

CONSTRUCTION AND OPERATION OF A PHOTOELECTRIC
FLICKER PHOTOMETER

by

MALCOLM LLEWELLYN ALSOP

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CONSTRUCTION AND OPERATION OF A PHOTOELECTRIC FLICKER PHOTOMETER

INTRODUCTION

Various types of photometric devices have been constructed for comparing illumination intensities of light sources, but they may be conveniently divided into four classes: (1) those dependent upon visual acuity, which compare light sources by the ability of the eye to identify objects illuminated by them; (2) those in which an equality of brightness is produced on two surfaces, as in the Bunsen photometer; (3) those using the contrast method as in the Lummer-Brodhun photometer; and (4) those using the flicker method where two lights are alternately presented to the eye.

The photoelectric flicker photometer uses the flicker principle in connection with the photoelectric cell, in an attempt to secure a sensitive photometer by the amplification of electrical effects. The photometer is constructed to flicker two lights alternately upon a photoelectric cell, and to produce a flicker of a sinusoidal character. This

type of flicker upon a photoelectric cell produces electrical impulses of a similar character, which are suitable for amplification, for phones, and for a vibrating galvanometer.

The experiments with the photoelectric flicker photometer may be divided into three phases: (1) that dealing with the direct visual sensation from heterochromatic light; (2) the auditory effect with phones, in connection with an amplifier and photoelectric cell; (3) and the balancing of lights with the photoelectric cell, amplifier, and vibrating galvanometer.

CONSTRUCTION

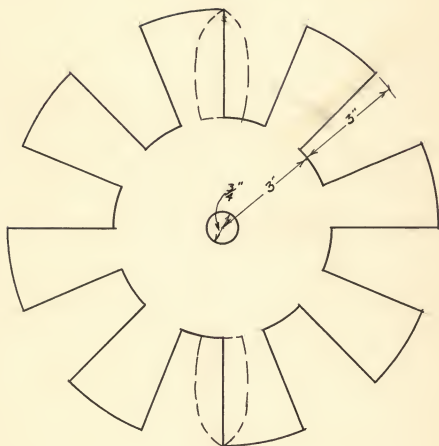
Flicker photometers have been constructed that differ somewhat in principle. Some throw an interrupted light upon a steady illuminated field to secure certain heterochromatic effects. Others throw a flickering light upon a screen that is not illuminated otherwise. While most flicker photometers follow the latter plan, the contour of the flicker cycle may differ widely. In some, the light enters abruptly and ceases in a like manner before it is replaced by another light. In others, the contour is less abrupt, but there is no actual mixing of the radiant streams. In the construction of the photoelectric flicker photometer it was desired

to mix the light from each side of the screen; to have one at its maximum while the other is extinct; and to have a sinusoidal contour of the cycle.

Two discs, twelve inches in diameter, were cut from sheet brass one-eighth of an inch thick. Eight equal sectors were cut radially three inches deep into each disc so that the teeth formed were geometrically congruent to the spatial sectors. The light interrupters were then mounted on a shaft twelve inches apart, and by use of a cathetometer they were aligned so that the projection of the teeth of one disc coincided with the apertures of the other. Figure 1 shows one of the sector discs, or light interrupters, and also the shape and size of the apertures in comparison with the sectors.

The method for plotting the size and shape of the apertures, so as to give a sinusoidal contour of the cycle, had been previously worked out by Mr. E. R. Lyon ^{1/}, Associate Professor of Physics, Kansas State College, while he was directing Mr. V. V. Cool in a research on the Electrostatic Inductor Alternator, in 1930. The simplest

1. E. R. Lyon, Manuscript, August 12, 1930.



*Light Interrupter
Figure 1*

case would be as shown in Figure 2, where a rectangular tooth with length D is moving with uniform velocity across the positive area of a sine curve having the same base D . Let the area under the curve be the aperture. Then the area of coincidence S_1 may be expressed by the following equations:

$$S_1 = \int z dx, \quad z = h \sin \pi x/D \quad (1)$$

$$S_1 = h \int_0^x \sin \pi z/D dx = (hD/\pi) (1 - \cos \pi x/D) \quad (2)$$

Substituting the supplement of $\pi x/D$.

