Designing a feedback system? Control it with a photo emitter-sensor

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GIVEN A controls-system application where isolation between the controlling element and the controlled circuit is a critical factor, one type of device, the photo-emitter-sensor, particularly stands out. In addition to its suitability for general feedback systems, it becomes especially attractive for agc, logic translation, facsimile and photomultiplier systems.

The photoconductive portion of the device features a controlled resistor that can be varied over a wide range by modulating the light falling on the photo-sensitive surfaces. To shut out ambient light and achieve controlled light intensity, proper isolation and minimum stray coupling, both light source and photoconductor are packaged in a single four-terminal device.

The analysis of the device characteristics and a number of design examples demonstrate its versatility, very-sensitive-control property, circuit isolation and lack of distortion in the signal.

Analysis of a typical device

The data plotted in Fig. 1 give the value of the photoconductor's resistance as a function of current in the lamp for a typical unit, the CK1116.* For the purposes of analysis, a curve with the following equation can be fitted to the experimental data:

$$\log_{10} R = \frac{a}{\sqrt{i-b}}, \qquad (1)$$

$$R = 10^{\sqrt{\frac{a}{i-b}}} \qquad (1a)$$

where R is photoconductor resistance, i is lamp current and a and b are experimentally determined constants.

For the unit tested (the CK1116),

$$a = 0.175 \text{ and } b = 0.0052. \qquad (2)$$

Then:

$$\log_{10} R = \frac{0.175}{\sqrt{i-0.0052}}.$$

The slope of the curve, obtained by the differentiation of Eq. 1 is:

$$\frac{dR}{di} = \ln 10 \; R\,(a)\,(-1/2)\,(i-b)^{-3/2} \qquad (3)$$

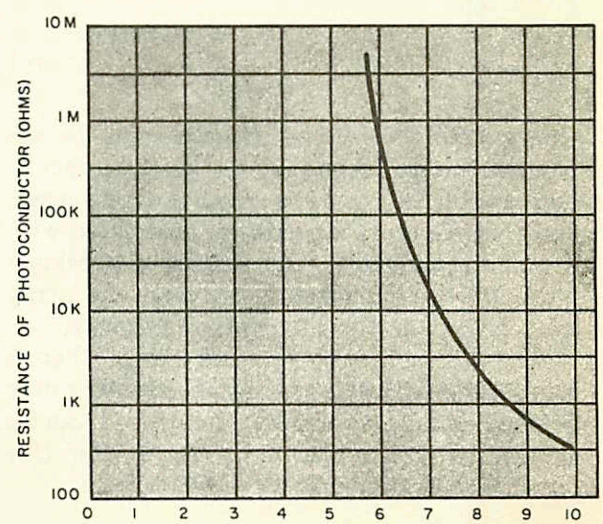
$$= \frac{1.15\,a\,R}{(i-b)^{3/2}},$$

which, for the CK1116, is:

$$\frac{dR}{di} = \frac{-0.201R}{(i-0.0052)^{3/2}} \qquad (4a)$$

The initial operating point is usually chosen where the resistance is relatively high. For example, at a current of 6 ma, R is approximately 1 Meg.
Eq. 4a now becomes:

$$\frac{dR}{di} = \frac{-0.201\times10^{6}}{2.26\times10^{-5}} \approx -9 \text{ Megs/ma} \qquad (4b)$$



1. Photoconductor resistance vs lamp current is shown for a typical photoelectric emitter-sensor.

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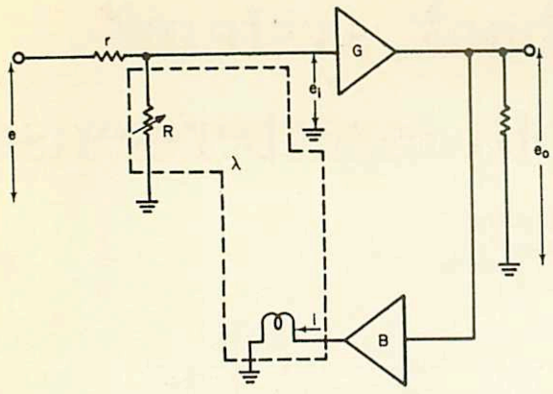
*One of a class of these devices manufactured by Raytheon and identified as the "Raysistor."



