signal ASIC and one or more digital chips if needed for special interface requirements. A combination of digital sensing and analog interpolation between wires is used to accurately determine finger location. The connections from the ASIC to the electrodes are designed to have equal capacitance despite unequal trace length.

Both the electronic and mechanical complexity of the touchpad are less than trackballs, and with no moving parts service life is much higher.

9.8.2 Accurate two-dimensional sensor

A more accurate two-dimensional transducer can be built with similar techniques if the finger is replaced with a close-spaced plane pickup electrode. Bonse et al. [1994] describe an 85 × 60 mm unit using a 14 × 10 array of 6 mm^2 square electrodes on the stator and a moving 3 × 3 electrode pickup. This device, fabricated with printed circuit board technology, demonstrated a 100 nm resolution and 200 nm repeatability. Sine wave excitation and a synchronous demodulator were used, and the major contribution to inaccuracy was determined to be the stability and tolerance of the printed circuit board.

9.9 SPACING MEASUREMENT

The CMOS 555-type timer and the *RC* circuit form an oscillator which changes frequency as $1/RC$. As the capacitance C is proportional to 1/spacing, the output frequency is directly proportional to plate spacing and may be easily measured by counting pulses for some fixed interval of time (Figure 9.21).

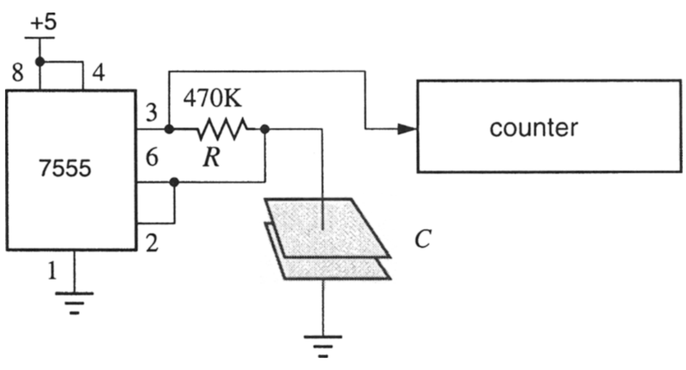

Figure 9.21 Spacing measurement system

If the plates are large and opened, a proximity detector is implemented which detects either dielectric or conductive material in the vicinity of the plates.

This circuit is not too accurate or sensitive, as the input capacitance of the 7555's pins 2 and 7 is about 15 pF and changes slightly with *Vcc*. For better performance, add a driven guard as described in Figure 4.3.

9.10 LIQUID LEVEL SENSE

Liquid level sensing is easily handled by capacitive sensors. Conductive sense electrodes are applied to the sides of the tank, inside the tank if it is conductive or outside if it is a nonconductor, and the capacitance between electrodes is measured. As the liquid level is measured by its volume characteristics rather than its surface properties, the liquid level can be measured reasonably well in the presence of sloshing which would confuse a standard float sensor, and if the electrodes are large (the complete top and bottom, say) a good zero-g or high-slosh liquid volume sensor is implemented.

The Levelite Store, Port Huron, MI (800)975-3835, specializes in level measurement, offering hundreds of different sensor types using every available technology. Levelite says this about capacitive level sensors:

- Unquestionably [the capacitive level sensor] is the Levelite Store Catalog's most versatile switch, used by industries all over the world involved with chemicals, foods, and wastewaters
- Ideal for dirty liquids and slurries as well as difficult dry solid applications
- Will detect interface between oil and water
- Sensor-Guard™ probe helps ignore buildup on the sensor
- Operates independently of specific gravity, conductivity, or viscosity
- A dielectric constant of 2.0 or more is recommended

The capacitance between electrodes can be measured directly, or more generally, an excitation voltage is applied with a drive electrode D and detected with a sense electrode S (Figure 9.22).