$$S_1 = (hD/\pi) (1 + \cos \pi x'/D). \quad (3)$$

Substituting the complement of $\pi x/D$.

$$S_1 = (hD/\pi) (1 + \sin \pi x''/D) \quad (4)$$

If these equations hold true throughout the cycle, they should be the same when the trailing edge arrives at the present position of the leading edge, and the area of coincidence becomes S_2 . Then

$$x_2' = x \text{ in Figure 2, and } x_1' = x' \text{ in Figure 2.}$$

That is, x_2' will be the distance of the leading edge to the right of the aperture, and x_1' will be the base of the area of coincidence.

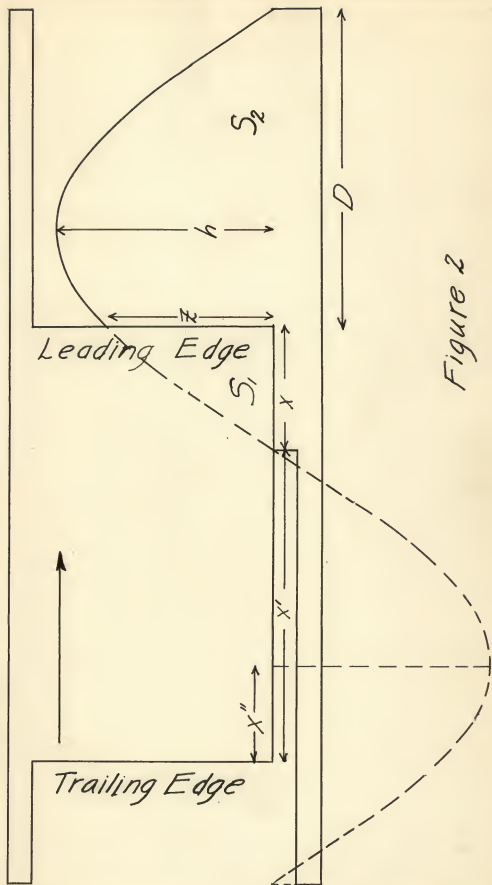


Figure 2

$$S_2 = 2hD/\pi - S_1 = 2hD/\pi - (hD/\pi)(1 - \cos \pi x_2'/D). \quad (4')$$

$$S_2 = hD/\pi (1 + \cos \pi x_2'/D) = (hD/\pi)(1 + \cos \pi x/D). \quad (5)$$

But, by equation (3)

$$S_1 = (hD/\pi)(1 + \cos \pi x'/D) = (hD/\pi)(1 + \cos \pi x_1'/D). \quad (6)$$

Therefore, if S is the area of coincidence of the tooth and aperture,

$$S = (hD/\pi)(1 + \cos \pi x'/D) = (hD/\pi)(1 - \cos \pi x/D),$$

$$S = (hD/\pi)(1 + \sin \pi x''/D). \quad (7)$$

A simple application of the above case would be to wrap Figure 2 around a cylinder with a circumference of $2D$, or some multiple of $2D$, and rotate the cylinder about its central axis that would be parallel to z . In such a case, the shape of the aperture would be governed by the equation in (1).

$$z = h \sin \pi x/D \quad (8)$$

Such an equation leads to equation (7) which is of sinusoidal type. But with a rotating sector disc, the relative motion of tooth and aperture is perpendicular to the axis of rotation, and the design of the heel-shaped aperture shown in Figure 3 would be governed by the following equations.

$$ds = \frac{1}{2}(r+y)(r+y)d\theta - \frac{1}{2}r \cdot r d\theta = ryd\theta + \frac{1}{2}y^2d\theta \quad (9)$$

