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" To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science."

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THE SILVER JUBILEE

A 25th Anniversary is an occasion celebrated in every walk of life. Measured in terms of an Institution or Corporation the achievement of a Silver Jubilee may be regarded only as a beginning—a period of surmounting initial obstacles and laying the foundation of tradition and status for the future. Whilst therefore, the membership can look forward to greater achievements and progress, the Institution's Silver Jubilee will be honoured in the knowledge that much has been accomplished.

The very first meeting of the Institution was held on October 31st, 1925, and the Council is now considering ways in which this anniversary may be celebrated—possibly during the course of next year's Convention. As already announced in the *Journal*, the Convention has been postponed until next year in order to coincide with the Festival of Britain.

When making these arrangements, the Council resolved that the Jubilee should also be marked by honouring a great Scot whose original work laid the foundation of radio science. It is 86 years since James Clerk Maxwell published his mathematical treatise on the possibility of electro-magnetic wave propagation, and in planning for the Institution to have an annual Clerk Maxwell Lecture, the Council feels that it will be appropriate for the first of these Lectures to be given during the Silver Jubilee year.

A Silver Jubilee also justifies some memories and reflections. A short history of the Institution has already been published in successive Year Books and the Lists of Members record the names of many who have assisted in establishing the Institution as we know it to-day; the regular increase in membership is a monument and a tribute to the founders.

Our present-day activities have developed far beyond the original scope of studies which provoked discussion at the initial meetings of the Institution. Difficulties were expected and experienced and not the least of these were the trials of war. Much incentive can be derived from the knowledge that a great part of the Institution's early life and a vital stage of its development were marred by wartime conditions.

Nevertheless, the world wide membership now includes those who practise in almost every sphere of radio engineering activity, throughout Industry, the Services, Government Departments and other research establishments. During the past 25 years the requirements for entry into the profession have gradually taken shape ; in order to meet those needs it has always been essential for the Institution to insist on a high standard of qualification for membership. This has necessitated constant effort in securing opportunity for training commensurate with industrial demand.

To-day, the Institution can claim much credit for securing the training facilities now available to the new entrant to the profession who has ample opportunity to receive adequate instruction and moreover, to choose his " line of country." Thus, there is little excuse for failure to prepare thoroughly for entry to the profession and to qualify for membership of the Institution —factors which cannot fail to be of advantage to the community generally.

It is in this spirit of service that the present membership will take delight in celebrating the Silver Jubilee of the Institution.

MEMBERS OF THE FINANCE COMMITTEE

Space precludes giving in one issue details of all members of the Committee. The following references to the Chairman of the Committee and the Honorary Treasurer recognise the long services of both Members to the Institution.

Born in London, February 1893, **Sydney Ronald Chapman** was educated at the Bedford Modern School where he Matriculated in 1910. Subsequently a student at King's College, London, he obtained his B.Sc. Degree in 1914.

After being commissioned in the Infantry, Mr. Chapman transferred to the Radio Branch of the Royal Flying Corps in 1917. On the termination of hostilities he joined the Edison Swan Lamp Factory at Ponders End before being appointed Scientific Officer in the Department of Scientific and Industrial Research (Radio Research Station). During his eleven years with the Department, his principal work was on direction finding and propagation—the main subject of his thesis for the M.Sc. Degree of the University of London.

In 1934, Mr. Chapman joined the Engineering Research Department of the British Broadcasting Corporation and at the outbreak of the last war rejoined the Royal Air Force as a Radar Officer. He was later appointed Wing Senior Technical Officer. On his release from the R.A.F. he returned to the B.B.C. Research Department.

Elected an Associate Member of the Institution in 1943, Mr. Chapman served on the Finance and Membership Committees before his transfer to Membership in July 1945. In that year he was also elected a member of the General Council and Honorary Treasurer of the Institution. Subsequently he has regularly been re-elected as Honorary Treasurer and in this capacity serves on the Finance Committee and on the General Council.

John Whinfrey Ridgeway was born in Sheffield in February 1903. After leaving school, Mr. Ridgeway studied metallurgy at Sheffield University and, until 1924, was engaged in electro-metallurgical research. He then joined the Metropolitan-Vickers Company as a radio engineer and, in 1929, was appointed assistant to the chief radio engineer in London.

In 1929, Metropolitan-Vickers Electrical Co., Ltd., together with the Edison Swan Electric Co., Ltd., and British Thomson-Houston Co., Ltd., became part of the Associated Electrical Industries, Ltd., and he was appointed Assistant Manager of the Group Radio Division under The Edison Swan name, and was appointed manager in this division in 1940. In 1943, he was appointed a director of the Valve Manufacturing Unit, and later became a director of the Edison Swan Electric Co., Ltd.

During the war he was chairman of the British Radio Valve Manufacturers' Association for five years, and a member of the Council of the Radio Manufacturers' Association. He became a member of the Radio Industry Council in 1943, and for the past two years has been chairman and he is also the chairman of the British Radio Valve Manufacturers' Association again for the current year.

He was appointed an O.B.E. in 1946.

Since his election to full membership of the Institution in November 1943, Mr. Ridgeway has been a most active and energetic member of several committees. He has served on the Professional Purposes and Finance Committees from 1944, until the present day, and was appointed chairman of the latter committee in 1945. He was also a member of the Membership Committee in 1945, and represented the Institution on the Radio Trades Examination Board during 1947.

Mr. Ridgeway has, in addition, served two complete terms as a member of the General Council.

INSTITUTION NOTICES

Honours

The Council offers its congratulations to the following members who were included in His Majesty's Birthday Honours List on June 8th, 1950 :—

Appointed a Commander (Military Division) of the Most Excellent Order of the British Empire :

Group Captain William Thomas MATTHEWS (Member).

Appointed an Officer of the Most Excellent Order of the British Empire :

Richard Percy RICHARDSON (Managing Director, Burndept, Ltd., Erith) (Companion).

Obituary

Council regrets to record the death of Gordon Stanley DIX (Associate) of Southall, Middlesex, at the age of 25 years after a short illness.

Mr. Dix first joined the Institution as a student member in February 1947, and qualified for transfer to the grade of Associate in October of that year. Subsequent to his employment in the Anti-interference department of E.M.I. Sales & Service, Ltd.; Mr. Dix transferred to the Receiver Design Department of Electrical and Musical Instruments, Ltd.

Stockport Councillor

Mr. Edwin Hodson (Associate) was recently elected to the Stockport Borough Council and is in addition a member of four sub-Committees. He was also a candidate for the Ardwick Division of Manchester at the recent General Election. Although unsuccessful, Mr. Hodson intends to contest the seat again at the next General Election.

November 1950 Graduateship Examination

With effect from the November 1950 Graduateship Examination Part I (Physics) is to become one three-hour paper instead of two $1\frac{1}{2}$-hour papers as at present. Candidates will be required to answer six questions, three from each section—(*a*) Heat, Light and Sound ; and (*b*) Electricity and Magnetism.