2. **Basic control circuit** uses the emitter-sensor in its feedback leg.

At an operating point of 7 ma, R is 20K, and

$$\frac{dR}{di} = \frac{0.402\times10^4}{0.72\times10^{-4}} \approx -560\text{K/ma} \qquad (4c)$$

It is evident that a very large change in resistance of the photoconductor is obtained for a small change in lamp current.

In general, the choice of an operating point or value of R depends on a number of factors. The lowest usable R can be determined from the relationship:

$$R_{min} = \frac{E^2}{P}, \qquad (5)$$

where P is the allowable dissipation of the photoconductor, E is the voltage applied to the photoconductor (whether dc or rms) and R_{min} is the minimum allowable resistance. On the other hand, R must not be chosen too high; that is, R must be less than some R_{max} given by:

$$R_{max} = \frac{1}{2\pi f_c C}, \qquad (6)$$

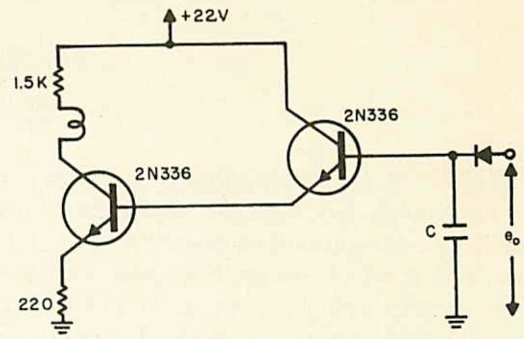
where f_c is the highest frequency to be applied to the photoconductor (i.e., the upper 3-db point of the required frequency response), and C is the total capacitance associated with the photoconductor (the sum of the capacitance of the photoconductor and the stray capacitance of the associated circuits).

Any R, such that $R_{min}<R<R_{max}$, that is compatible with the associated circuitry may be used. The lamp current for this R can be determined from Fig. 1 or Eq. 1. For this purpose, it is better to solve Eq. 1 for i:

$$i = \left(\frac{a}{\log_{10} R}\right)^2 + b \qquad (7)$$

How control is achieved

In Fig. 2, e, is the input voltage to the entire system, G is the amplifier gain, r is a fixed series resistor, R is the photoconductor's resistance, e_i is the input voltage to the amplifier, e_o is the output voltage of the amplifier and B is the transfer function between the output voltage, e_o, and the lamp current, i. B is better known as the feedback. The following relationships become evident:



3. **Lamp driver circuit** illustrates the agc action obtained with the emitter-sensor.

$$e_i = e\left(\frac{R}{R+r}\right) \qquad (8)$$

$$e_o = Ge_i \qquad (9)$$

$$i = Be_o \qquad (10)$$

From Eqs. 8 and 9:

$$e_o = Ge\left(\frac{R}{R+r}\right) \qquad (11)$$

$$e_o R + e_o r = GeR \qquad (12)$$

$$R = \frac{e_o r}{Ge-e_o}. \qquad (13)$$

Substituting Eq. 10 into Eq. 13 yields:

