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Ideas for Design

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Generate Realistic Models For LED Current Versus Voltage

LEDs ARE NONLINEAR devices with I/V curves that resemble the curves of rectifier diodes. Designers of lighting drivers require a good approach to modeling the LED device performance in the first quadrant of the I/V plane.

For engineering applications, there are three approaches to consider: the linear, bias-voltage plus resistor equivalent; a quadratic equation; and an exponential equation. Let's use the three techniques with Cree's XLamp XM-L LED as the LED to be modeled *(Fig. 1)*.

THE LINEAR MODEL

This model is the simplest, but the most inaccurate. It consists of a dc bias voltage plus a resistor *(Fig. 2a)*. The equivalent mathematical form is given by:

$$i_F(v_F) = a + \frac{1}{R}(v_F - b) = \frac{v_F - v_{bias}}{R}, \quad v_F \geq v_{bias} = b - a \cdot R \qquad (1)$$

You select two data points (v_F, i_F) in coordinate form (i.e., 3.28 V, 2.6 A and 2.71 V, 0.2 A). Then, R is evaluated and yields 0.2375. The selection also implies a = 0.2 and b = 2.71. With all three parameters (a, b, R) properly assigned, the linear model yields Figure 2b. Evidently, the linear model offers the advantage of simplicity, but suffers in accuracy.

THE QUADRATIC MODEL

The curve of Figure 1 has a concave portion that resembles one arm of a parabolic curve. It can be expressed with a quadratic equation of the form $a_2 v_F^2 + a_1 v_F + a_0$. The key is the determination of three coefficients: a_2, a_1, and a_0.

To determine these coefficients, you can use the well-known Least Square Polynomial Curve-fitting algorithm of linear algebra. To do this, select more than a dozen data points from Figure 1 (15 in this case) and place them in two matrixes.

One is a 3x15 rectangular matrix C *(Equation 2)*. The other is a 1x15 column vector i_F *(Equation 3)* where vF_j, for j = 0 to 14, are the corresponding LED forward voltages at the selected forward currents given in vector i_F. The three coefficients are then given by a column vector of:

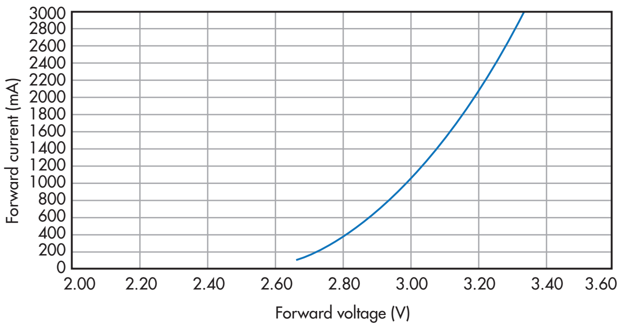
$$a = (C \cdot C^T)^{-1} C \cdot i_F^T \qquad (4)$$

Using software tools such as Matlab from the Mathworks or MathCAD from Mathsoft, you can easily compute Equation 4. For this example, we obtain:

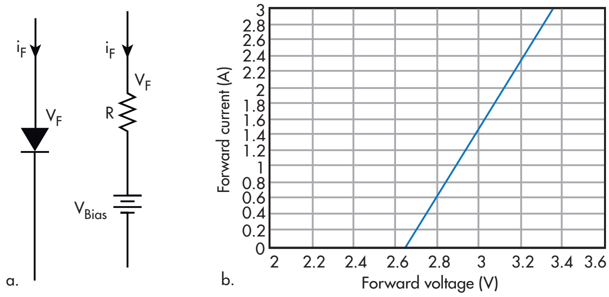
$$a = \begin{pmatrix} 24.849 \\ -20.093 \\ 4.058 \end{pmatrix} \qquad (5)$$

$$C := \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ vF_0 & vF_1 & vF_2 & vF_3 & vF_4 & vF_5 & vF_6 & vF_7 & vF_8 & vF_9 & vF_{10} & vF_{11} & vF_{12} & vF_{13} & vF_{14} \\ (vF_0)^2 & (vF_1)^2 & (vF_2)^2 & (vF_3)^2 & (vF_4)^2 & (vF_5)^2 & (vF_6)^2 & (vF_7)^2 & (vF_8)^2 & (vF_9)^2 & (vF_{10})^2 & (vF_{11})^2 & (vF_{12})^2 & (vF_{13})^2 & (vF_{14})^2 \end{bmatrix} \qquad (2)$$

$$iF := \begin{pmatrix} 200m & 400m & 600m & 800m & 1000m & 1200m & 1400m & 1600m & 1800m & 2000m & 2200m & 2400m & 2600m & 2800m & 3000m \end{pmatrix} \qquad (3)$$