The Education and Examinations Committee wishes to stress that the syllabus will remain unaltered.

Premiums Awarded by the Institution

Council has under consideration the establishment of a number of further premiums which will recognize original or outstanding papers on specialist subjects. The Institution at present offers seven Premiums as follows :—

The Clerk-Maxwell Premium.

Awarded annually to the author who, in the opinion of the Council, presents the most outstanding paper published in the Institution's Journal during the year. (*Value* 20 *guineas.*)

The Heinrich Hertz Premium.

Awarded annually to the author who, in the opinion of the Council, presents the most outstanding paper dealing with the mathematical or physical aspects of radio, published in the Institution's Journal during the year. (*Value* 20 *guineas.*)

The Louis Sterling Premium.

Awarded annually to the author who, in the opinion of the Council, presents the most outstanding paper on television technique published in the Institution's Journal during the year. (*Value* 15 *guineas.*)

The Marconi Premium.

Awarded annually to the author who, in the opinion of the Council, presents the most outstanding engineering paper published in the Institution's Journal during the year. (*Value* 10 *guineas.*)

The Leslie McMichael Premium.

Awarded annually to the author who, in the opinion of the Council, presents the most outstanding paper on improvements in the technique of broadcast or television reception published in the Institution's Journal during the year. (*Value* 10 *guineas.*)

The Dr. Norman Partridge Memorial Award.

Awarded annually to the author who, in the opinion of the Council, presents the most outstanding paper on improvements in the quality of sound reproduction published in the Institution's Journal during the year. (*Value* 5 *guineas.*)

Students Premium.

Awarded annually by the General Council for the most outstanding paper presented by a registered Student of the Institution. (*Value* 10 *guineas.*)

The Premiums awarded for 1949 will be published in the Annual Report which will appear in the July issue.

AUTOMATIC STABILIZATION OF AMPLIFIER GAIN*

by

A. W. Keen† (*Associate Member*)

SUMMARY

The conventional method of measuring the voltage gain of an amplifier by equating it with the loss introduced by a calibrated attenuator is adapted to provide a continuous and automatic method of accurately defining and maintaining constant amplifier gain. The resultant arrangements are all forms of negative feedback systems and are characterized by high loop gain and the use of a precision attenuator in the β network. Two types are distinguished according to whether the " error " signal representing the discrepancy between the input and attenuated output signals is made self-cancelling by being fed back into the amplifier, as in conventional feedback amplifiers, or used to control the gain of one or more of the amplifying valves, as in A.G.C. systems. Appropriate circuit technique is indicated and suitable applications of the method are briefly described.

1.0. Introduction

1.1. An amplifier valve may be regarded as a device which converts an input voltage change (δe_i) into a corresponding change of output current (δi_o) and the relationship

$$\delta i_o = y_T \, . \, \delta e_i \quad \ldots\ldots (1)$$

defines a " mutual-" or " trans-admittance " operator ($y_T \equiv g_T + ib_T$) which transforms the voltage change in the input mesh into the current change in the output mesh, as illustrated by Fig. 1(*a*).

1.2. The change of current δi_o may be the required form of output; more usually it is desired to develop an output voltage change which is an enlarged copy of the input voltage change; i.e. y_T is required to be a pure scalar ($b_T = o$) of greater than unit magnitude. This is achieved by passing the output current through an impedance (usually the input impedance of a quadripolar coupling network) which should remain substantially constant and of the greatest realizable magnitude over the frequency interval occupied by the signal to be handled. The output voltage

$$\delta e_o = z_o \, . \, \delta i_o \quad \ldots\ldots (2)$$

where z_o ($\equiv y_o^{-1}$) defines an impedance operator which characterizes the inserted load, as shown at (*b*) in Fig. 1.

1.3. It is convenient at this stage to introduce three simplifying restrictions, as follows :—

(i) y_T is independent of the load network into which the valve is operating.

(ii) y_T acts unilaterally from the input mesh to the output mesh.‡

(iii) z_o is independent of the current applied to it (i.e. linear).

Then (i) and (ii) may be combined into

$$y_o \, . \, \delta e_o = y_T \, . \, \delta e_i \quad \ldots\ldots (3)$$

Ideally, y_o, y_T will be constant conductances g_o, g_T respectively, and the quotient g_T/g_o a scalar (μ) which measures the " gain " of the voltage amplifier. For the gain to exceed unity $g_o \ngtr g_T$.

1.4. In practice, g_T, which characterizes the valve, and g_o, which measures the load, may vary in a random manner with time and prevent the gain factor g_T/g_o from remaining constant. For most purposes the variation is insufficient to justify the application of special circuit technique, but in certain cases the normal fluctuation is intolerable and counter-measures must be taken. In general, it may be stated that g_T contributes considerably more than g_o to this variation so that any steps taken to preserve its constancy are more effective than action upon g_o. On the other hand, the stabilities of g_o, g_T need only be made comparable since there is little to be gained in making one considerably more stable than the other. The two quantities differ also in that the magnitude of g_T is easily varied while that of g_o may not be. A third distinction may be made in respect of the readiness with which the quantities may be measured or monitored (as may be required in

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* Manuscript received February 15th, 1950

† EMI Research Laboratories, Ltd.

UDC No. 621.394.665.

‡ Since the term mutual implies bilateral action " trans-admittance " will be preferred to " mutual-admittance."

some methods of automatic control), for while g_o is a separate two terminal device, g_T does not appear as a distinct element, and is not amenable to simple direct measurement. The foregoing comparisons disappear, of course, where the load impedance is also electronic in character; this rarely happens in practice and such a special case will be ignored in the present discussion.

1.5. Three methods of controlling the gain factor g_T/g_o arise according to whether the one or the other of the two admittances is varied separately, or the gain is controlled by a quantity derived from them both. Thus :—

(i) g_T may be controlled by varying one or other of the mean operating potentials of the amplifier valve(s) itself or of a second control valve associated with it, as when a cathode impedance valve determines the available space current.

(ii) g_o may be arranged to be adjustable in magnitude or associated with an attenuator.

(iii) Both quantities are involved when the effective input is diminished by returning a fraction of the output voltage to the amplifier input in such phase that it subtracts from the actual input (degeneration, or negative feedback) or when both are involved in the production of the gain control potential in (i).

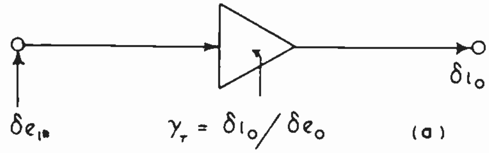

Fig. 1 (a).—Basic amplifier property (e → i conversion)

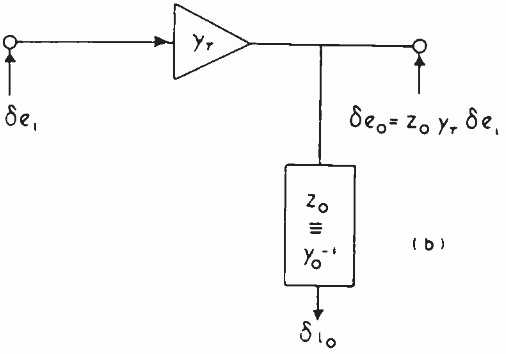

Fig. 1 (b).—Basic voltage amplifier arrangement.