$$\text{But } d\theta = dx/r \quad (10)$$

$$ds = (y + y^2/2r)dx \quad (11)$$

By equation (1),

$$ds = zdx, \quad z = h \sin \pi x/D \quad (12)$$

$$ds = h \sin \pi x/D dx \quad (13)$$

By equation (11) and (13),

$$y + y^2/2r = h \sin \pi x/D \quad (14)$$

$$y^2 + 2ry + r^2 = r^2 + 2rh \sin \pi x/D \quad (15)$$

$$y = \sqrt{r^2 + 2rh \sin \pi x/D} - r \quad (16)$$

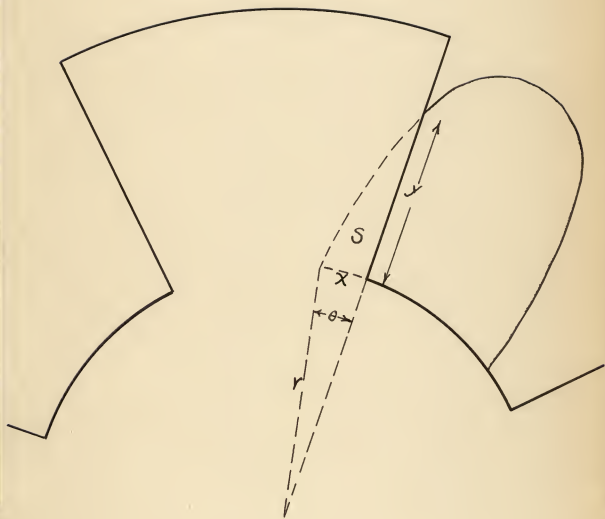
If p is the number of cycles per revolution of the disc, and θ the angle of revolution,

$$D = \pi r/p, \quad x = r\theta, \quad \text{and } \pi x/D = p\theta \quad (17)$$

$$y = \sqrt{r^2 + 2hr \sin p\theta} - r \quad (18)$$

In the above equations, z can assume only positive values as shown in Figure 2, but the sinusoidal variation of z holds true throughout the cycle, as shown in equations (4), (5), and (6), when the phase was changed 180° .

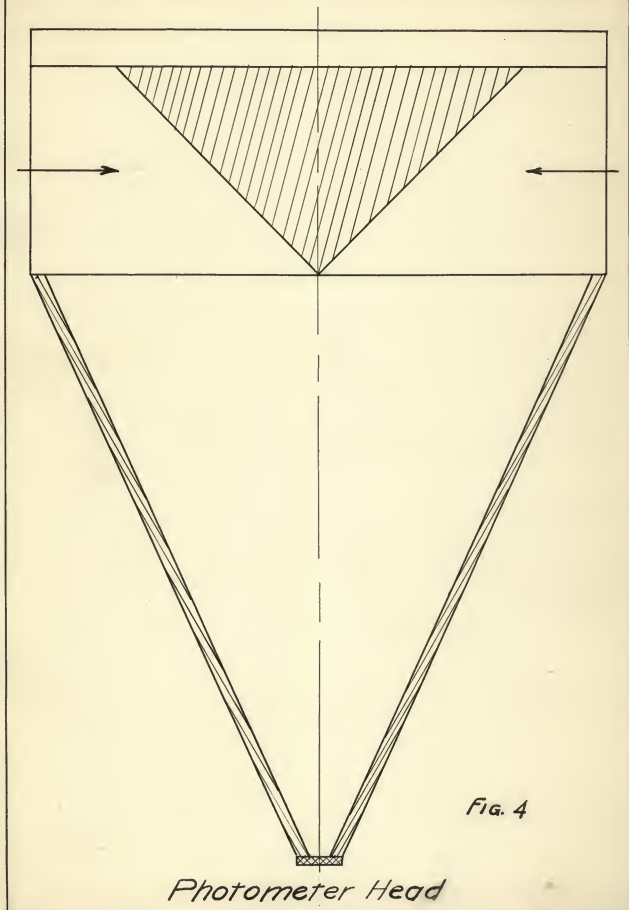
Figure 3 shows the shape of the aperture when plotted for a four blade sector disc, and Figure 1 is the design when plotted for an eight blade sector disc. The

*Fig. 3*

latter was used in the construction of this photometer, for it was desired to have a frequency well up into the audible range without excessive rotational speed.