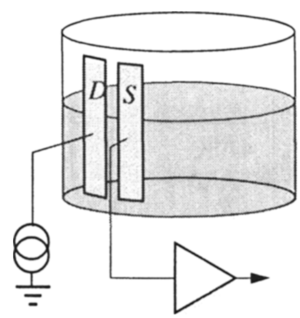

Figure 9.22 Liquid level sense

If the tank is conductive, the electrodes are applied to the inside or a small-diameter nonconductive manometer tube is used outside the tank. Alternatively, a single electrode can be used and its capacity to ground measured, or a probe immersed in the fluid.

9.10.1 Dielectric liquids

The total electrode capacitance for dielectric liquids is the sum of the electrode capacitance in air plus the variable capacitance. The variable capacitance varies as the percent of the electrodes immersed in the liquid times the dielectric constant of the liquid and increases with liquid level. The circuit measures the ratio of the capacitance between the plates and the amplifier capacitance to ground as shown in the equivalent circuit (Figure 9.23) with *Rgnd* infinite. The sense plate should be guarded on the back side as shown previously to minimize the effects of stray capacitance and pickup of unwanted signals.

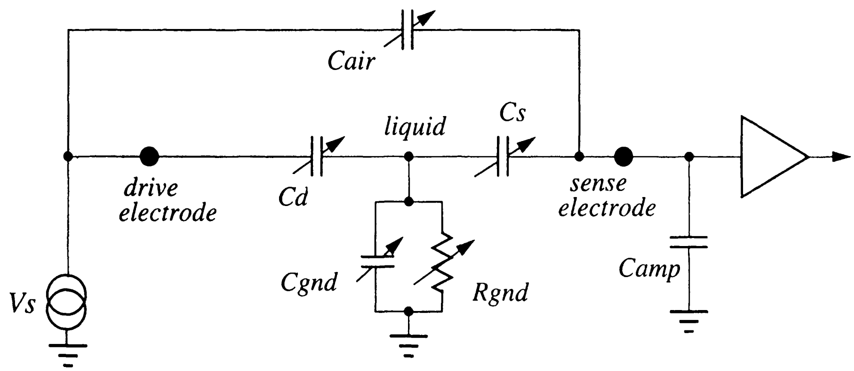

Figure 9.23 Liquid level equivalent circuit

9.10.2 Conductive liquids

For conductive liquids, the electrodes must be insulated or applied outside an insulating tank, and the capacitance may increase or decrease with liquid level. Two different effects are seen with conductive liquid sensors, or when sensing any conductive object. This is explained by considering the object's capacity to ground and drawing an equivalent circuit.

- *Cair* is the total capacitance through air paths with no liquid. It can be minimized by spacing the electrodes well apart, and by shielding air paths with a ground electrode.
- *Cd* is the variable capacitance between drive electrode and liquid; *Cs* is the variable capacitance between the liquid and the sense electrode. These are the capacitances to be measured.
- *Cgnd, Rgnd* is the impedance coupling the liquid to ground. *Rgnd* represents the resistivity of the liquid and often can be ignored.
- *Camp* is the amplifier input capacitance.

Several other variables such as dielectric leakage have been ignored.

The capacitive component *Cgnd* can be fairly large. The capacitance of an isolated sphere with diameter *d* in air

$$C = 2\pi\varepsilon d = 55.6 \cdot 10^{-12} d \qquad \text{f, m}$$

is 55.6 pF for a 1 m diameter. Measuring *Cd* with the shunting effect of *Cgnd* is difficult. Guarding the entire tank to eliminate *Cgnd* would work, but is impractical. One easy approach is to use small electrodes and consider *Cgnd* large with respect to *Cd* and *Cs*. For this case, the circuit above does not work, as *Cgnd* would totally shunt the signal, so the level must be measured by measuring the capacitance of the drive electrode to ground as in

Figure 9.21. This can provide a solution for systems where approximate results are acceptable, or where a computer can be used to calculate an error table automatically.

With intermediate ratios of *Cd, Cs,* and *Cgnd*, the increase of *Cgnd* with liquid level may cause a decrease in coupling which exactly tracks the increase due to dielectric constant, thereby producing an unusable zero output at any liquid level.

9.10.3 Low-Z amplifier

A circuit rearrangement removes the effect of *Cgnd* and provides a more linear output (Figure 9.24).