1. Modeling the I/V curve of the Cree XLamp XM-L LED with increasing accuracy is the objective of this analysis.



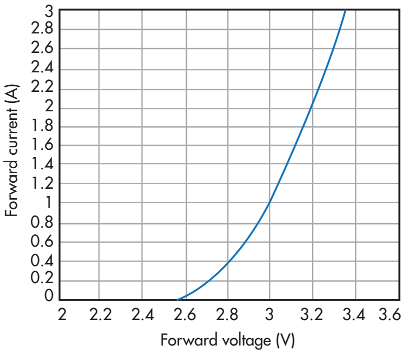
2. The linear model (terminal view) is simplest and easiest to understand, but also the least accurate (a). The linear model results in this "curve," which clearly has some shortcomings (b)

Note that the first element of vector a is coefficient a_0, etc., which leads to the quadratic model of Figure 3. This approach yields significant improvements in the model across the whole operating range of the LED.

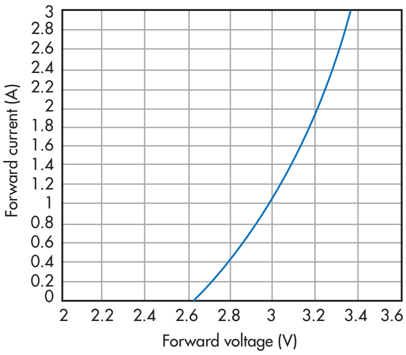
THE EXPONENTIAL MODEL

Figure 3 appears to bend more near the low current, which is where the exponential model may offer further improvement. This model comes in the form of $ae^{b \cdot vF} + c$ with three unknown parameters a, b, and c to be determined. Again, software tools such as MathCAD help you find those parameters numerically.

Under the specialized regression section, an exponential regression statement expfit (v_F, i_F, vg) can find all three parameters, given a data set in vectors and initial guess value vg, also a column vector. For this example, $a = 9.66 \cdot 10^{-3}$, $b = 1.818$, and $c = -1.157$ are obtained. This results in the exponential model of Figure 4.



3. The curve based on a quadratic model curve is much closer to the reality of the I/V curve for this LED.



4. The exponential model further refines the quadratic model and provides a better approximation in the low-current region of the LED.

Overall, the best fit near the low-current region may be found between the quadratic and the exponential models. It is unrealistic to expect a single, perfect prediction from any given model, since almost all such analytical efforts are an attempt to represent the complexities of nature.

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PWM-Based Analog Calculator Provides Four-Quadrant Multiplication, Division

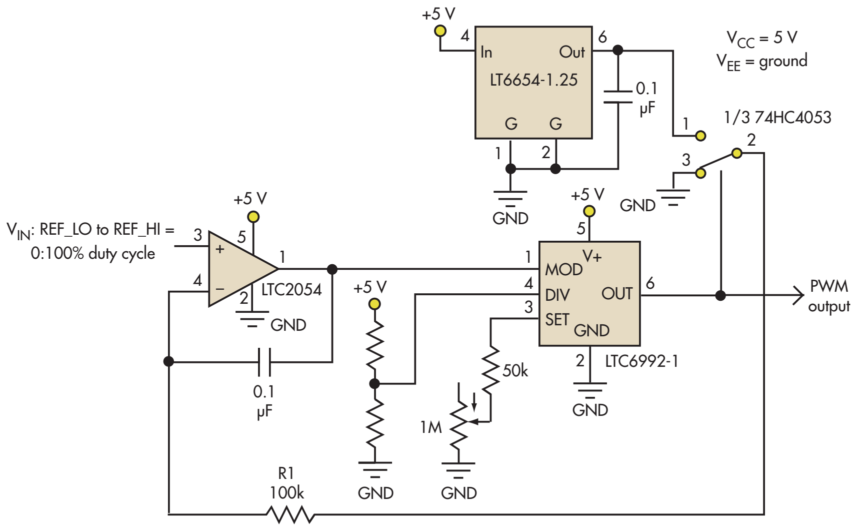
YOU CAN BUILD an analog calculator using a pulse-width modulator (PWM) to perform accurate four-quadrant multiplication and division. While this approach won't help you ace any math tests, it demonstrates some useful sub-circuits that extend the functionality of the LTC6992 TimerBlox voltage-controlled PWM.