In constructing the photometer head, as shown in Figure 4, an effort was made to mix the light rays from two sources as much as possible without a great amount of absorption from the reflecting surfaces. The apertures were of ground glass to give diffused transmission. The wedge in the center was cast from plaster of Paris, and this gave further mixing by diffused reflection. The walls of the funnel were coated with zinc oxide paint, which has a diffuse reflecting power of approximately 70 per cent. To give still further mixing of the light rays, ground glass was placed over the end of the funnel. The photometer head fitted closely between the two light interrupters so as to allow little chance for diffraction around the edge of the sectors before the light entered the aperture. With the photometer head in place, the apertures held the same angular position about the axis of rotation, but the light interrupters, mounted on one shaft, held a phase relation of π .

The shaft was of mild steel, turned down on each end to make a shoulder against which the sector disc was securely clamped. The boxings were cast from brass, and



placed between the interrupters and the ends of the shaft. Supplying the boxings with shims permitted adjustment and close fitting to prevent vibration. The frame was made of $1\frac{3}{4}$ inch oak, glued and securely screwed together. This gave weight and rigidity that held the photometer steady at high speeds. The whole photometer was painted a dull black, including motors, shaft, interrupters, frame, and the outside of the photometer head. This lessened the possibility of reflected light interfering with tests. The inside of the photometer head was coated with zinc oxide paint to give diffused reflection after the light entered the apertures.

The dimensions for the interrupters and the sectors are shown in Figure 1. The length of the apertures is the same as the depth of the spatial sectors, and the shape of the apertures is governed by equation (18) with

$$r = 3", h = 4.3", p = 8 \text{ and } \theta = 0^\circ \text{ to } 22\frac{1}{2}^\circ.$$

The dimensions for the frame, shaft, boxings and motor couplings are shown in Figure 5.

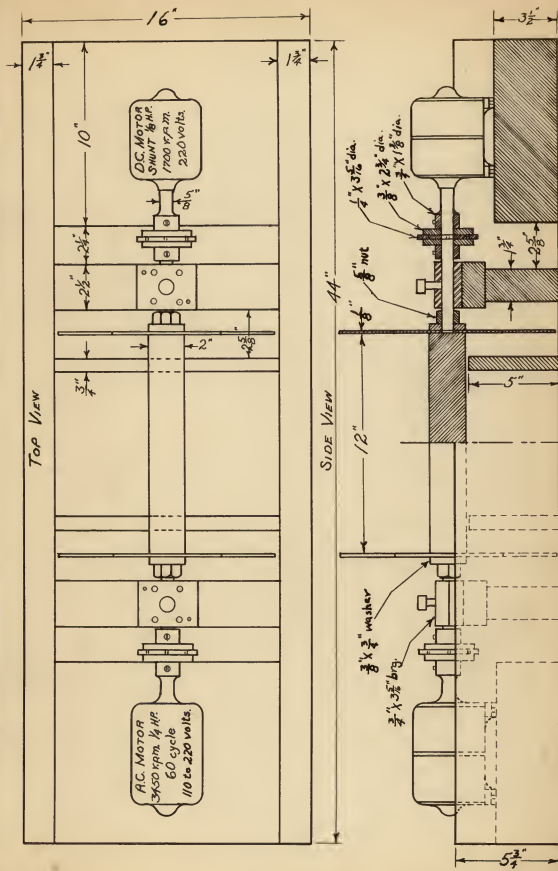


FIG. 5

PHOTOMETER CHASSIS

SCALE 3/16" = 1"

THE DRIVING POWER

To give a wide range of frequencies, two types of electric motors were used: (1) a slow speed (1700 r.p.m.) D.C. motor of $1/8$ H.P., and (2) a high speed motor (3400 r.p.m.) A.C. motor of $1/4$ H.P., one motor was coupled directly to each end of the driving shaft by means of two flanged collars pinned to a leather coupling. The leather coupling served to eliminate vibration and strain in case the motors were not exactly aligned with the drive shaft. Each motor was mounted on a sliding base to permit disengagement when it was not in use. The slow speed motor proved to be fast enough for practically all the experiments, and considerably safer when taking observations at close range. The D.C. motor was of a shunt type, so that speeds less than 1700 r.p.m. could be secured by rheostat control of the armature circuit. A variable speed could be secured by letting one motor act as an electrical brake upon the other, but such a procedure continued for any length of time would result in overheating the armature, especially the one driven in the opposite direction to the applied electrical torque.

