Capacitive sensor "likes" parasitics

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Stray capacitance is a common problem with capacitive sensors. The capacitance changes within the measurement range are normally much smaller than the strays; the result is a loss of sensitivity. Various methods are available to increase the relative sensitivity (Df/f_0): frequency subtraction, the use of bridges, and the use of a negatron to subtract the strays, for example. The idea here is not to do battle with the stray, but rather use it and turn its drawbacks to your advantage. This method uses frequency-dependent hysteresis in a classic op-amp multivibrator. **Figure 1** shows a simple, flexible design for a capacitive sensor.

Without capacitor C_2, the design is a classic multivibrator based on comparator IC_1 with output buffer IC_2. If $R_1=R_2$, the frequency is

$$f = \frac{1}{2R_4C_1 \ln\left(1 + \dfrac{R_2}{R_3}\right)}.$$

R_1, R_2, and R_3 define the hysteresis, 900 mV with the values shown. Frequency (f) is a function of capacitor C_1, as **Figure 2** shows. Without C_2 and with $C_1=60$ pF and DC=20 pF, $f_0=159$ kHz and the relative sensitivity Df/f_0 is −18%. With C_2 connected in parallel with R_2, the hysteresis becomes frequency-dependent. The capacitive reactance ($X_C=1/2pfC$) in parallel with R_2 reduces the hysteresis in an inverse proportion to the frequency. As a result, the frequency increases. This increase reduces X_C, further reduces the hysteresis, and leads to a further increase in frequency. Thus the relative sensitivity Df/f_0 increases significantly (see **Figure 2** with $C_2=40$ pF).

With $C_2=40$ pF, $C_1=60$ pF, and DC=20 pF, $f_0=945.5$ kHz and the relative sensitivity (Df/f_0) is −82%. The sensitivity (Df/f_0) (38.6) in this case is 26 times as high as the case without C_2 ($Df/f_0=1.45$). You can obtain even more interesting results by replacing C_2 with a sensing capacitor. If $C_1=200$ pF, changing the value of C_2 from 0 to 200 pF changes the hysteresis from 900 to 28 mV, and changes the frequency from 30 to 1300 kHz. **Figure 3** shows output frequency (f) as a function of capacitance C_2. With $C_2=100$ pF and DC=20 pF, $f_0=145.2$ kHz and the relative sensitivity (Df/f_0) is +393%. Thus, the frequency is directly proportional to the capacitance.

As **Figure 3** demonstrates, you can adjust the desired initial frequency with R_3, and the sensitivity with R_5. Note that the higher sensitivity in this

The addition of "stray" capacitance to Figure 1's circuit significantly increases the sensor's sensitivity.
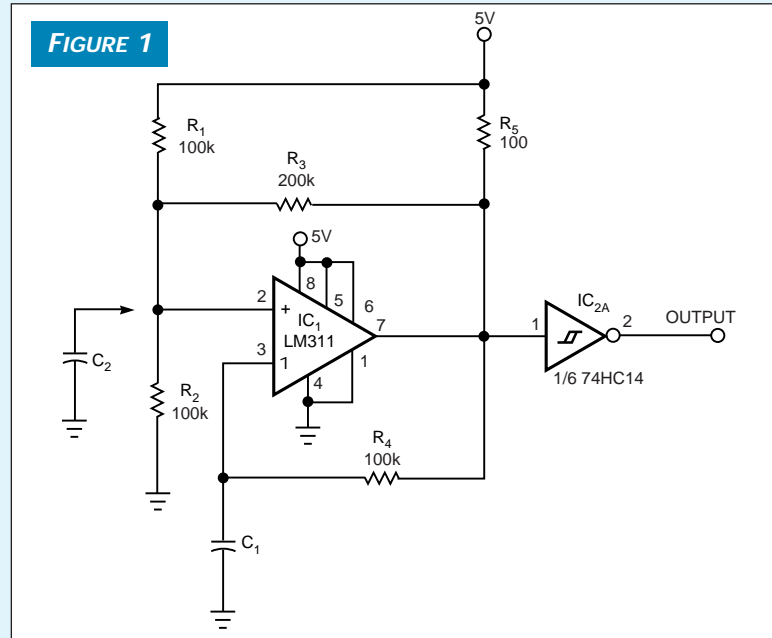
FIGURE 1

If you can't beat 'em, join 'em. This circuit exploits stray capacitance to increase its own sensitivity in making capacitance measurements.