The LTC6992-1 translates a 0-1 V input at the MOD pin into an output with a 0% to 100% duty cycle at a frequency of 3.81 Hz to 1 MHz. A resistor at the SET pin and a resistor divider at the DIV pin control this frequency. In some applications, the LTC6992 will be in the feed-forward path of a closed-loop control system (as in a motor-speed controller), so its 1% typical linearity provides consistent overall loop performance.

Figure 1 shows a basic linearized PWM generator for applications where accurate PWM is required without an external feedback mechanism. This circuit easily achieves 0.1% PWM accuracy. The output of the LTC6992 controls one section of a 74HC4053 triple single-pole double-throw (SPDT) analog switch whose output is switched between ground and an LT6654-1.25 reference. An integrator compares this signal to the control input. The output duty cycle will settle on a value that equals the fraction of the 1.25-V reference that's present at the input. The term "fraction" implies that this circuit performs division, as the output PWM duty cycle is V_{In}/V_{Ref}.

Figure 2 extends this concept, with X as the input (numerator) and Y as the reference (denominator). An LT1991 configured in a gain of –1 provides a precise negative copy of Y, extending operation to four quadrants (positive and negative X and Y), with duty cycle = 50% × [1 + (X/|Y|)].

As with any physical realization of division, a zero value for the denominator (Y) will produce an undefined output. A negative voltage applied to the Y input inverts the polarity of the feedback signal to the integrator, which requires another inversion



1. This basic linearized PWM generator, without an external feedback mechanism, can still provide accuracy of 0.1%.

DIVCODE PROGRAMMING					
DIVCODE	POL	N_{DIV}	Recommended f_{OUT}	R1 (kΩ)	R2 (kΩ)
0	0	1	62.5 kHz to 1 MHz	Open	Short
1	0	4	15.63 to 250 kHz	976	102
2	0	16	3.906 to 62.5 kHz	976	182
3	0	64	976.6 Hz to 15.63 kHz	1000	280
4	0	256	244.1 Hz to 3.906 kHz	1000	392
5	0	1024	61.04 to 976.6 Hz	1000	523
6	0	4096	15.26 to 244.1 Hz	1000	681
7	0	16384	3.815 to 61.04 Hz	1000	887
8	1	16384	3.815 to 61.04 Hz	887	1000
9	1	4096	15.26 to 244.1 Hz	681	1000
10	1	1024	61.04 to 976.6 Hz	523	1000
11	1	256	244.1 Hz to 3.906 kHz	392	1000
12	1	64	976.6 Hz to 15.63 kHz	280	1000
13	1	16	3.906 to 62.5 kHz	182	976
14	1	4	15.63 to 250 kHz	102	976
15	1	1	62.5 kHz to 1 MHz	Short	Open

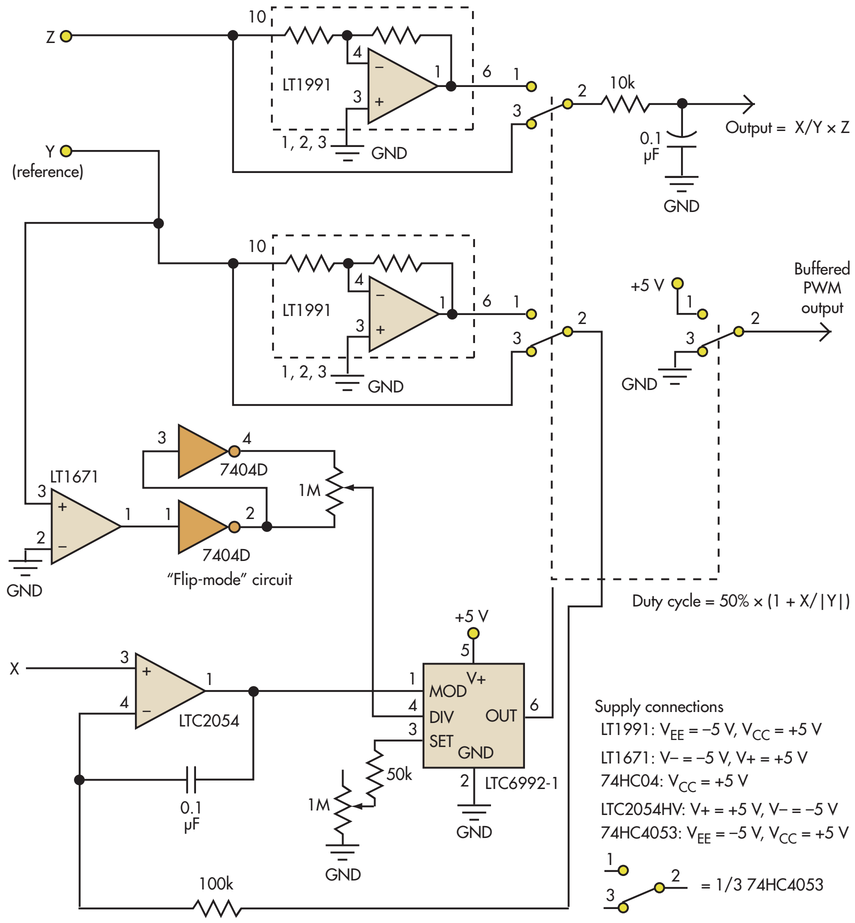
somewhere in the loop to ensure feedback is negative.