VISUAL EXPERIMENT WITH FILTERED LIGHT

The first experiment consisted in observing the sensation of two colored lights when mixed by the flicker photometer, with a sinusoidal contour of the flicker, and the colors alternating with a phase relation of π . Some difficulty was met in securing a light source strong enough to be filtered, and still reach the end of the funnel with much intensity. By use of projecting lanterns 50 cm. from the apertures, fairly good results were obtained. With a projecting lantern on each side of the photometer, and a different colored glass filter directly in front of each lantern, the results were observed on the ground glass at the end of the funnel. The frequency of alternation was far above the vanishing-flicker frequency, and the result was similar to that of a revolving color disc. The results are tabulated on the following page. It will be noticed that the mixing of the complementary colors, red and green, produced white, as would be the result with a revolving disc having these colors. But the result of transmission of light through the same two filters, is dark amber or dull red, which would be expected by mixing red and green pigments. It is probably safe to assume that as long as the

frequency is above the vanishing-flicker frequency the contour of the flicker will not affect, to much extent, the resulting color. In a series of experiments by Mr. M. Luckiesh ^{2/}, he shows that the contour of flicker does affect the vanishing-flicker frequency. Quoting from Mr. Luckiesh he says:

"The effect of the contour of flicker was also studied to ascertain the possibility of the character of the flicker in influencing results obtained by means of a flicker photometer. Four contours of flickers were studied, in each case the minimum brightness being zero, and the maximum values equal. In these cases the critical or vanishing-flicker frequencies were found to be quite different throughout a wide range of illumination."

Result of Color Mixing and of Double Filtering

Color of Filters	Result by Mixing	Result by Double Filtering
Deep violet and amber	Light purple	Very dark red
Red and green	White	Dark amber
Red and dark blue	Lavender	Very dark red
Red and amber	Light pink	Red

Red and violet	Lavender	Very dark red
Red and light blue	Pink	Dark red
Red and light green	White	Dark red
Red and light yellow	Very light pink	Red
Red and yellow	Very light pink	Red
Green and amber	Light amber	Light green
Green and dark blue	Light blue	Dark green
Green and violet	Light blue	Black
Green and light blue	Pale green	Dark green
Green and yellow	Pale green	Light green

Another interesting experiment performed by Mr. Luckiesh in his work on chromatic photometry was to compare two sources of light of the same color but differing in spectral character. For instance, two yellows, one a pure yellow and the other a subjective yellow composed of green and red, were compared with a flicker photometer. He found these colors, and other like colors differing in spectral composition, to balance the same within 1 per cent as when compared by the direct comparison method. This showed that, within the limits of experimental error, the rate of growth

and decay of color sensation did not affect the results of the flicker photometer.

THE PHOTOELECTRIC CELL AND PHONES

A photoelectric cell was first placed at the end of the funnel shown in Figure 4, but it was found that the cell received more light and gave better results when placed in the photometer head, directly in front of the plaster of Paris wedge. With light entering each aperture of the photometer while the interrupters were in motion, the cell received a modulated light from each side with a phase difference of π . Professor Lyon ³/₃, my major instructor, continues to show in his manuscript that the electrical effect upon the photoelectric cell is of a sinusoidal character. Returning to equation (7),

$$S = (hD/\pi)(1 + \cos \pi x^1/D) = (hD/\pi)(1 - \cos \pi x/D)$$

$$S = (hD/\pi)(1 + \sin \pi x^n/D). \quad (19)$$

$$\text{Since } D = \pi r/p, \text{ and } x = r \theta, \quad (20)$$

we may write the above equations in the following form:

3. E. R. Lyon, Electrostatic Inductor Alternator. Proceedings of Kansas Academy of Science, 1931.

$$\begin{aligned}
 S &= (hr/p)(1+\cos p \theta') = (hr/p)(1-\cos p \theta) \\
 S &= (hr/p)(1+\sin p \theta'') \quad (21)
 \end{aligned}$$