The first method suffers from the risk of introducing excessive amplitude distortion when the range of control is sufficient to shift the operating point to a less linear region of the valve characteristic. Moreover, particularly where several stages are controlled, change of mean potentials may cause considerable fluctuation in the total H.T. current drain and necessitate improved regulation of the supply. Again, when the amplifier is intended for D.C. signals, changes of operating potentials will (except in certain types of balanced amplifier) be transmitted as spurious signals through subsequent stages. While the second method is free from these defects it is inferior to the third in that any sacrifice of gain, which is inevitable in any method of control, is not turned to advantage as when negative feedback is applied. On the other hand, negative feedback needs careful application in view of the possibility of what may be termed " Nyquist instability " (this form of instability will not be considered in the present paper except in so far as it arises as a result of the high loop gain needed in automatic control methods employing negative feedback).

2.0. Principles of Automatic Gain Stabilization

2.1. The problem to be discussed is that of automatically maintaining constancy of gain (i.e. of the quotient g_T/g_o, or its equivalent over several stages) where either g_T or g_o (or both) may vary in an arbitrary and excessive manner. If the one admittance changes the other must therefore be changed correspondingly. To minimize the range of control required it would appear to be more convenient to allow the more constant quantity (i.e. g_o) to fluctuate and make the other (i.e g_T) follow automatically, and it is fortunate that the latter quantity is the more easily varied. Where g_o can be made sufficiently stable a possible method of partial gain stabilization would be to monitor g_T and continuously compare its value with that of a stable reference and derive a control potential representing any discrepancy, which could be used, by forming a negative feedback loop, to make the difference self-cancelling. Where necessary a similar technique could be applied to g_o, but it would obviously be more direct and convenient to treat the gain factor as a single entity. A satisfactory method would therefore appear to involve comparison of the amplifier gain with that of a standard reference amplifier, and the use of a quantity representing the difference gain, to make that of the amplifier tend to that of the reference.

2.2. The circuit developments capable of carrying out the process just stated in a continuous and automatic manner are suggested by the conventional method of measuring gain, as illustrated in Fig. 2. The amplifier under investigation is connected in cascade with a sufficiently accurate and stable calibrated adjustable attenuator. A suitable signal is supplied by a generator and the output of the combination measured by an appropriate type of output meter. A changeover switch allows the input to be compared with the attenuated amplifier output and the attenuator is, of course, systematically varied until both readings are the same. The loss over the attenuator then equals the amplifier gain. The important feature of the method from the present point of view is the use of an attenuator as a gain reference. Being a passive network, the attenuator can be made much more stable than a reference amplifier incorporating active devices.

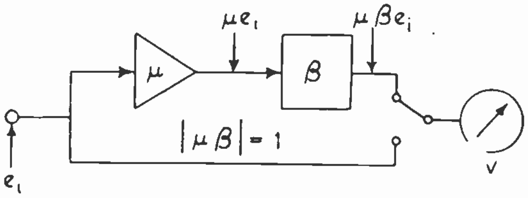

Fig. 2.—Measurement of amplifier gain.

2.3. Adaptation of the arrangement just described to the continuous maintenance of constant gain in an amplifier is straightforward in principle (see Fig. 3). An attenuator (β) is associated with the amplifier (μ) and its output fed together with a copy of the input signal to an amplitude discriminator (δ) which, in comparing the two signal amplitudes, provides a difference signal measuring the deviation of the amplifier gain from the reciprocal of the loss of the reference attenuator and may be used by one or other of the methods listed in 1.5 to shift the amplifier gain in the direction which makes the gain difference tend to zero.

Two possibilities arise according to whether the discriminator circuit operates on the entire signal or, particularly in the case of an A.M. signal, on a measure of its amplitude only. In the first case the arrangement will be recognized as a normal negative feedback system except that the feedback network is constructed as an attenuator of accurately known loss and arranged to be the only factor appreciably affecting the overall gain. In the second case, the arrangement represents an extension of A.G.C. wherein the control voltage is not proportional to the amplitude of the output signal alone, but to its difference (after attenuation) from that of the input signal. Both cases are covered by the schematic in Fig. 3, whose configuration is of a more general form than that encountered in most conventional N.F.B. and A.G.C. systems. Both arrangements involve the negative feedback principle and a network configuration potentially of bridge (or lattice) form. The maintenance of gain at a constant predetermined level necessarily requires the use of a standard of reference and it is chiefly in this respect that the circuit technique to be described differs from conventional A.G.C. and the straightforward application of N.F.B. since, while both tend to compress the permissible range of gain, in neither is a standard of gain reference normally consciously provided.

2.4. It may be mentioned that the suggestion has been made[1] that gain be controlled by a separate signal having a frequency outside the band occupied by the normal signal. This control signal would be passed through the amplifier, rectified and used to control the gain of one or more of the amplifiers in the A.G.C. manner. The further suggestion that this control signal be generated by self-oscillation of the amplifier is of doubtful practical significance. In either case the technique is similar to the introduction of a carrier; the signal modulates a locally generated oscillation at the amplifier input and the output is

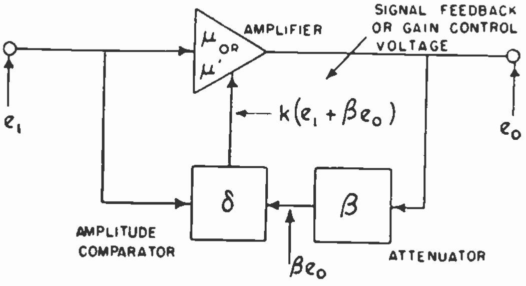

Fig. 2.—Basic schematic for automatic gain stabilization.

demodulated, rectified and used for gain control. Such frequency translation is helpful in wideband circuits and also in amplifiers in which D.C. signals have to be passed.

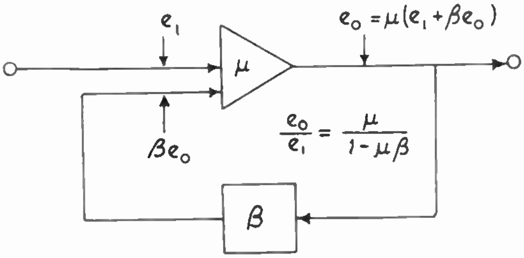

Fig. 4.—Conventional N.F.B. amplifier.