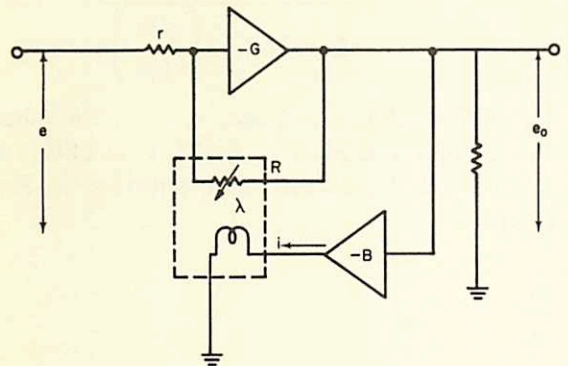
$$R = \frac{\dfrac{ri}{B}}{Ge-\dfrac{i}{B}} \qquad (14)$$

$$= \frac{ri}{GBe-i}. \qquad (15)$$

To obtain the variation of R with input voltage, R is differentiated with respect to e in Eq. 15:

$$\frac{dR}{de} = \frac{(GBe-i)r\left(\frac{di}{de}\right) - ri\left(GB - \frac{di}{de}\right)}{(GBe-i)^2} \qquad (16)$$

Since:



4. **Operational amplifier** arrangement has the resistor portion of the device used as the feedback element.

$$\frac{dR}{de} = \frac{di}{de} \times \frac{dR}{di}, \qquad (17)$$

Eq. 16 can be rewritten as:

$$\frac{di}{de} = \frac{riGB}{ri + r(GBe-i) - (GBe-i)^2\left(\frac{dR}{di}\right)} \qquad (18)$$

dR/di has been previously evaluated (see Eqs. 4a and 4b), and the third term of the denominator of Eq. 18 can be shown to be much greater than the sum of the first two terms. Thus, for practical considerations, the relationship is expressed as:

$$\frac{di}{de} = -\frac{riGB}{(GBe-i)^2\left(\frac{dR}{di}\right)}. \qquad (19)$$

From Eq. 10:

$$\frac{de_o}{de} = \frac{1}{B}\left(\frac{di}{de}\right), \qquad (20)$$

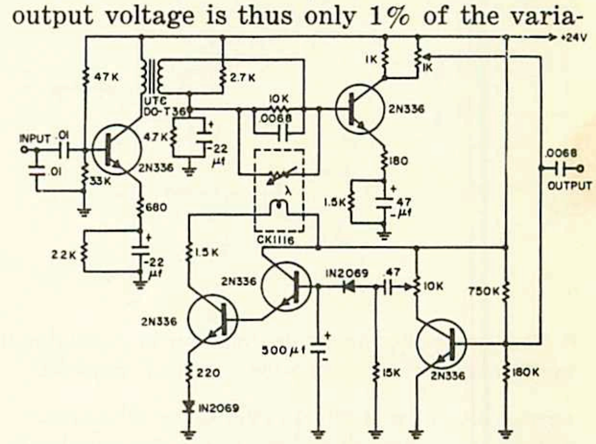
which, upon substituting Eq. 19, becomes:

$$\frac{de_o}{de} = -\frac{riG}{(GBe-i)^2\left(\frac{dR}{di}\right)} \qquad (21)$$

In a typical circuit, the values of these parameters would be: $e = 2$ volts, $r = R = 20\text{K}$, $i = 7$ ma, $e_o = 3.6$ volts, $G = 3.6$ and $B = 0.005$. Using dR/di from Eq. 4b,

$$\frac{de_o}{de} = \frac{-20{,}000(3.6)(0.007)}{\{[(3.6)(0.005)2]-0.007\}^2(-5.6\times10^7)}$$
$$= 0.0107$$

For these conditions, the variation in the output voltage is thus only 1% of the variation in the input. The reason for using $e_o = 3.6$ volts and B = 0.005 is evident from Fig. 3, a lamp-driver circuit, which is the *B* element. The 3.6 volts are required to maintain 7 ma in the 220-ohm resistor and a 0.7-volt drop across both the charging diode and the two base-emitter diodes. Any further increase in e_o gives an increase in i of $e_o/220$.



5. **Control of an AM facsimile signal** is accomplished by emitter-sensor and Darlington in feedback loop.

The capacitor *C* charges rapidly through the diode, but it discharges very slowly due to the Darlington transistor connection. Thus the value of *R* remains approximately constant at a level corresponding to the maximum signal, while the signal itself varies, and agc action is obtained.