FIGURE 2

$R_3=200k$
$R_5=100V$

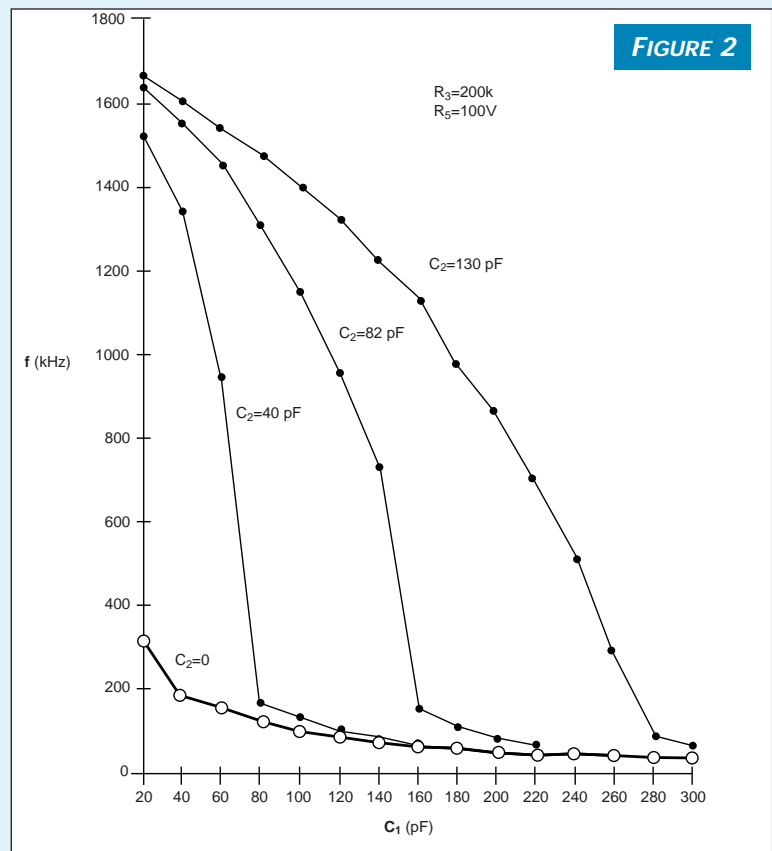$C_2=130$ pF

$C_2=82$ pF

$C_2=40$ pF

$C_2=0$

f (kHz)

C_1 (pF)

example occurs with a significant stray capacitance (100 pF, for example). If the real sensor has lower initial capacitance (50 pF, for example) the simple addition of a 50-pF capacitor in parallel with the sensor increases the sensitivity. The sensor "likes" the stray capacitance as it produces frequency-dependent hysteresis that, in turn, provides higher sensitivity. You could also use the added capacitor for temperature compensation.

If you use an extremely fast op amp or comparator in this design, there is a certain value of C_2 for which the output frequency jumps up a few kHz with a hysteresis of 5 to 7 pF (**Figure 4**). This quirk is particularly useful in the design of super-sensitive capacitive switches. You can adjust the switching point with R_3 and/or a capacitor in parallel with C_2. You can adjust the hysteresis by using a small resistance connected in series with C_2. On the other hand, the use of a slower comparator linearizes the frequency-versus-capacitance characteristic. For example, test results show that with an LM319 comparator, $R_3=200$ kV, $R_5=200$V, and $C_1=200$ pF, the output frequency follows the empirical equation $f=140+3.327(C_2-100)$ kHz with 3% nonlinearity within the range $C_2=100$ to 400 pF. (DI #2258). **e**