The aperture has an area of $2S_0$,

$$hr/p = hD/\pi = S_0. \quad (22)$$

$$\begin{aligned}
 S &= S_0 (1+\cos p \theta) = S_0 (1-\cos p \theta) = \\
 &S_0 (1+\sin p \theta''). \quad (23)
 \end{aligned}$$

$$dS/d\theta = pS_0 \sin p \theta. \quad (24)$$

It may be shown that S as a function of an interval of time t , is also of a sinusoidal character. There is a frequency f , a number of revolutions per second n , a period of revolution $1/n$, and a period of action $1/f$ such that, with a uniform rotational speed,

$$x/2D = t/(1/f), \quad \theta = 2\pi nt, \quad p\theta = 2\pi pnt \quad (25)$$

By substituting in equation (23),

$$S = S_0(1 - \cos 2\pi ft), \quad f = pn, \quad (26)$$

$$dS/dt = 2\pi S_0 f \sin 2\pi ft. \quad (27)$$

Figure 3 shows S as the area of coincidence between a tooth and aperture, in which case the quantity of light Q that enters the aperture will be proportional to $(2S_0 - S)$. But we may as well consider S as the area of coincidence between a spatial sector and aperture, with no change in the above equations, for the spatial sectors are geometrically

congruent with the teeth. Then with

$$k = \text{constant}, \quad Q = kS, \quad Q_0 = kS_0. \quad (28)$$

By equation (26),

$$Q = Q_0(1 - \cos 2\pi ft), \quad (29)$$

$$dQ/dt = 2\pi Q_0 f \sin 2\pi ft. \quad (30)$$

The electrical effect of the light upon a photoelectric cell is proportional to the intensity, within certain limits. Therefore,

$$E = KQ, \quad E_0 = KQ_0 \quad (31)$$

$$E = E_0(1 - \cos 2\pi ft) \quad (32)$$

$$dE/dt = 2\pi E_0 f \sin 2\pi ft. \quad (33)$$

For any particular position of the light source, and a constant speed of the motor, the above equation may be more simply expressed as

$$dE/dt = k' \sin k'' t \quad (34)$$

With electrical impulses of a sinusoidal character, a single fundamental tone should be produced by use of phones. It was found that the output of the photoelectric cell was not sufficient to operate phones directly. But after two stages of amplification, a tone was produced that corresponded to the frequency of the interrupters. To study the nature of the tone, it was found desirable to eliminate any

null effect by extinguishing the light on one side of the photometer head, and having a strong light on the other side. This gave a clear tone above other electrical disturbances that came through the amplifier. With the aperture shaped according to the plot of equation (18); the tone, as detected by the ear, was only that of the fundamental, which roughly indicated that the alternating current in the phones was of a sinusoidal character. On the other hand, when the shape of the aperture was modified by partly covering it with a straight edge placed radially to the axis of the sector disc, harmonics became prominent and the fundamental tone could be made to disappear. Just as a combination of harmonics produces a series of abrupt waves, the process was reversed whereby a series of abrupt electrical impulses produced harmonics. The most abrupt change in the quantity of light entering the photoelectric cell could be obtained by having dS/dt pass instantaneously from maximum to zero, or from zero to maximum. Equation (27) shows that dS/dt is at its maximum when the sine is maximum, or at the position of $\pi/2$; and it was when the straight edge stop was held at this position on the aperture that the harmonics became most prominent.

In testing the machine for possibilities of measuring light sources, two lamps of equal candle power were used. With a light on each side of the photometer head, the illumination upon each aperture was regulated by adjusting the distance of each lamp from the photometer head. The two lights were flickered sinusoidally upon the photoelectric cell, with the flickering lights having a phase relation of π . This gave a complete null effect when the illumination upon each aperture was the same. The difficulty lay in detecting a slight unbalanced condition when the illumination upon one aperture was slightly increased or decreased. Motor commutation disturbances and other electrical effects were carried to the phones and prevented the detection of weak tones that may have been present with a slightly unbalanced condition. With proper shielding and high amplification it is possible that a fairly accurate balance could be secured by use of phones. Some improvement was made by covering the motor with a metal shield and grounding it, and by placing the motor some distance from the amplifier and leads. However, enough disturbances remained to prevent having a very sensitive photometer by the use of phones.

