21
Digital level

SmartTool Technologies of San Jose, CA (a division of Macklanburg-Duncan) specializes in smart tools, tools that make construction jobs easier. An example is the SmartLevel® (Figure 21.1) which looks like the ordinary spirit level with a digital display. But where the spirit level is capable of measuring only inclinations of 0° and 90°, SmartLevel handles a full 360°. RS-232 serial output is available in some models, and a hold button simplifies hard-to-get-at measurements. Display can be angle in degrees or rise/run or angle in percent, and the display reads right-side-up even when the level is inverted, courtesy of the level's gravity sensor. Smaller models are available, 6" long, for machinists and model makers. Resolution can be as good as 0.01° and accuracy in some models is 0.05° at small angles. An OEM module with just sensor and electronics occupies a 1.3 × 2.6 × 0.6" volume, with the pillbox-size capacitive sensor occupying about half the space.

The SmartLevel design shows the evolution of the product from a simple concept with minimum performance to a refined design with excellent specifications. More than 500,000 SmartLevels have been sold.

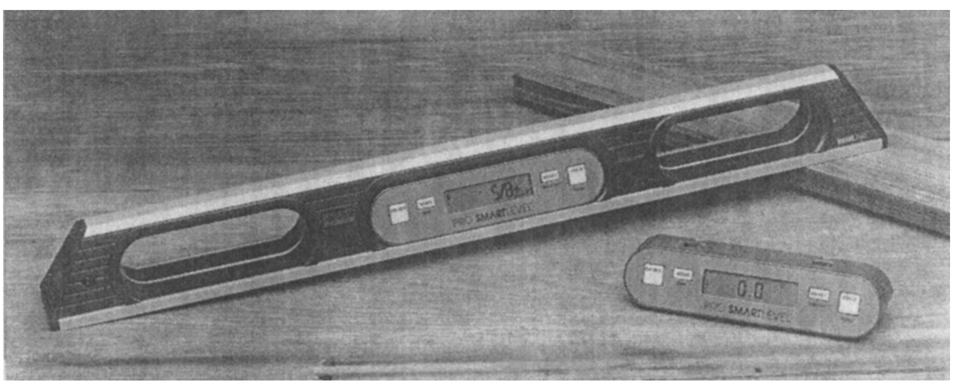

Figure 21.1 SmartLevel®

21.1 SPECIFICATIONS

The product specifications for one version of the sensor module are:

Range	360°
Resolution	
serial port	0.00549°
PWM	4096 steps
Accuracy	
at level and plumb	± 0.1°
at other angles	± 0.2°
Calibration points	128
Temperature coefficient	
at level or plumb, ± 1°	0.006°/°C
at other angles	0.012°/°C
Repeatability	± 1°
Hysteresis	0.1°
Noise	± 0.02°
Settling time	3 s typ; 5 s max
Angle output rate	533 ms
Size	6.6 × 3.3 ×1.5 cm
Power	5 V DC, 2 mA
Temperature range	–5 to +50°C operating
Price	$85.00 (1)

21.2 SENSOR

Simple sensor

A simple level sensor, or inclinometer, can be built with rotating air-spaced capacitor plates (Figure 21.2).

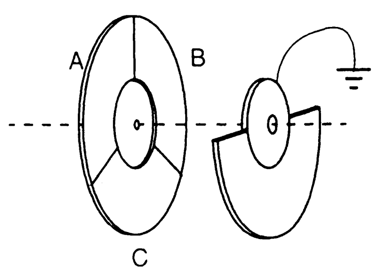

Figure 21.2 Level sensor plates

The disk on the left is a metal plate fixed to the body of the level and divided into three equal 120° segments. A circuit measures the capacity of each plate to ground. The semi-disk on the right is a rotating metal plate on a good bearing, so it tends to hang as shown with gravity. The capacitance of the three plates to ground, normalized to equal plus and minus excursion, changes with tilt angle (Figure 21.3).