The DIV pin also can invert the PWM polarity (a 0- to 1-V input = 100% to 0% duty-cycle output), in addition to selecting one of eight N_{Div} values to set the frequency. The N_{Div} magnitudes are mirrored around $V_{CC}/2$, where swapping values in the resistor divider inverts the transfer function while maintaining the same divider value *(see the table)*.

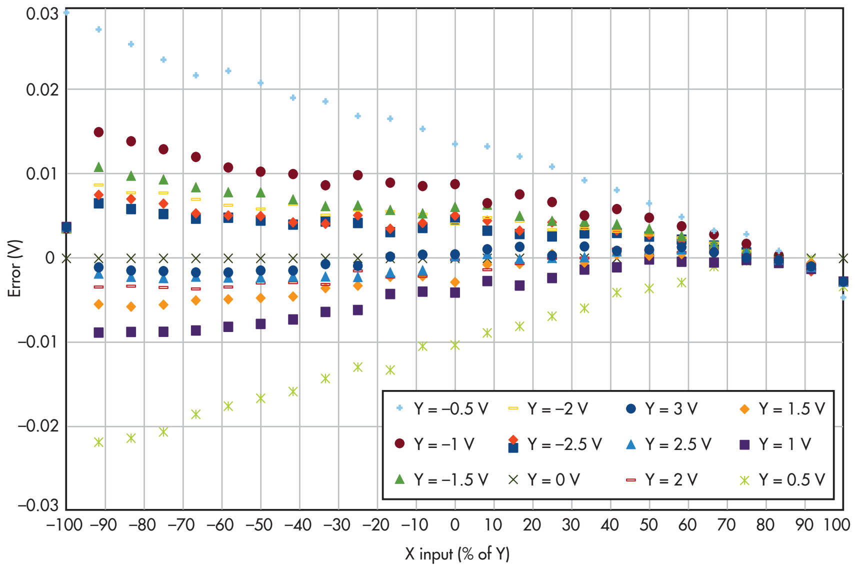
An LT1671 comparator detects the polarity of the Y input and sets the polarity by switching the divider potentiometer's excitation accordingly, maintaining correct operation. Note that a 10-turn potentiometer works well for experimentation. You could replace it with a fixed resistor once you have selected the desired N_{Div}.

The "Z" input is multiplied by the X/Y quotient by supplying the inputs to another switch with Z and –Z. (Once again, an LT1991 provides precision inversion.) This is a "pulse width/pulse height" multiplier, also with four-quadrant operation.

Figure 3 shows the absolute error of the circuit at a 1.5-kHz frequency, sweeping X from –Y to +Y for values of Y from –3 V to +3 V, while holding Z constant at 5 V. Even with Y at 0.5 V (where error sources are more significant), the worst-case error is about 0.6% and rapidly improves with larger values of Y. Error sources include the 0.04% error of the LT1991, mismatch in switch resistance between its two positions compared with the resistance of the downstream filter's resistance, and the response of the LT1991 outputs to switching transients, whose effect will vary with PWM frequency.



2. This enhancement to the circuit of Figure 1 extends the analog multiplication/division to all four analog signal quadrants.