3.0. The Negative Feedback Method

3.1. It will be realized that the conventional method of applying N.F.B., which yields the configuration shown in Fig. 4, represents a special case of the scheme given in Fig. 3. The quantities involved are related thus :—

$$e_o = \mu(e_i + \beta e_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)^*$$

which may be written

$$e_o = \mu e'_i$$

where $e'_i = e_i + \beta e_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5a)$

or as $e_o = \mu' e_i$

where $\mu' = \dfrac{1}{1-\mu\beta}\,\mu \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5b)$

These two interpretations correspond to the two methods of automatic stabilization stated in 2.3. The first is more representative of the actual circuit action ; the second suggests the alternative A.G.C. method wherein the actual μ of the amplifier valve is usually controlled.†

The condition required for the gain of the amplifier (μ network) to be dependent entirely on the attenuator (β network) is obtained by making $|\mu\beta| \gg 1$ so that $\mu' \ll \mu$ and $e_o \simeq \beta^{-1} e_i$. Thus, for a given degree of attenuation (β), i.e. for a given required gain ($= \beta^{-1}$) the latter is approached more closely as μ increases, i.e. as $\mu \to \infty$, gain $\to \beta^{-1}$. In assessing the extent to which the actual gain fails to reach the theoretical upper limit (β^{-1}) it is convenient to set

$$\mu' = \eta\beta^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where η ranges from 0 to 1 as μ ranges from o to ∞. From (5*b*) and (6)

$$\eta = \frac{\mu\beta}{1-\mu\beta} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

from which the required loop gain $\mu\beta$ for η to be any desired fraction of the limiting gain (β^{-1}) may be determined. It is useful to remember that for η to be within 1 per cent. (i.e. $\eta \not< 0{\cdot}99$) of β^{-1}, the loop gain must be not less than 99 times. Clearly, if it is desired that the attenuator should define the gain accurately, the amplifier loop gain must be quite high.

3.2. In narrow band amplifiers the sacrifice of " available " (i.e. without feedback) gain necessary in obtaining adequate feedback to ensure satisfactory gain stabilization and close approach to the defined value still allows the latter to have a useful magnitude but when it is desired to amplify over a considerable bandwidth the available gain may not be adequate for these purposes. In such cases the use of the more general arrangement shown in Fig. 3 alleviates this difficulty to some extent. Two amplifiers are involved. The principal one provides a gain of the order of the value required and corresponds to the normal amplifier. The additional amplifier (μ_2) is fed with the voltage representing the error between the attenuated principal amplifier output and the input signal. Its output is injected into the main amplifier (or their outputs fed in parallel to a common load) in such polarity as to cause the error signal to tend to zero. Since the contribution of the additional amplifier to the total output is small compared with that of the principal amplifier its gain may be raised to some

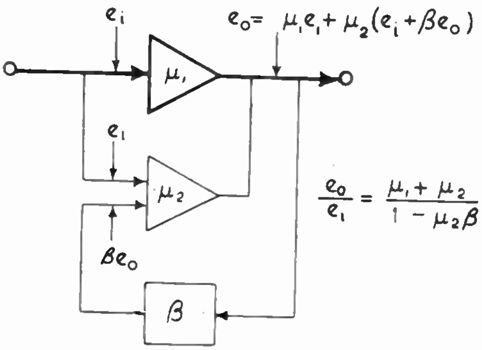

Fig. 5.—More general form of N.F.B. amplifier (cf Fig. 4).

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* β is conventionally taken negative.

† Throughout the paper dash superscript (as μ', β') denotes functional dependence on a control potential.

extent at the cost of bandwidth before the effective bandwidth of the system as a whole is very adversely affected.

Analysis of the system (see Fig. 5) yields :—

$$\frac{e_o}{e_i} = \frac{\mu_1 + \mu_2}{1 - \mu_2\beta} \rightarrow \beta^{-1} \text{ as } \mu_2 \rightarrow \infty \; (\mu_1 \text{ finite}) \quad \ldots\ldots\ldots\ldots\ldots (8)$$

where μ_1 refers to the principal amplifier and μ_2 to the gain stabilizing amplifier. It will be noted that in the special case $\mu_1 = 0$ the arrangement reduces to the conventional feedback amplifier, wherein the error voltage is the only effective input. Actually μ_1 will be set approximately to β^{-1}. Assuming $\mu_1 = \beta^{-1}$, (8) becomes

$$\left.\frac{e_o}{e_i}\right|_{\mu_1 = \beta^{-1}} = \frac{1 + \mu_2\beta}{\beta - \mu_2\beta^2} \triangleq \frac{\mu_2}{1 - \mu_2\beta}$$

$$\text{when } 1 \ll \mu_2\beta \text{ (cf. (7))} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Again $\frac{e_o}{e_i} \rightarrow \beta^{-1}$ as $\mu_2 \rightarrow \infty$.

3.3. Difficulties encountered in applying the methods of the last two paragraphs (such as the probability of Nyquist instability) arise from the need for very high loop gain, since the limiting value of gain set by the attenuator (β section of the feedback loop) is approached only as $\mu \rightarrow \infty$. That it is possible to shift the β-controlled gain limit to a finite value of μ is suggested by transposition of the μ and β sections of the basic feedback loop (cf. Fig. 4). The stage gain then becomes

$$A = \frac{\beta}{(1 - \mu\beta)} \quad \ldots\ldots\ldots (10)$$

(note symmetry of denominator in μ, β),

which falls from β to 0 as μ ranges over $0 \rightarrow \infty$. This case represents the opposite extreme of that shown in Fig. 4; intermediately, insertion of a μ section in both forward and return portions of the feedback loop shifts the gain limit set by the β section to some finite and non-zero value of μ. It may be pointed out that although both the μ and β sections now occurring in the return path are both amplitude transforming networks they must be kept distinct since β is regarded as a constant while μ is a variable.

As an example of the arrangement just developed it is interesting to consider the special case of identical μ sections in each portion of the loop (see Fig. 6 (*a*)). Such a system might be expected to exhibit independence of overall gain from fluctuations in μ in so far as variations in forward μ are countered by similar changes of μ in the return path. The gain

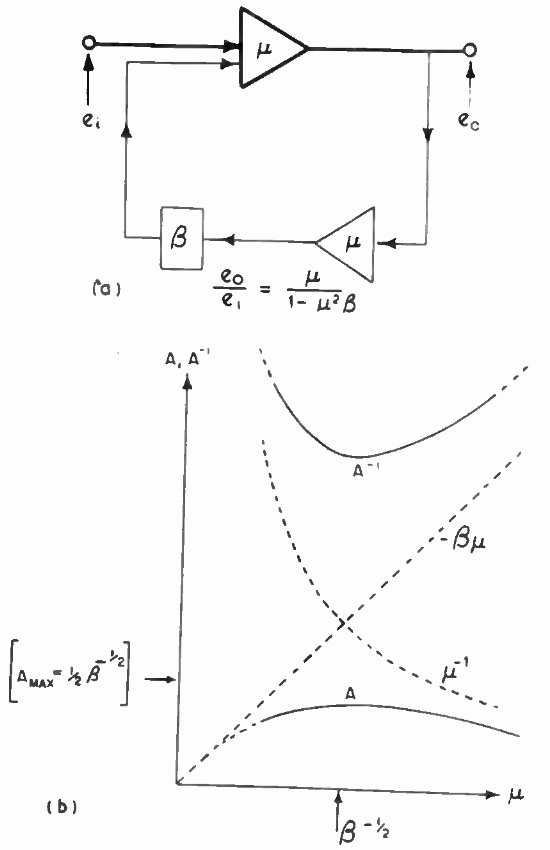

Fig. 6 (a) (b).—Feedback amplifier having identical μ-sections in both forward and return portions of feedback loop.

