5

Capacitive micrometers

One of the conceptually simplest and most effective applications of capacitive sensors is for measuring very small spacing changes with close-spaced parallel plane electrodes. Early research dates back nearly to the turn of the century with J. Villey's 1910 publication in *Nature*, and development has continued since, with much research conducted in Europe and the United Kingdom, Jones and Richards describe 15 years of research into ultrasensitive capacitive micrometers, clinometers, gravmeters, and seismographs in their important 1973 paper.

Capacitive micrometers use the capacitance variation caused by changing the plate spacing with two-plate systems, or the capacitance difference or ratio change when the center plate is moved in a three-plate system (Figure 5.1).

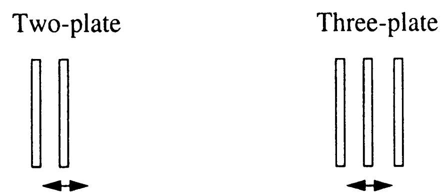

Figure 5.1 Two-plate and three-plate micrometers

The capacity of a pair of parallel square plates in air from eq. 2.13, ignoring fringe effects, for a 1×1 cm pair of plates with 0.1 mm spacing, is 8.85 A/d (pF, meters) or 8.85 pF. Edge effects, additional capacitance caused by coupling to the edges or the back of the plates, will increase the capacity by 2–4%. Edge effects are minimized by using close-spaced thin plates, shielding the back, and chamfering the edges. The additional stray capacity due to edge effects is not a strong function of plate spacing and may be assumed constant for most applications.

Electrostatic force for this capacitor (see eq. 2.3) with 10 V excitation is 4.43 μN. Electrostatic effects are normally small, and with the three-plate configuration electrostatic force will be completely nulled when the moving plate is centered. Electrostatic effects are also nulled with a high-Z amplifier.

The design challenge with the ultrasensitive capacitive micrometer is to detect very small variations of plate capacitance and eliminate unwanted environmental variations due to pressure, temperature, and electronic component changes. Researchers have achieved remarkable results [Jones, 1973], with detectable displacement of 10^{-10} mm and a limiting resolution corresponding to a 0.3 aF capacitance change (0.3×10^{-18} farads).

5.1 CIRCUITS

5.1.1 Two-plate micrometer

For less critical applications the *RC* oscillator can be used to detect plate spacing, but for maximum performance the synchronous demodulator should be used. For the two-plate micrometer (Figure 5.2) the suggested amplifier configuration is a single-ended circuit with a low-Z amplifier. This connection assures that stray capacitance to ground will not affect the performance, and that a grounded shield can be used to shield the device from unwanted local electrostatic fields. This circuit is not useful for very sensitive micrometers as there is no provision to offset the input to amplify small voltages in the presence of DC offset, but it can be used for micrometers with large displacements. DC restoration is not shown; see "DC restoration" (Section 4.3.4).

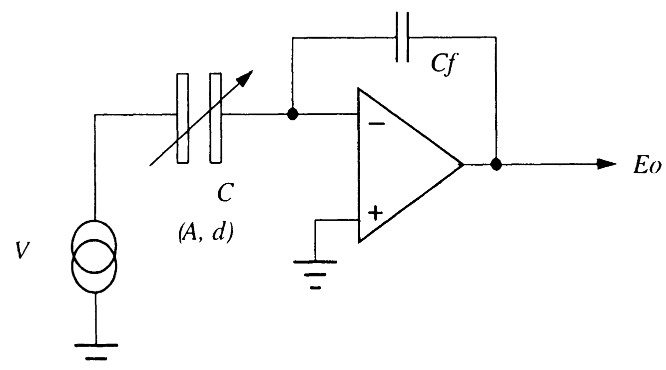

Figure 5.2 Two-plate micrometer

Transfer function of two-plate micrometer

The transfer function of spacing *d* to output voltage with the low-Z amplifier shown above, with capacitive feedback *Cf*, is

$$Eo = -\frac{\varepsilon_0 \varepsilon_r A}{Cfd} V \qquad 5.1$$

which has a parabolic shape. The sensor can be linearized by exchanging it with Cf in the circuit above, or a bridge circuit as in Figure 5.3 may be preferred as its output is higher, it is more linear, and it can be made more stable by matching two bridge capacitors with identical construction.

5.1.2 Three-plate micrometer

The circuit shown in Figure 4.11 is redrawn in Figure 5.3.

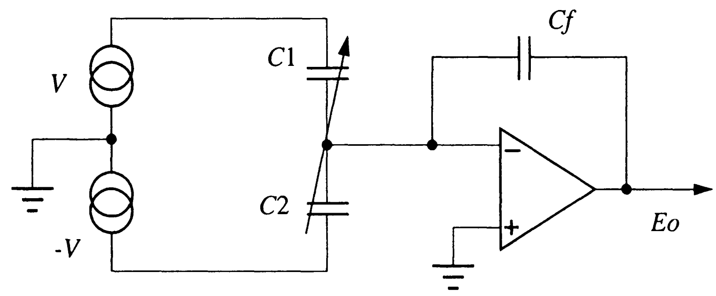

Figure 5.3 Three-plate micrometer

$C1$ and $C2$ represent the capacitances between the micrometer plates, with an average value of C_0 and undeflected spacing d_0. With center plate deflection x, Eo is (Figure 3.9).

$$Eo = V \cdot \frac{C1 - C2}{Cf} = V \cdot \frac{2x}{d_0^2 - x^2} \cdot \frac{C_o}{Cf} \tag{5.2}$$

Transfer function with low-Z amplifier

The transfer function of the circuit above with $V = 1$ shows a range of linear operation near the center of travel (Figure 5.4).