3. This plot of absolute error shows better than 0.1% for large values of Y.

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Driven Shield Enables Large-Area Capacitive Sensor

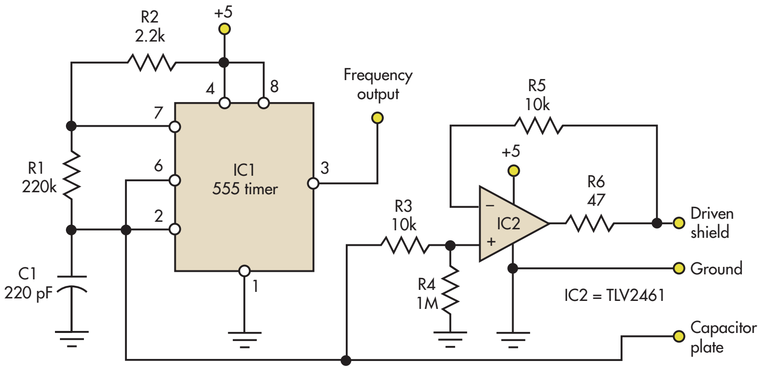
CAPACITIVE SENSORS ARE common in today's consumer electronics, since they are used in many touchscreen applications. Most of the circuits for such applications are designed for small-area capacitors and finger contact operation.

This circuit is designed for large-area touch plates that can be activated at a distance and hidden behind walls or inside other structures. It uses the "driven shield" concept that was popular in the early days of audio engineering, when high-impedance sound sources such as crystal microphones were used. Shielded cables are needed to connect these devices, but the cable capacitance limits the high-frequency response.

The solution to this problem is to go back to the physics of a capacitor to find a way to reduce the cable capacitance. Driving a conductor between the outer shield and the inner, signal conductor with the same voltage as the signal conductor largely eliminates the capacitance. NASA used this driven-shield idea in a large-area capacitive sensor two decades ago (John M. Vranish, et al., US Patent No. 5,116,679).

The circuit in Figure 1 performs the main capacitance-sensing task, while leaving detection to a microcontroller. IC1 is a 555 timer wired as an astable multivibrator with as small a timing capacitance as possible. With the component values shown, the frequency is slightly above 10 kHz. IC2 buffers the voltage on this capacitor to drive a shield plate.

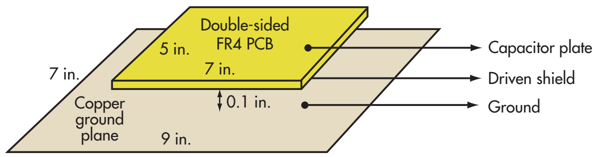
For IC2, resistors R3 and R4 decrease the buffered voltage by about 1%. This prevents oscillation that may occur because of the external capacitance. R6 is included since some operational amplifiers have difficulty driving a capacitive load. IC2 should have a high gain-bandwidth product to allow a faithful representation of the signal voltage without phase shift.



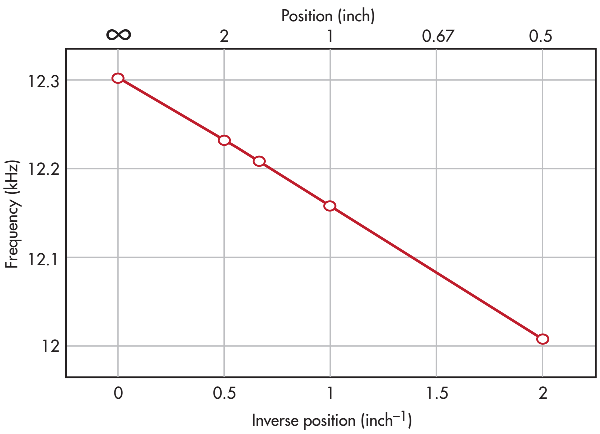
1. In this large-area capacitive sensor, C1 and any parallel capacitance set the frequency of the 555 astable multivibrator IC1, while IC2 buffers the voltage at the capacitor to drive the shield plate. (The pin-outs for IC1 are for the "N" package.)

Figure 2 shows the construction of the sensing plate. These are the dimensions used in the author's tests, but quite a lot of variation is permissible. A practical implementation would be to build the circuitry onto an edge of the ground plane.

The frequency response decreases in a nearly linear fashion with respect to inverse position *(Fig. 3)*. In the author's test, hand contact reduced the frequency to 10.47 kHz. Hand contact through a 0.375-in. (10 mm) thick piece of plywood or gypsum wallboard resulted in a frequency change of 10%, which is easy to detect. Although frequency-detection ICs are available, a simpler, less expensive solution is to use a microcontroller to detect a change in signal period.



2. In the constructed sensor, a double-sided printed-circuit board (PCB) has one conductor as the signal plate and the other as the driven shield. The semi-infinite ground plane, which is slightly larger in area than the sensing or shield plates, can be another PCB or an aluminum plate.



3. The circuit response is a close-to-linear inverse-position relationship between hand position and the sensing plate.

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