TESTS WITH THE VIBRATING GALVANOMETER

In connection with the vibrating galvanometer, the photometer gave better results in comparing light intensities, than when used with phones. Since the vibrating galvanometer does not respond, to any extent, to electrical frequencies not synchronized with its natural vibrating frequency, foreign electrical disturbances were slight. The galvanometer was connected directly to the output of a two stage push pull amplifier, and then adjusted to the flicker frequency of the photometer. By rheostat control, the flicker frequency could be varied from fifty to two hundred and twenty-five cycles per second, but the galvanometer proved to be the most sensitive in the range of about one hundred cycles per second. A difficult task was encountered in keeping the flicker frequency synchronized with the natural frequency of the galvanometer, for a very slight change in the speed of the interrupters would cause the galvanometer to beat, or to cease vibrating entirely. With a brush motor and rheostat speed control, the frequency of the flicker could not be held exactly constant for any great length of time. Nevertheless, an unbalanced illumination of 10 per cent could be picked up by the galvanometer.

In testing the accuracy of the photometer, the same light sources were used as were used in connection with the head phones. One light was placed on each side of the photometer head and 100 cm. away. With each light source of the same candle power, the same illumination was thrown upon each aperture. Under this condition there would be no vibration of the galvanometer, whether synchronized or not. So, to adjust the galvanometer to the flicker frequency, one light was extinguished. This very unbalanced condition gave a forced vibration to the galvanometer, but this could easily be detected from the synchronized vibration because of the wide difference in their amplitude. When the galvanometer was adjusted to the flicker frequency the light was immediately turned on, and the balanced condition brought the galvanometer to rest. The question might arise as to whether a balanced condition or a loss of synchronism caused the vibration to cease; but when the vibration returned upon extinguishing the light again, it may be concluded that there was no loss of synchronism. If either light was changed less than 5 cm. from the 100 cm. mark there appeared to be no change in the result. That is, the galvanometer still indicated a balanced condition. A change of 5 cm. or more of either lamp caused a slight vibration when

synchronized. Since the illumination upon the aperture varies inversely as the square of the distance, the difference of illumination from 100 cm. to 105 cm. may be expressed as follows:

$$\text{c.p.}/100^2 - \text{c.p.}/105^2 = 1025 \text{ c.p.}/11025000.$$

The percentage change from the balanced condition is

$$1025 \text{ c.p.}/11025000 \div \text{c.p.}/100^2 = 9.3\%$$

This is the least unbalanced condition that could be detected with any certainty, but an unbalanced flicker greater than 10 per cent could be readily observed.

CONCLUSION

While this photometer, as constructed and operated, does not prove very sensitive in comparing light intensities, it gives possibilities of a photoelectric flicker photometer that may be accurate when used with high amplification. A four sector disc, instead of an eight sector disc, would permit a larger aperture, and hence more light could enter the photometer head. This would give more current through the photoelectric cell in case of a slight unbalanced flicker. This small current, or E.S.F., may be highly amplified and the output connected to a sensitive

galvanometer. It seems probable that the vibrating galvanometer will prove more suitable than phones in connection with high amplifications, for outside electrical disturbances picked up by the amplifier will have little effect upon the galvanometer unless synchronized with it. Furthermore, if a Campbell type of vibrating galvanometer is used, the result may be recorded on a moving film and examined more closely, or measured in amplitude more accurately.

The motor for driving the interrupters should be of a synchronous type, operated by an alternating current of as near constant frequency as possible. With the galvanometer once synchronized with a constant flicker frequency, it would remain so for closer observation and more accurate measurement.

If the photoelectric cell with a quartz window is used, together with quartz apertures, or open apertures, the photometer may be used to measure ultra-violet rays, or to compare infra-red intensities. Lights differing in spectral character may be balanced or compared with a standard lamp. Other possibilities of the flicker photometer are discussed by Prof. E. R. Lyon in his manuscript on "A Photoelectric Flicker Photometer."

ACKNOWLEDGMENT

Grateful acknowledgment is due to Prof. E. P. Lyon, the writer's major instructor, who conceived the idea of the photoelectric flicker photometer, gave guidance in its construction and operation, and permitted the use of his drawings and equations in the preparation of this thesis.

The writer is also deeply indebted to Prof. E. V. Floyd, who gave continual assistance and guidance throughout the construction of this machine, and gave much of his time in shaping some of the parts.

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