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May 19, 1964

An Automatic Gain Control for Photomultiplier Tubes*

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ABSTRACT

When using a photomultiplier to scan photographs of bubble chamber tracks or other dark signals on a light background, the output signal one obtains depends strongly on the intensity of the background. In this paper we describe and analyze an automatic-gain-control circuit that helps to remove this dependency. The circuit is both simple and transistorized. Furthermore, it can adjust its gain within microseconds to a large increase in light background.

INTRODUCTION

This paper describes a technique for automatically adjusting the gain of a photomultiplier (PM) tube as a function of background-light level. The method described involves generating a voltage related to background-light level and applying this voltage to the last dynode of the tube through a negative-feedback circuit. When a PM tube is used to monitor dark lines on light background, the following advantages are gained:

- a. The amplitude of the output signal tends to depend only on the opacity of the line and not on variations in light background or PM supply voltage.
- b. The circuit tends to establish a fixed dc reference for light background as well as for absolute dark.

These advantages are demonstrated in Fig. 1, which shows some scans of hydrogen bubble chamber film (black bubble tracks on a light background). Parts (a) and (b) of Fig. 1 were taken without automatic gain control (AGC), whereas parts (c) and (d) were taken with AGC. The light level for the lower traces was $1/20$ of that for the upper traces. The circuit that performed this gain control is discussed below.

PRINCIPLES OF OPERATION

The PM tube used in these studies was an RCA 6199. Figure 2 shows output anode current as a function of light flux at the photocathode for such a tube. In this figure, last-dynode to anode voltage is the running parameter and the slope of each curve represents the PM-tube gain for that particular dynode voltage. The voltages on the other dynodes were set by a standard resistor string. Figure 3 shows the gain of the PM tube as a function of dynode voltage. Most of the gain control occurs with the dynode voltage between +1.25 and -3 volts with respect to the anode.

In order to use these characteristics we constructed the circuit of Fig. 4 which is shown in block diagram form in Fig. 5. The input transistor of this circuit has a low input impedance so that the dynode-to-anode voltage can be set independent of anode current. Resistor R_1 adjusts the loop gain and R_2 and R_3 set the dc level. Capacitor C_2 , resistor R_4 , and transistor T_2 comprise a peak detector and discharge circuit. Capacitor C_2 can charge positively very quickly, thus allowing the gain to decrease quickly with increasing light background. However, when the signal tends negatively (a dark signal) the base-emitter junction of T_2 reverse biases and C_2 stores a voltage related to the light background. If the signal remains relatively dark for a duration of many normal track widths, the capacitor voltage becomes more negative (increasing the gain) through R_4 , until the base-emitter junction of T_2 becomes forward biased once more. In summary, the action of the peak detector is:

- a. In response to increasing light, to change the gain of the PM tube very quickly, and
- b. In response to decreasing light, to change the gain of the PM tube slowly. The object here is to have the gain not change so quickly that the track signals are distorted and yet have it change quickly enough to follow the background variations. This presupposes that the signal information is of higher frequency than the background variation.

The output of the peak detector is emitter-followed in order to provide a low impedance source to drive the dynode.

Although the output of the AGC loop is v_0 (Fig. 4), performance can be further improved by taking the difference between that voltage and the dynode control voltage. This is accomplished by the final differential amplifier, which further eliminates baseline variations. The performance of this

circuit is illustrated in Fig. 1. Figure 1(a) and (b) shows the open-loop output with a peak-to-peak anode current of $34 \mu\text{A}$ and $1.7 \mu\text{A}$, respectively, and a background current of $50 \mu\text{A}$ and $2.5 \mu\text{A}$. The closed-loop output for the same light levels is shown in Fig. 1(c) and (d).

ANALYSIS OF THE CIRCUIT

We used the model of Fig. 5 to help us analyze the circuit. Some of the assumptions inherent in the model are:

- a. There is a single dominant pole, T_1 , in the forward loop.
- b. The diode in the peak detector is an ideal switch.
- c. The PM-tube gain is linearly related to dynode voltage.
- d. When the light flux equals zero, $i_1 = 0$; when the light flux increases, i_1 becomes more negative.

In this model i_1 corresponds to the current of the last dynode, i_2 to the anode current, y to the multiplication of the last dynode; and v_3 is the last-dynode voltage minus a constant. The constant is due to the tube having zero gain when the dynode voltage equals 1.25 V with respect to the anode.