$$A = \frac{\mu}{(1 - \mu^2\beta)} \quad \ldots\ldots\ldots (11)$$

has a derivative

$$\frac{dA}{du} = \frac{(1 + \mu^2\beta)}{(1 - \mu^2\beta)^2} \quad \ldots\ldots\ldots (12)$$

having a zero at $\mu = \beta^{-\frac{1}{2}}$ which is dependent only on the attenuation of the β section. As μ increases beyond $\mu = \beta^{-\frac{1}{2}}$, the gain falls only gradually compared with the continual linear (unit slope) increase which is characteristic of the absence of feedback. For graphical illustration it is more convenient to consider the reciprocal gain

$$A^{-1} = \mu^{-1} - \mu\beta \quad \text{..........(13)}$$

whose components are plotted separately in Fig. 6 (*b*), added and inverted to obtain the plot of A. For stability the range of values likely to be occupied by μ during the working life of the amplifier (i.e. while valve performance deteriorates) should lie a little above $\mu = \beta^{-1}$. In this respect the situation is similar to the matching of a load resistor R to a source of resistance *r* in order to obtain maximum power transfer, where, for $R > r$, the change of power transfer is very gradual compared with the rise from zero to max. power over the interval $o < R < r$. Thus R is often made a little greater than *r* to secure added stability with little loss of power. In the present case it may be stated, by analogy with the maximum power transfer theorem that, for equal partition of the variable component μ of the loop voltage transfer factor (μβ) between the forward and return paths, maximum voltage transfer over the entire system occurs when the total μ matches (i.e. equals in magnitude) the reciprocal of the constant β section included in the return path.

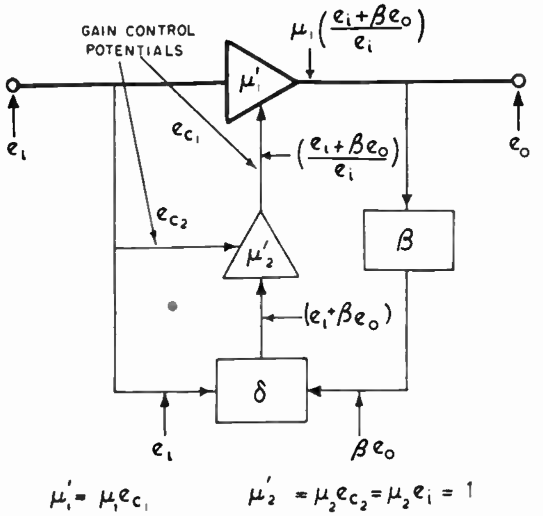

Fig. 7(*a*).—*Exact A.G.C. equivalent of conventional N.F.B. amplifier* (*cf Fig.* 4).

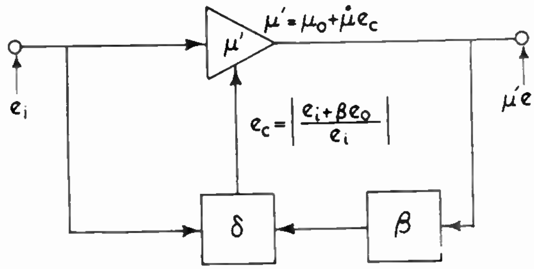

Fig. 7(*b*).—*Approximate equivalent of conventional N.F.B. amplifier* (*cf. Fig.* 4).

4.0. The A.G.C. Method

4.1. The A.G.C. method is characterized by the use of the error signal to control the amplification factor of one or more of the valves in the amplifier rather than by the reintroduction of a copy of the signal into the amplifier. The processes required for exact equivalence to the simplest form of feedback amplifier (Fig. 4) may be derived from consideration of the second interpretation of equation (4) given in 3.1. Dividing (4) by e_i yields :—

$$\frac{e_o}{e_i} = \mu\left(\frac{(e_i + \beta e_o)}{e_i}\right) \quad \text{............(14)}$$
$$= \mu'$$

so that if μ′ is linearly proportional to a control voltage e_c it is necessary to form. (See Fig. 7(*a*).)

$$e_c = \frac{e_i + \beta e_o}{e_i} \quad \text{..................(15)}$$

i.e. to :—

(i) Attenuate e_o by the factor β (<1),

(ii) Add βe_o to e_i,

(iii) Normalize $(e_i + \beta e_o)$ to e_i.

4.2. Alternatively, the more practical configuration (Fig. 7 (*b*) may be directly analysed. Assuming that μ′ is a linear function $(\mu_1 + \dot{\mu}_1 e_c)$ of the gain control voltage the following result is obtained :—

$$\frac{e_o}{e_i} = \{\mu_1 + \dot{\mu}_1 (e_i + \beta e_o)\} \quad \text{........(16)}$$

where μ_1 = absolute gain at mean operating point,

and $\dot{\mu}_1$ = slope gain at mean operating point $(d\mu_1/de_c)$, from which

$$\frac{e_o}{e_i} = \frac{\mu_1 + (\dot{\mu}_1 e_i)}{1 + (\dot{\mu}_1 e_1)\beta} \rightarrow \beta^{-1} \text{ as } (\dot{\mu}_1 e_i) \rightarrow \infty \quad \text{..............(17)}$$

which is similar in form to equation (8) but involves the amplitude of the input voltage because, for simplicity, the normalization process has not been carried out. Clearly $\dot{\mu}_1$ and e_i

should be large for e_o/e_i to approach β^{-1} closely. Extra gain in the feedback loop may be obtained by the insertion of an additional (gain stabilizing) amplifier (μ_2), as shown in Fig. 8, giving the result

$$\frac{e_o}{e_i} = \frac{\mu_1 + \dot{\mu}_1\mu_2 e_i}{1 + \dot{\mu}_1\mu_2\beta e_i} \rightarrow \beta^{-1} \text{ as } \dot{\mu}_1\mu_2 e_i \rightarrow \infty \qquad \ldots\ldots\ldots\ldots\ldots(18)$$

This arrangement is the A.G.C. analogue of the N.F.B. system shown in Fig. 5.