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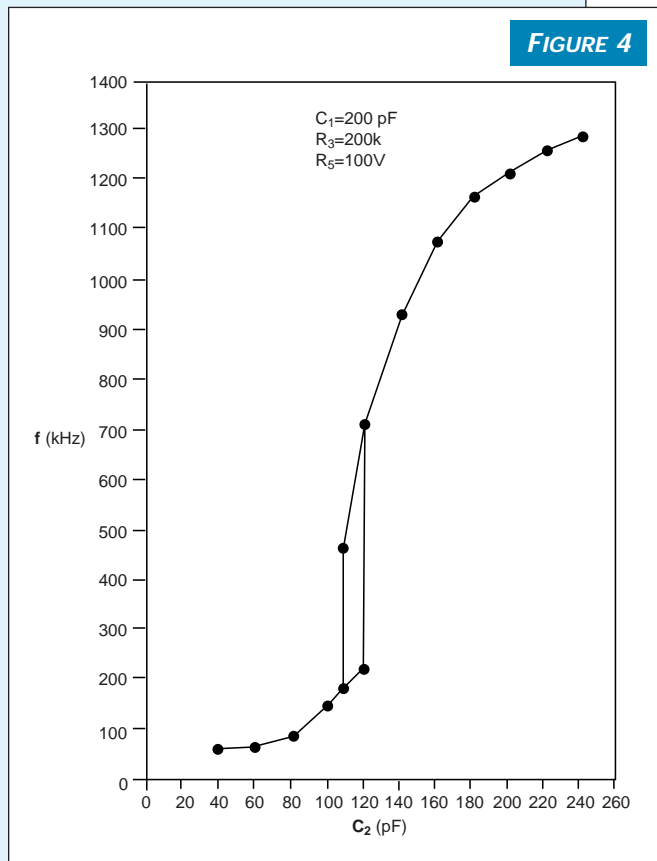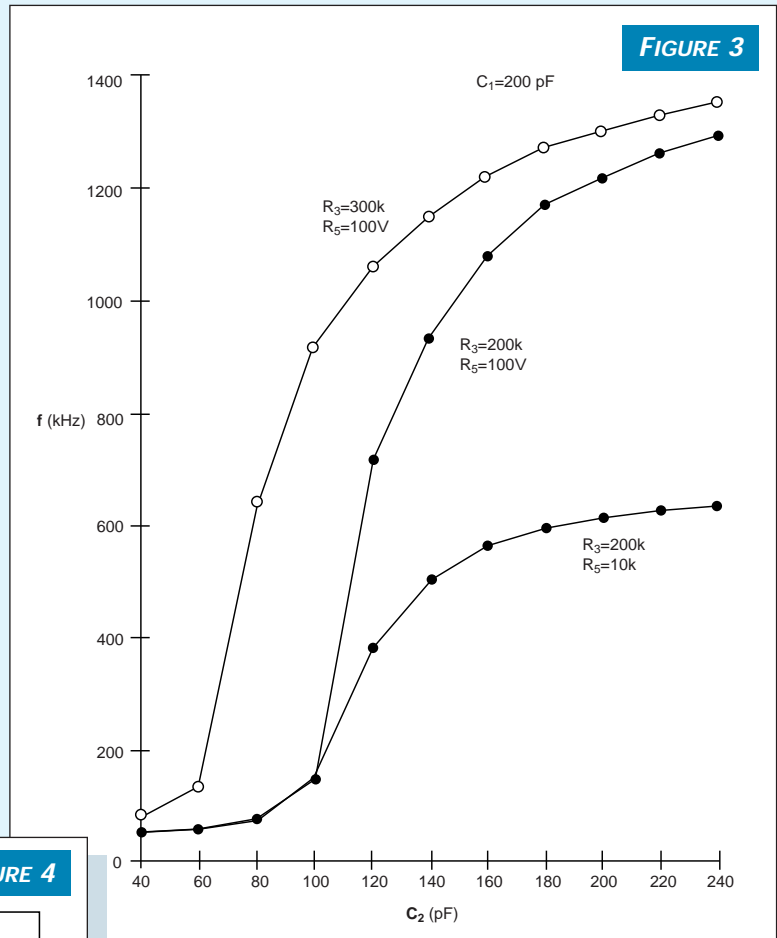
FIGURE 3

This response is the result of using the "stray" capacitance as the sensing element in the Figure 1's circuit.

FIGURE 4

An idiosyncrasy inherent in fast op amps or comparators produces an abrupt jump in frequency for a small change in capacitance.