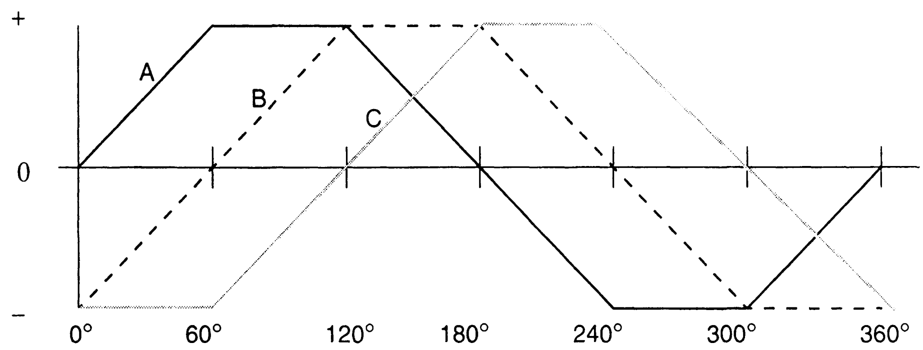

Figure 21.3 Capacitance variation vs. rotation angle

The position can be coarsely estimated to the nearest 60° segment by observing that the signs of ABC in the first 60° of rotation are + - -, and that each 60° segment has a unique order of signs. Then the fine position can be calculated by choosing the plate with the lowest voltage (hence changing the fastest) and performing a simple conversion or table look-up to fine pitch angle. Note that the preferred ratiometric techniques shown in Chapter 8 could also be applied, as the three-phase angle measurement is equivalent to the sine-cosine measurement and coarse plate count. Also, the multiplate techniques of Chapter 8 could be applied to trade analog resolution for digital resolution.

Problems with the three-electrode metal-disk method include:

- Hysteresis caused by friction in the bearing
- Spacing variation causes erroneous pitch angle reading
- Drift due to absolute rather than ratiometric measurement of capacitance

Liquid filled sensor

The first improvement, replacing the metal rotor with a partially conductive liquid, has some important advantages. The liquid has insignificant friction, and the air gap alignment problem disappears as the air gap is replaced with a thin, stable dielectric coating on the metal segment plate. The liquid is poured into a flat cylindrical chamber, and with the chamber half full the liquid acts nearly the same as the semicircle of metal, with the periphery of the chamber grounded to ground the liquid. But a problem with the liquid approach is that while the free surface of the liquid tilts correctly with the desired pitch-angle direction of measurement, it also tilts slightly in the orthogonal axis when the level is rolled slightly, producing an unwanted response to roll.

The roll angle sensitivity is improved by placing similar electrodes on opposing faces of the liquid capsule (Figure 21.4). Now, the capacity to ground of pairs of electrodes, $A + D$, $B + E$, and $C + F$, is measured. The benefit is that as the liquid level tilts up on, say, the left side, increasing the capacitance of A, B, and C to ground, the liquid level tilts down on the right side, causing a compensating decrease in the capacitance of D, E, and F to ground, so $A + D$, e.g., is unaffected. See Figure 21.5.

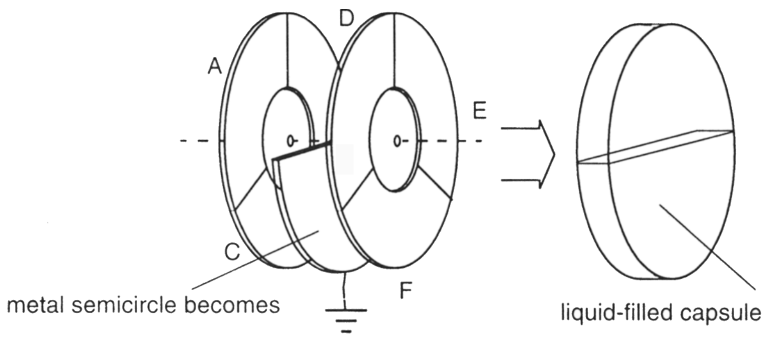

Figure 21.4 Liquid-filled level sensor

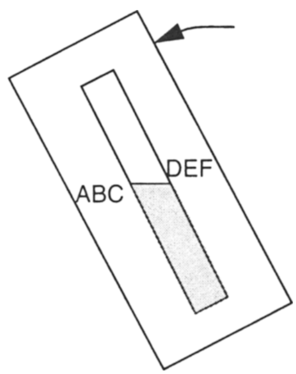

Figure 21.5 Sensor tilted in roll axis

Optimizing the geometry of the sensor plates is also important to resist roll; pie-shaped plates are not optimum. If full pie-shaped plates are used, the increase in capacitance on the *ABC* side is not exactly compensated by the decrease on the *DEF* side if the plates are in some orientations (Figure 21.6). This error, which would amount to about 2°, can be eliminated by use of donut-shaped plates (Figure 21.7).