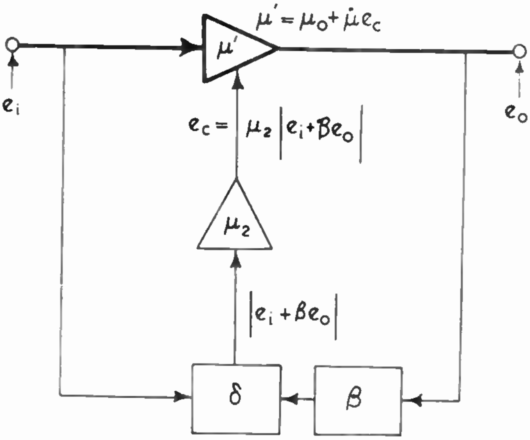

Fig. 8.—More general form of A.G.C. system employing control voltage amplifier (μ_2).

5.0. Relative Applicability of the Two Methods

5.1. In addition to stabilizing gain N.F.B. introduces other benefits such as spurious signal reduction and decrease of distortion of both phase and amplitude of the desired signal. It is not inherently dependent on input signal amplitude and is less subject to overloading and blocking (paralysis). No error signal rectification is necessary in the control loop. However careful design is required, particularly with the high loop gain needed for accurate definition of gain by the attenuator, to avoid self-oscillation by satisfying Nyquist's criterion. This difficulty increases rapidly with the number of stages contained in the feedback loop. In wide band amplifiers it is difficult to achieve adequate loop gain.

5.2. The A.G.C. method is particularly suitable to amplifiers intended for modulated H.F. signals in so far as the modulation may be removed and the carrier alone used to operate the gain control circuit. The required loop gain is more easily achieved and with less difficulty in avoiding self-oscillation. However, it is dependent on signal amplitude, is more likely to introduce distortion than direct signal N.F.B. and requires rectification in the discriminator. Some benefits of N.F.B. can be introduced into the A.G.C. method by using the gain control valve to operate on an amplifier inserted in a localized feedback loop, as indicated in Fig. 9, at the cost of increased circuit complexity.

6.0. Circuit Technique

6.1. *Attenuator Aspect of N.F.B. Amplifiers*

In conventional feedback amplifiers stability and accurate definition of gain are not often the most important requirements and no attempt is made to fashion the network associated with the valve in such a manner that the factor β is precisely defined. In general β will, of course, depend to some extent on all the components comprising the external circuit and some of these may lack the required degree of constancy. The practical problem (in addition to achieving adequate gain) is to arrange the external network so that β depends almost entirely on a limited group of components which are capable of having stable known values and are arranged to form a precision attenuator. This point is well illustrated by a comparison of the simplest examples of the two basic types of feedback. The voltage feedback case shown in Fig. 10 (*a*) makes use of the ˥ type attenuator formed by R_1, R_2 which reduces the output voltage (to form the feedback voltage) by the factor $R_1/(R_1+R_2)$. While the gain without feedback would vary with the load impedance the latter does not

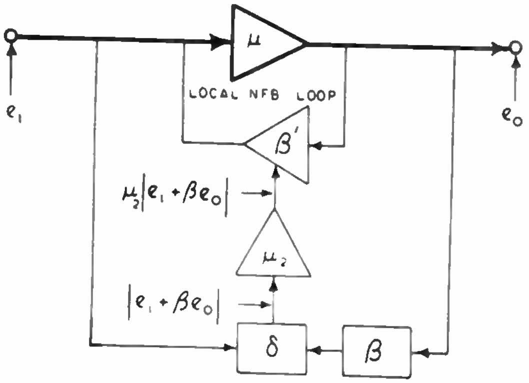

Fig. 9.—Use of A.G.C. to control gain by operating on valve in β section of localized feedback loop.

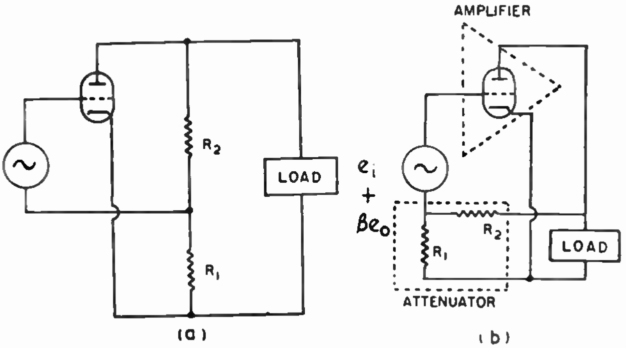

Fig. 10 (*a*) (*b*).—*Simple example of voltage feedback amplifier* (*cf. Fig.* 11).

influence the degree of attenuation provided by R_1, R_2, and it is not usually difficult to arrange that the impedance placed across R_1 by the valve is sufficiently great to be neglected. An important practical point is that R_1, R_2 do not carry the valve feed current. The gain of this arrangement is given by

$$A\left(=\frac{e_o}{e_i}\right)=\frac{-\mu R_o(R_1+R_2)}{(r_a+R_o)(R_1+R_2)+\mu R_o R_1} \quad \ldots\ldots\ldots\ldots\ldots(19)^*$$

where R_o is the total impedance presented to the valve by the external network and is very nearly equal to the load impedance when (R_1+R_2) is made sufficiently large. As $\mu \to \infty$, $A \to -(R_1+R_2)/R_1$, so that provided μ is sufficiently large, A is defined entirely by the feedback attenuator R_1, R_2. In the simplest example of current feedback, on the other hand (Fig. 11 (*a*)) the local impedance forms part of what may be regarded as the feedback attenuator, so that the voltage gain

$$A=\frac{-\mu R_2}{r_a+(\mu+1)R_1+R_2} \quad \ldots\ldots\ldots(20)$$

has the limiting value $-R_1/R_2$, which differs from the previous result because the attenuator input

$$=\frac{R_1+R_2}{R_2}\,e_o \text{ rather than } e_o.$$

This arrangement suffers from the disadvantages that both arms of the attenuator carry the valve standing current and the load R_2 may, in certain applications need to be a more complex and less stable component than a simple resistor. The basic circuits of Fig. 10 (*a*), 11 (*a*) have been recast into the more instructive forms of Fig. 10 (*b*), 11(*b*), in which the attenuator aspect has been emphasized. The voltage feedback arrangement is clearly the more suitable for the present purpose.