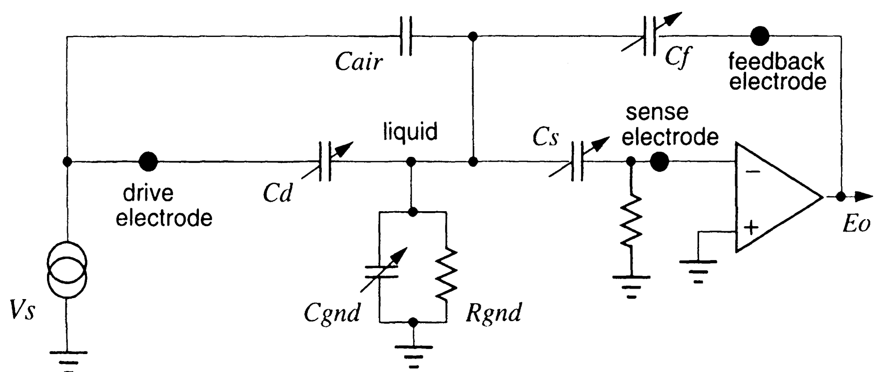

Figure 9.24 Liquid level with virtual ground amplifier

Here, a third feedback electrode is added. The voltage on the liquid is sensed through *Cs* and feeds the inverting input of the operational amplifier, so the liquid is at virtual ground and the effects of *Cgnd* and *Rgnd* can be ignored. Also, the variation of *Cs* and any stray capacitance at the amplifier input can be ignored. This produces a simpler equivalent circuit (Figure 9.25).

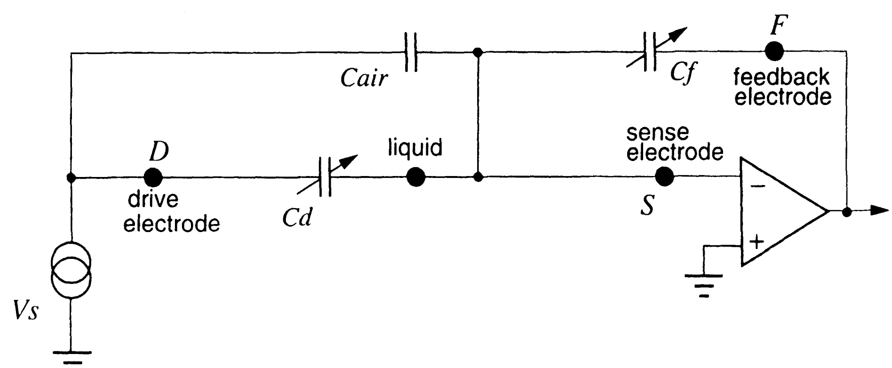

Figure 9.25 Liquid level with virtual ground, simplified circuit

With rectangular electrodes as above, the ratio of *Cf* to *Cd* is constant and the circuit output voltage does not change with liquid level. Changing the electrodes to triangle-shaped electrodes fixes this (Figure 9.26).

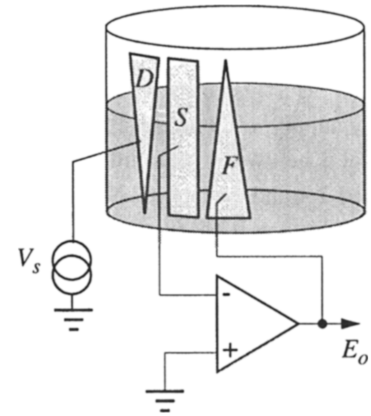

Figure 9.26 Electrodes for virtual ground liquid level sensing

The output voltage is then

$$E_o = V_S \frac{C_{DS}}{C_{FS}}$$

and will increase from near zero to *Vs* as liquid level increases.

9.11 LIQUID LEVEL SWITCH

A simple but accurate circuit generates an alarm signal when liquid level falls below a pre-set level (Figure 9.27).