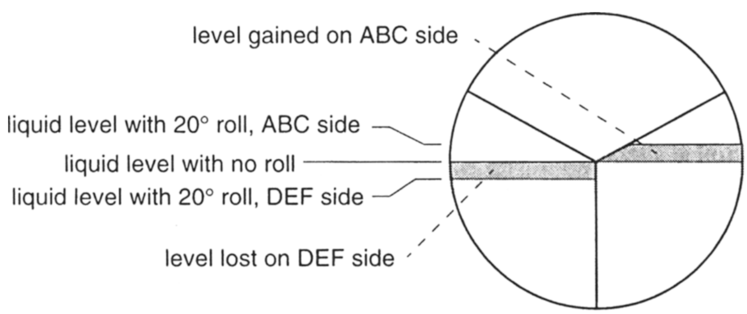

Figure 21.6 Pie-shaped plates produce roll couple

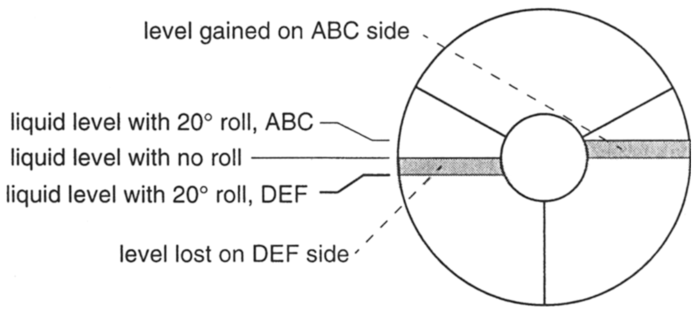

Figure 21.7 Donut-shaped plates eliminate roll couple

Excessive roll will still produce a roll couple, but the addition of two extra electrodes in the hub provides a method of detecting excess roll and flashing the display to warn the user of a potentially inaccurate reading.

21.2.1 Sensor construction

The sensor is 3.2 cm in diameter, and is built using printed circuit board electrodes and an aluminum ring (Figure 21.8). The materials used are carefully chosen. An inert nonconducting layer protects the PC board electrodes and acts as the dielectric for the variable-area capacitor formed by electrode and liquid. The thickness uniformity of the dielectric layer is critical for good linearity.

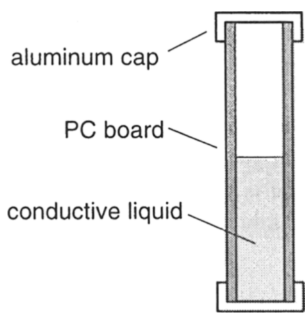

Figure 21.8 Sensor cross section

The liquid needs to be slightly viscous so the liquid-air interface is stable, but not so viscous to add to settling time, and it needs to be inert when in contact with aluminum and have a reasonable surface tension to control the liquid-air interface. A combination of an alkane and a ketone were chosen to optimize these properties. A dielectric, nonconducting fluid could also be used, or a resistive fluid could be measured by resistive rather than capacitive sensing, but a manufacturing tolerance problem would be found in keeping the gap very accurate. With the chosen technique, the dielectric layer needs to be accurate, but the gap can vary.

21.3 CIRCUIT DESCRIPTION

The circuit needs to measure six different capacitors to ground, calculate the angle, apply various calibration factors and display the result. A single 555-type *RC* oscillator is multiplexed with an analog switch to the six electrodes to guarantee stable capacitance measurements that track over temperature (Figure 21.9).

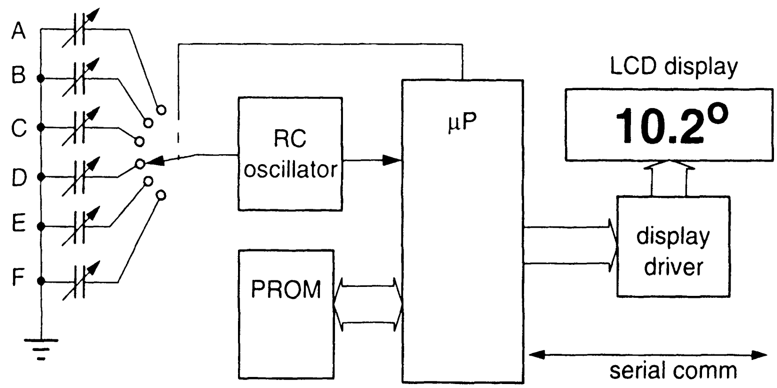

Figure 21.9 Circuit diagram

The PROM is an electrically reprogrammable type which is used to store calibration data, both from a production calibration sweep and from field recalibration, and an LCD display is used to conserve power.

21.4 CALIBRATION

The accuracy specifications of the instrument, 0.1–0.2°, represent 1/1200 of a 120° sector. This is a very difficult target for a single analog measurement, and the best technique to achieve this performance is to calibrate each sensor and store the results in the PROM. Two different types of calibration are needed.

Linearity

The level is rotated slowly through 360° as the last step in production, and automatic test equipment detects the sensor error and stores it in the PROM. There are 128 points of calibration used, and values are interpolated between these points. This calibration compensates for electrode shape error, dielectric thickness error, fill level error, and several other perturbations.

Zero set

During use, another calibration can be performed. The user sets the level on a flat surface and presses the CAL button, reverses the level end-for-end and presses the CAL button again. The microcomputer then averages the readings and can determine the zero offset even if the flat surface is not completely level.