6.2. *Combination of Input and Attenuated Output Voltages*

In the two cases just considered, the input and attenuated output voltages are compared by series connection (with opposing polarity) into the grid-cathode circuit of the amplifier valve. The first arrangement (see Fig. 10) has the disadvantage that both terminals of the input voltage source are "floating." A rearrangement of the input circuit, involving transposition of e_i and R_1, avoids this situation at the cost of introducing e_i into one branch of the attenuator; the result represents a special case of a different method of combining the two voltages. The latter is shown in Fig. 12; here e_i and e_o drive proportional currents through the common resistor R_3, thereby producing a resultant p.d. which measures the combined input (e_i, e_o). In the special case $R_3=\infty$ the circuit reduces to a rearrangement of Fig. 10 just described. The T network formed by R_1, R_2, R_3 takes part in what has been termed a "see-saw" action since, given sufficiently high loop gain, a balance is reached in which the magnitudes concerned are related by

$$\frac{e_o}{e_i}=\frac{R_2}{R_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(21)$$

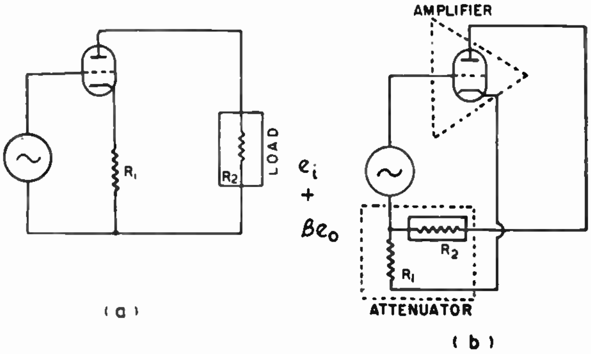

Fig. 11 (*a*) (*b*).—*Simple example of current feedback amplifier* (*cf. Fig.* 10).

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* In eqns. (15), (16) and (18) μ refers to valve only and not, as previously, to entire stage.

The exact gain expression is

$$A = \frac{-\mu R_o R_2}{(r_a + R_o)\frac{1}{R_3}\sum R_1 R_2 + \mu R_o R_1} \qquad \ldots\ldots\ldots\ldots\ldots(22)$$

where $\sum R_1 R_2 = R_1 R_2 + R_2 R_3 + R_3 R_1$, which approaches $-R_2/R_1$ as μ increases without limit.

A most convenient method of combining or comparing the input and attenuated output voltages in most of the N.F.B. and A.G.C. arrangements outlined in §§3, 4, is provided by the cathode-coupled double-triode valve. The basic arrangement is shown in Fig. 13. One signal is applied to each grid and either output polarity may be obtained by appropriate choice of anode.

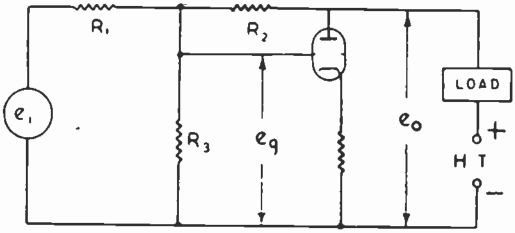

Fig. 12.—*More general form of voltage feedback amplifier* (*cf. Fig.* 10).

6.3. *Production of Gain Control Voltage in A.G.C. Systems*

A.G.C. systems differ from N.F.B. arrangements as they need some method of extracting the amplitude of the signal or of producing a voltage representative of the signal amplitude.

The signal itself will usually consist of an amplitude fluctuation whose instantaneous magnitude represents the information being transmitted so that it is necessary to derive an amplitude measure of it, preferably of such a form that it occupies a considerably narrower bandwidth than the signal itself. Conventional methods of peak rectification, detection or demodulation are suitable for this purpose. The bandwidth of the control circuit as a whole (amplitude comparator, control amplifier, etc.) should be restricted as much as possible in order to allow the highest possible stable loop gain to be achieved. The amplitude comparator should be followed by some form of integrator in order to develop a relatively steady gain control potential. The latter may be applied to a gain control electrode in one or more of the amplifying stages or used to control the impedance or gain of a valve acting in the feedback loop, as indicated in Fig 9.

7.0. Typical Applications

7.1. *Combined Amplifier-Attenuator for General Laboratory use or Incorporation into a C.R. Oscillograph*

In laboratory work it is sometimes desired to amplify a signal by an accurately known amount. Unless a stable and accurately calibrated amplifier is available it is necessary to set up an arrangement of the form shown in Fig. 2, as when measuring amplifier gain. A cathode-ray oscillograph may well be used as the output meter with the advantage of allowing visual inspection of waveform while adjusting the attenuator for unit overall gain. The better class oscilloscopes are often provided with both an amplifier and an attenuator in order to allow a wide range of signal amplitudes to be displayed at a convenient amplitude. While the attenuator is often accurate the deflection amplifier gain controls are rarely even approximately calibrated.

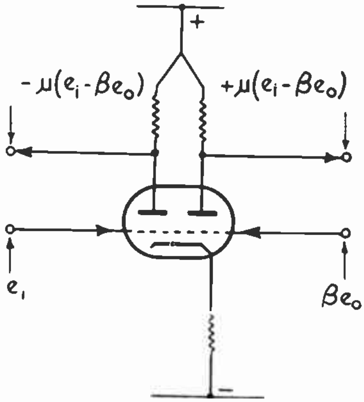

Fig. 13.—*Use of cathode-coupled pair for comparing input and attenuated output signals.*

The foregoing sections suggest the possibility of associating a high gain amplifier and its auxiliary gain control circuits with a precision attenuator, together with suitable switching to allow the latter to be used separately, in a single instrument, for general laboratory work. The attenuator and vertical deflection amplifier of a cathode-ray oscillograph might well be combined in a similar manner, with the advantage of greater convenience of control since separate attenuator and amplifier gain controls would not be necessary. The basic arrangement is shown schematically in Fig. 14. This technique is particularly applicable to D.C. and narrow-band A.C. signals where the high order of inherent (i.e. without-feedback) amplifier gain needed to allow the actual gain to approach sufficiently closely the reciprocal of the attenuator setting may be obtained without undue difficulty.

7.2. *Computer Multipliers*

A more obvious application of the foregoing technique is to multiplier circuits in computers. In this application the signal usually takes the form of a direct voltage level which corresponds to a particular numerical magnitude and the amplifiers often multiply in decades (scale of ten). Some arrangement must be provided for setting zero (i.e. zero output for zero input) and elaborate precautions must be taken to preclude drift of the mean operating potentials throughout the system.

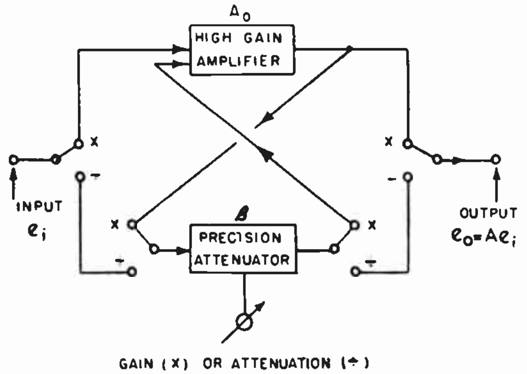

Fig. 14.—Schematic showing combination of high gain amplifier and precision attenuator with switching to allow use of attenuator.