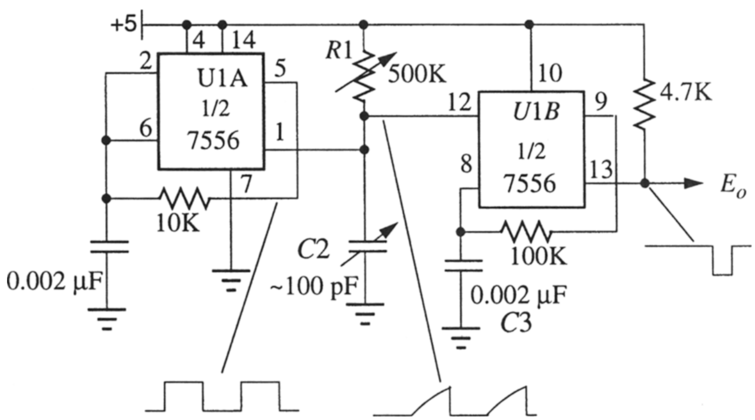

Figure 9.27 Liquid level switch

U1A is a square-wave oscillator at approximately 36 kHz, using the dual CMOS version of the popular 555 timer. *C2* is the capacitor to be measured, and can be the electrodes of Figure 9.22 except with the excited electrode grounded. During the 555's negative output

$C2$ is discharged; during the positive output $C2$ is allowed to charge towards +5 with a time constant of about 15 μs, adjusted by $C2$ and the potentiometer. When the liquid level falls below its set point, as adjusted by $R1$, the peak voltage at $C2$ rises until $U1B$ is triggered at 2/3 of the 5 V supply. $U1B$ produces a train of interrupt pulses at about 3.6 kHz as long as the liquid level is below the set point.

The timer can be a standard bipolar NE/SE556 or a CMOS ICM7556. The CMOS device will be more accurate as it has less input current and a more stable output voltage if impedances are kept high.

This circuit can also be used to build a single-plate proximity switch.

9.12 SIX-AXIS TRANSDUCER

A simple capacitive transducer is capable of measuring three axes of translation and three axes of rotation. The plate pattern is etched on two parallel printed circuit boards (Figure 9.28).

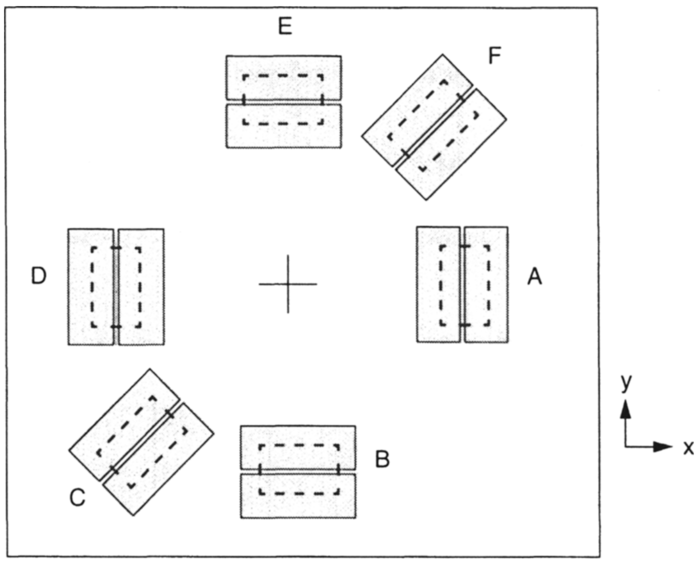

Figure 9.28 Six-axis plate pattern

The six driven electrode pairs shown shaded are on the bottom PC board and the six pickup electrodes shown dotted are on the top PC board. The bottom electrodes can be excited, for example, with 0° and 180° square wave signals at 50 kHz. Clockwise rotation around a perpendicular through the page is sensed by area variation of the pairs $F + C$, that is, the F pickup will pick up more of the plate on the right while the C pickup picks up more of the plate to its left. If the two pickups are exactly balanced, the sum will be sensitive only to rotation. Similarly, area variation of $A + D$ handles translation in the x axis, area variation of $E + B$ handles translation in the y axis, spacing variation of $E - B$ handles rotation around the x axis and spacing variation of $A - D$ handles rotation around the y axis. Spacing variation of $A + B + D + E$ measures board separation.