If the capacitor is removed, and if the signal frequency is not greater than that which the lamp can follow, then volume compression is obtained. Volume expansion, on the other hand, can be realized by inverting the sense of the correction, either by using *R* in a different location or by causing the amplifier to invert. But then, the dangers of oscillation that are inherent in positive-feedback arrangements are encountered.

In this example, the emitter-sensor provides the negative feedback function, but the precautions necessary in all feedback amplifiers must still be observed. The capacitor, *C*, is normally large enough to stabilize the loop. In cases where it is small or omitted entirely, either the GB product must be reduced or stabilizing networks have to be added. This is based on the assumption that the lamp is able to follow frequencies at which oscillations could occur. Where this is not the case, the lamp itself prevents oscillations.

Fig. 4 shows R used as the feedback element in an operational amplifier. Both G and B now have negative signs. In place of Eq. 8 through 10, the following now hold:

$$e_o = -e\frac{R}{r}\ (\text{for large } G) \tag{22}$$

$$i = -Be_o \tag{23}$$

From Eqs. 22 and 23:

$$R = \frac{-e_o r}{e} = \frac{ri}{Be} \tag{24}$$

$$\frac{dR}{de} = \frac{Ber\left(\frac{di}{de}\right) - riB}{B^2 e^2} = \frac{er\left(\frac{di}{de}\right) - ri}{Be^2} \tag{25}$$

Since:

$$\frac{dR}{de} = \frac{di}{de} \times \frac{dR}{di}, \tag{26}$$

we now have:

$$\frac{di}{de} = \frac{ri}{er - Be^2\left(\frac{dR}{di}\right)} \tag{27}$$

and:

$$\frac{de_o}{de} = \frac{ri}{-Ber + (Be)^2\left(\frac{dR}{di}\right)} \tag{28}$$

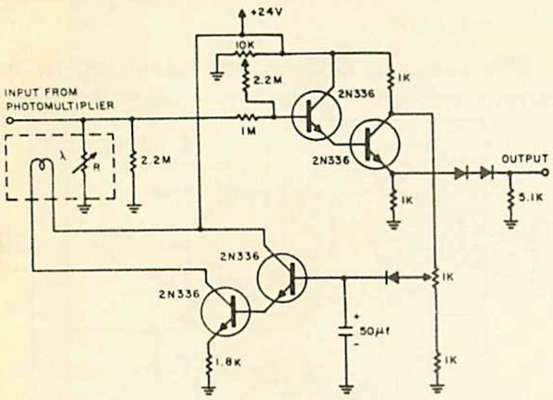
For R = 20K, i = 7 ma, e_o = − 3.6 volts, e = 2 volts and B = − 0.005, r = 20K/1.8 = 11K, dR/di has the value obtained in Eq. 4c and:

$$\frac{de_o}{de} - =$$

$$\frac{11000(0.007)}{(2)(11000)(0.005) - (0.005\times 2)^2(5.6\times 10^7)} = -0.014$$

In addition to the two common configurations discussed above, many others are possible and can be analyzed in a similar manner. Two practical circuits developed for use in facsimile systems to provide background control are included here. Fig. 5 shows the control for an AM facsimile signal. This circuit is used in AN/GXC-5 equipment, which is a portable facsimile system that transmits graphic material. The equipment operates from 22-30-volt batteries in the field and can be used in fixed stations with auxiliary power supplies. In addition to the AM signal, an audio frequency shift (AFS) signal is generated. The AM carrier is 2400 cycles. The AFS is between 1500 and 2300 cycles. Transmission is either over phone lines or by radio.

Fig. 6 shows an amplifier for a baseband photomultiplier. The lamps built into the control elements are incandescent, with filaments made extremely small for maximum speed of response. ■ ■



6. **Photomultiplier facsimile amplifier** incorporates the emitter-sensor to improve the speed of response.