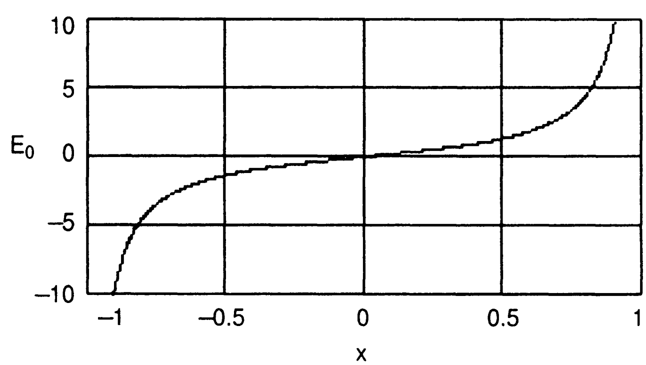

Figure 5.4 Three-plate micrometer transfer function

The input, x, is the normalized center plate position which moves from touching one fixed plate to touching the other. Eo is the normalized current output. If the center 20% of this graph is expanded, the curve is more linear (Figure 5.5).

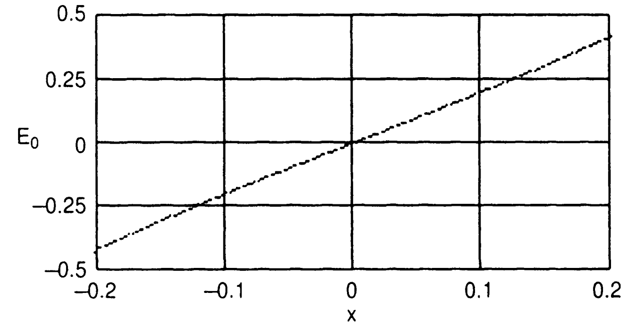

Figure 5.5 Three-plate micrometer transfer function, expanded

A best fit straight line through this curve (Figure 5.6) shows a nonlinearity of less than 1% for almost all of the 20% input range in this expanded scale graph.

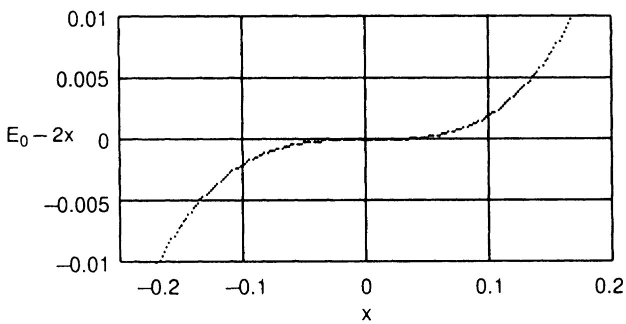

Figure 5.6 Three-plate micrometer transfer function, best fit

The low-Z amplifier is convenient in this application, as a grounded shield can be used to reject extraneous E-fields. If a high-Z amplifier is used, the shield should be connected to the amplifier output. The use of a high-Z amplifier, however, linearizes the bridge. Also, with a high-Z amplifier the electrostatic force on the center plate is zero at all center plate deflections if the deflections are not slower than the amplifier input time constant. The only disadvantage of the high-Z amplifier is the need to use a guard rather than a grounded shield, but with the feedback amplifier circuit (Figure 4.8), the shield may be grounded. The limiting sensitivity of the two types of amplifiers due to noise is similar as shown in Chapter 12. Grounding with the low-Z amplifier is easier than guarding as an extra isolated conductor structure is not needed; a ground shield can usually be fabricated as an extension of an existing conductive enclosure.

The low-Z amplifier is useful for a few applications which can sacrifice linearity for circuit simplicity, but in general it is the last choice for this application due to the extreme nonlinearity.

5.2 CIRCUIT COMPARISON

The different amplifier options for capacitive micrometers can be compared (see Table 5.1)

Table 5.1 Micrometer amplifier comparison

	High-Z (Figure 4.6)	Low-Z (Figure 4.7)	Feedback (Figure 4.8)
Linearity	good	poor, 2% in center 20% of range	good
Shield connected to:	guard voltage	ground	ground
Gage factor depends on:	input cap. to ground	in-out capacitance, *Cf*	in-out capacitance, summer accuracy
Noise	~ same	~ same	~ same
Parts count	middle	least	most

The high-Z amplifier fixes most of the problems with the low-Z amplifier, but it adds the inconvenience of needing a shield which is not at ground potential, and the gage factor (the gain, or output voltage/input displacement) is affected by the stray input capacitance which often cannot be made zero.

The feedback amplifier uses a grounded shield and the gage factor is sensitive only to amplifier input-to-output capacitance and a resistor ratio. Although a single operational amplifier will usually have an unusably high input-to-output capacitance for small sensors, a two-stage amplifier can be easily designed with negligible input-output capacitance. If the summing circuits are implemented with precision resistors, gage factor is accurate. This circuit is preferred for high precision uses.