The electronic circuit can be simple, as only one pickup amplifier is needed with various analog switches used to connect the pickup electrodes as area-variation-linear or spacing-variation-linear for the different measurements, and also to reconnect the drive electrodes to arrange for addition or subtraction as required.

9.12.1 Demodulator

Three axes of motion for the six-axis transducer are spacing variation sensors and three are area variation, but a single amplifier can be configured to linearize both.

Spacing variation

For a linear-with-spacing demodulator, if all eight drive electrodes in groups A, B, C, and D are connected together and all four associated pickups are connected together, the resulting capacitor can be connected as $C2$ in Figure 4.7. A reference capacitor is connected as $C1$ and is excited with, say, 0° at 50 kHz. The usual synchronous demodulator converts the output amplitude to DC.

Area variation

The linear-with-area circuit of Figure 10.26 can be used to demodulate the three area-variation motion axes. The driven electrodes are connected as $C1$ and $C2$.

Another method is to use the oscillator circuit of Figure 4.2 which can be used as both an area- and spacing-linear demodulator. Note that the analog switching circuits will contribute a large capacitance to ground, more than 80 pF for a 74HC4051 analog 8-input multiplexer. A virtual-ground amplifier with high bandwidth as in Figure 10.26 will handle 1 pF signal levels despite 80 pF stray capacitance, but canceling analog switch capacitance with the circuit of Figure 4.3 would require bootstrapping the *Vee* and *Vcc* pins of the analog switch.

9.13 CLINOMETERS

Clinometers measure inclination using the gravity vector as a reference. One model is discussed in Chapter 21; another with similar specifications is available from Lucas Control System Products, 1000 Lucas Way, Hampton, VA 23666, (800)745-8004. Lucas makes a clinometer using capacitive plates, a conductive liquid, and an inert gas, demodulated by two timers and providing analog ratiometric, PWM, and RS-232 output formats. Small-quantity prices are below \$200. The specifications of a packaged version, DP-60, with a four-digit LCD display include a range of ± 60°, resolution of 0.01°, and cross axis error of less than 1% in a case 38 × 138 × 86 mm. Another clinometer with a similar capacitive sensor is available from Lucas without a display and comes in a 50 mm round by 29 mm high enclosure. It offers 0.001° resolution and 0.1° linearity at small angles; the small quantity price is \$120. Lucas can tailor the output curve to nonlinear functions such as sine and cosine by changing the electrode shape.

Tiltmeter

A clinometer with a small linear range, called a tiltmeter (Figure 9.29), has been described by Jones [1973]. Jones, as usual, explores the limits of precision available with very careful design. The instrument on a stable platform is capable of measuring 10^{-8} degree tilt, but the instability of the earth's crust is 10–100× larger than the limiting sensitivity. As the frequency of these microseism tremors is in the 3–8 s range, a lowpass filter should be used to improve the measurement capability. Comparison of two instruments has shown that drift caused by mechanical instability is about one part in 10^9/day.

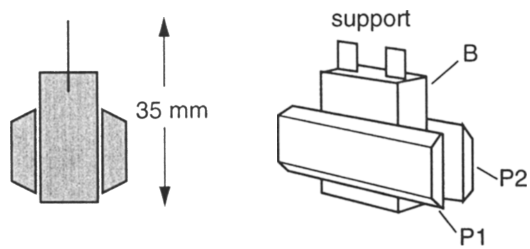

Figure 9.29 Tiltmeter

The two fixed electrodes $P1$ and $P2$ are adjusted with a narrow 75 μm gap to the weight B, which is suspended by two vertical strips. The size of the gap is calculated to provide a viscous damping force as air is squeezed from between the plates with motion, so that the expected resonance peak is critically damped. A 3 V rms excitation at 16 kHz is used with a 0°–180° balanced bridge circuit. The springs can be constructed from fused silica or single-crystal silicon for good stability and low hysteresis, and 70-30 brass and mica, with excellent stability, are used for the electrodes and for insulation.