Figure 5 shows that this circuit has two modes of operation. When $v_0 > v_3$ the circuit operates in a closed-loop mode, but when $v_3 > v_0$ the loop is opened.

Case 1, $v_0 > v_3$

We first consider the closed-loop operation ($v_0 > v_3$).

$$T_1 \frac{dv_0}{dt} + v_0 + A i_2 = 0 \quad (1)$$

and

$$T_2 \frac{dv_3}{dt} + v_3 = a v_0 - \beta E \quad (2)$$

where

$$\alpha = \frac{R_y}{R_D + R_y}, \quad \beta = \frac{R_D}{R_D + R_y}, \quad \text{and} \quad T_2 = \frac{R_D R_y}{R_D + R_y} C_2.$$

The variation of gain with dynode voltage is expressed by

$$y + K v_3 - a = 0 \quad (3)$$

where a is the maximum amount of multiplication occurring at the last dynode, K is the change in multiplication per voltage change on the last dynode, v_3 is the voltage on the last dynode minus a constant, and y is the multiplication resulting from the action of the feedback circuit.

With the aid of one more expression

$$i_1 y - i_2 = 0, \quad (4)$$

we may write the differential equation for this circuit as

$$\begin{aligned} \frac{d^2 v_0}{dt^2} T_1 T_2 + \frac{dv_0}{dt} \left[T_2 + T_1 - \frac{T_1 T_2}{i_1} \frac{di_1}{dt} \right] \\ + v_0 \left(1 - \frac{T_2}{i_1} \frac{di_1}{dt} - aAK i_1 \right) + aA i_1 + AK\beta E i_1 = 0. \end{aligned} \quad (5)$$

Since this expression contains the product of the input and output and their derivatives, it cannot be solved for a general input. The solution for a specified input is difficult because of time-varying coefficients that depend on the input. We have, therefore, simplified our analysis of the closed-loop operation by analyzing only the response to a steady-state dc input and by discussing the qualitative effects of the time constants.

If we assume that R_y is much greater than R_D , and that $\alpha = 1$ and $\beta = 0$, and if we consider the response to a steady-state dc input, we find that

$$v_0 = - \frac{i_1 aA}{1 - i_1 AK} \quad \text{for } i_1 \leq 0. \quad (6)$$

Figure 6 shows v_0 as a function of $i_1 A$ for a PM tube that has $a = 4$ and $K = 1 \text{ volt}^{-1}$. This figure shows how well the circuit regulates the output current of the PM tube as a function of background-light level (i_1 is proportional to light flux). The percent dc regulation is precisely the same as the percent gain control. If we make $T_1 = T_2 = 0$, then Fig. 6 shows the time response to a negative ramp (the $i_1 A$ axis being replaced by a time axis).

We now discuss the qualitative effects of T_1 and T_2 not equaling zero. If T_2 is not equal to zero and there is a negative step at the input, then a disturbance will appear at the output and the gain adjustment will be delayed. After several time constants have passed, the output will decay to its proper value. If T_1 is not equal to zero, the effect is more complicated. A negative step input would tend to cause an exponential output. This output, however, is continually readjusting the gain and the output will therefore be something less than exponential.

Case 2, $v_3 > v_0$

If v_3 is greater than v_0 , the loop is opened. In analyzing this mode, we assumed that i_1 is a dark-going (positive) ramp

$$i_1 = h + gt \quad (7)$$

and that v_3 is also a ramp

$$v_3 = c - bt. \quad (8)$$

The v_3 ramp is generated by the current source $[(E - v_3)/R_4]$ charging the capacitor C_2 .

The open-loop-ramp response ($T_1 = 0$) is given by

$$v_0 = i_1 AK v_3 - i_1 aA. \quad (9)$$

Substituting (7) and (8) in (9), we obtain

$$v_0 = -AK bgt^2 + t [AK (gc - bh) - aAg] + AKhc - aAh. \quad (10)$$

From Eq. (10), the open-loop response to a dark-going ramp is a section of a parabola.

By differentiating Eq. (10) and setting the derivative equal to zero, we find that the maximum of the parabola occurs at time

$$t_{\max} = \frac{a}{2Kb(hKA - 1)} - \frac{h}{2g}. \quad (11)$$

Since h is a negative number, $t_{\max}$ will typically be a negative number, provided that the slope of the ramp is not too small. We will see later that for small slopes the loop will be closed even though the ramp is tending toward dark. For a sufficiently steep ramp the parabola will appear as in Fig. 7 and the output will be equal to that part of the parabola for which $t \geq 0$. The more negative $t_{\max}$ is, the more linear will be the output.

Conditions for the Loop Being Closed

It is of interest to know for which class of inputs the loop is closed and for which class it is open. In this discussion we consider a ramp input only and we establish conditions for the loop being closed as a function of the slope of the ramp and value of the ramp at $t = 0$. If the loop is closed when the dark-going ramp begins, then the output voltage, v_0 , will be negative going and will tend to make the loop open. In contrast, the ramp generated by the $-E$ volt source operating through R_4 will tend to keep the loop closed. Whether the loop will open or stay closed depends upon whether the slope of the output parabola

(assuming the loop is opened) is less than the slope of the ramp generated by the $-E$ volt supply,

$$\left(\frac{dv_0}{dt}\right)_{t=0} = AK(gc - bh) - aAg < b. \quad (12)$$

Solving this equation, we find that the condition for the loop being opened is

$$g \leq \frac{h^2 AK^2 b}{a} - \frac{b}{aA}.$$

This is a parabola in the g - h plane (Fig. 8). For practical applications, when $h > -1/AK$ the loop will stay closed for dc inputs and even for positive-going ramps of moderate slope.

EXPERIMENTAL RESULTS

In order to see how well our theory agreed with practice we observed the regulation of i_2 as a function of i_1 . The experimental and calculated [Eq. (6)] results are shown in Fig. 9. In these calculations we measured $A = 2v/\mu A$ and assumed $K = 1 \text{ volt}^{-1}$ and $a = 2.3$. The results seem to support the theory.

When we made the dynode more than 1.25 volts positive with respect to the anode, the anode current reversed phase and the circuit, of course, failed to function properly. We do not know the cause of this, but we speculate that perhaps the anode becomes a secondary emitter; the electrons emitted from it going to the last dynode.

CONCLUSION

We have described a simple method of controlling the gain of a photomultiplier tube as a function of background-light level. The method used is much simpler than controlling the high-voltage supply and this method does

regulate variations in both the PM-supply voltage and light background. The circuit also has the advantage of being able to respond within microseconds or less to an increase in light input.

We sensed the background-light level by using a peak detector with a controlled rate of discharge. One could use a second photomultiplier to sense the background, but this technique is not discussed or analyzed.

The regulation of the device is very effective for high currents in the last dynode. The regulation remains good for lower currents, but for quite-low currents (typically $0.5 \mu\text{A}$) the regulation becomes poor. The higher the loop gain, the better the regulation at low currents.

With the background-sensing technique described in this paper, it is important that the background variations have frequency components lower than the signal.

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FOOTNOTES

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FIGURE CAPTIONS

Fig. 1. Amplifier output with and without AGC for two different light backgrounds: (a) and (b) taken without AGC to same scale, (c) and (d) taken with AGC to same scale.

Fig. 2. Anode current versus light input, with last dynode-to-anode voltage as a running parameter.

Fig. 3. PM gain as a function of last-dynode to anode voltage. The dashed line indicates the linear gain relationship used in the model.

Fig. 4. Signal amplifier with automatic gain control.

Fig. 5. Model for AGC circuit; i_1 represents last dynode current and i_2 represents anode current. Except for a dc shift, v_0 and v_3 represent the output and dynode-to-anode voltages; y is the multiplication of the last dynode; a is the maximum gain of the last dynode; and K is the rate of change of gain with dynode voltage.

Fig. 6. The output voltage as a function of input current times gain. The curve asymptotically approaches 4. If the i_1 A axis is replaced by a time axis, this is the time response of the circuit to an input ramp.

Fig. 7. Typical open-loop ramp response.

Fig. 8. The division of the g - h plane into closed-loop and open-loop regions for a ramp input.

Fig. 9. Regulation of i_2 in theory and practice.

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Fig. 1.

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Fig. 2.

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Fig. 3.

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Fig. 4.

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Fig. 5.

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Fig. 6.

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Fig. 7.

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Fig. 8.

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Fig. 9.

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