Notes :—(i) $A_0 > \beta^{-1}$. *(ii)* $A \triangleq \beta^{-1}$. *(iii) All switches ganged together. (iv) Substitute + for ×, − for ÷ if calib in. db. (v) " High Gain Amplifier" may incorporate auxiliary amplifier* μ_2) *and comparator* (δ), *cf. Fig. 5.*

7.3. *Maintenance of Constant Gain over other Variables*

There are many cases in electronic circuit practice where amplitude changes occur as secondary effects resulting from the control of another factor, e.g. of frequency response. Thus, in a television system, the total voltage range of the signal applied to the transmitter modulator should be held constant in order to achieve full modulation on peak white, but without overloading. On the other hand, at some earlier part in the system, a gamma control circuit may be introduced with the result that adjustment of gamma causes changes of peak-to-peak signal amplitude. It may be of interest that a British Patent[2] discloses an A.G.C. system which is basically of the form shown in Fig. 7 (*b*), for counteracting this spurious amplitude variation.

8.0. Acknowledgment

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9.0. Appendix

Derivation of Gain Formula for Circuit of Fig. 12

We have :—

$$e_g = \frac{\dfrac{R_1 . R_3}{R_1 + R_3}}{R_2 + \dfrac{R_1 . R_3}{R_1 + R_3}} e_o + \frac{\dfrac{R_2 . R_3}{R_2 + R_3}}{R_1 + \dfrac{R_2 . R_3}{R_2 + R_3}} e_i$$

$$= \frac{R_1 . R_3}{\sum R_1 . R_2} e_o + \frac{R_2 . R_3}{\sum R_1 . R_2} e_i \quad \ldots .(A1)$$

$$e_o = -\frac{\mu R_o}{r_a + R_o} e_g \quad \ldots\ldots\ldots\ldots\ldots\ldots .(A2)$$

Equating (A1) with the expression for e_g obtainable from (A2), in order to eliminate e_g, gives :—

$$-\left(\frac{r_a + R_o}{\mu R_o} + \frac{R_1 . R_3}{\sum R_1 . R_2}\right) . e_o = \frac{R_2 . R_3}{\sum R_1 . R_2} . e_i$$

whence

$$\frac{e_o}{e_i} = -\frac{\mu R_o R_2}{\mu R_o R_1 + \dfrac{1}{R_3}\sum R_i R_2 (r_a + R_o)} \quad (A3)$$

which → $-\dfrac{R_2}{R_1}$ as $\mu \rightarrow \infty$

10.0 References

1. J. J. Zaalberg van Zelst. *Philips Technical Review*, Vol. 9, No. 1. pp. 25-32, 1947.
2. British Patent No. 562.482 (F. J. Somers).

FLICKER AND COLOUR FRINGING PHENOMENA IN COLOUR TELEVISION*

by

P. C. Goldmark†

Contributed by the Columbia Broadcasting System and based on the evidence laid before the Federal Communications Commission of the U.S.A. in September, 1949.

Flicker has always been an important factor in television. The current black-and-white system in the United States employs a field repetition rate of 60 per second. The picture brightness, which will exhibit threshold flicker at this value, is well above 100 foot-lamberts. Thus, there is sufficient brilliance available below flicker level to establish adequate contrast range in the presence of ambient illumination. It will be shown that the use of mere brightness is not the most advantageous way of obtaining a desired contrast range.

There are two basic colour television systems known to-day. The simultaneous system, in effect, makes use of three black-and-white television channels (of varying bandwidth) each assigned to one of the three primary colours. Therefore, in this system, the requirements regarding flicker are the same as in the current black-and-white system.

In a sequential colour television system, where all the information is transmitted over a single channel, flicker becomes an important factor when the colour changes occur after each field period. If a complete colour change cycle occurred within 1/60th of a second, flicker conditions would be even more favourable than in the black-and-white system. Scarcity of space in the radio spectrum makes it desirable to reduce to an absolute minimum the bandwidth required for colour television. This is possible by operating the field sequential colour television system with a colour frame frequency of 48 per second, rather than 60.

It might be well to define some of the terms to be used in the discussion of flicker in the sequential system :

1. *Colour Field Frequency*

   The highest vertical scanning frequency employed in the system.

2. *Colour Frame Frequency*

   Colour cycle repetition rate per second. This corresponds to colour field frequency divided by three (in a three-colour system).

3. *Colour Picture Frequency*

   Number of times per second entire picture area is scanned in all three primary colours. For a double-interlaced system, this value is one-half that of the colour-frame frequency.

4. *Frame Frequency*

   Identical to the term used in monochromatic television ; that is, number of times per second the picture area is scanned by the total number of lines. In a double-interlaced system, this value is one-half the colour field frequency.

In the CBS field sequential colour television system, a colour frame frequency of 48 per second has been found to represent a satisfactory compromise between video bandwidth and maximum permissible picture highlight brightness (flicker threshold illumination). The corresponding value for colour field frequency is 144 per second ; for colour picture frequency, 24 per second; and for frame frequency, 72 per second.

The well-known Ferry-Porter Law[1] in its simplest form states that the critical fusion frequency is proportional to the logarithm of the apparent luminosity. Porter was the first to establish the fact that this critical fusion frequency is to a large extent independent of the wavelength of light within the visible spectrum, provided that the apparent luminosity and not the radiant energy is used as the

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† Columbia Broadcasting System Inc.

independent variable. Based on this law, employing the flicker photometer, he derived the well-known colour-luminosity curve which then, for a constant energy spectrum, represents the eye's sensitivity to flicker (see Fig. 1).

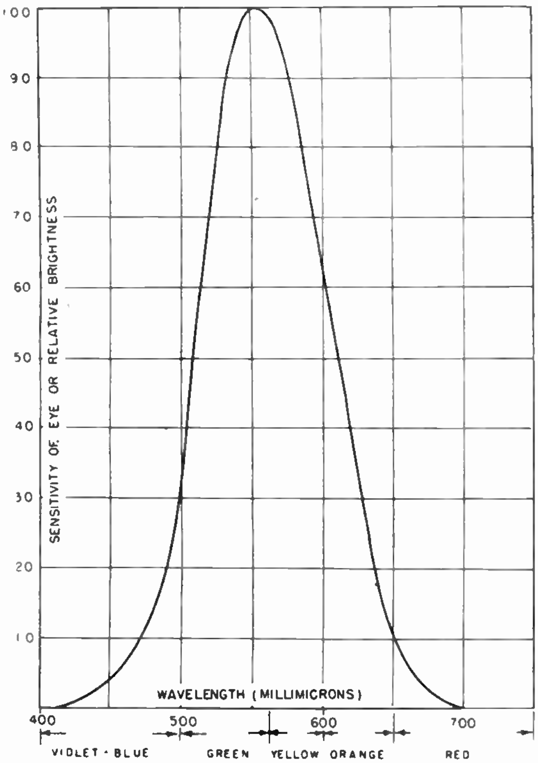


Fig. 1.—Variation of the eye's sensitivity to flicker with colour.

The validity of Talbot's law has been checked for all colours by Porter[2] and others. When applying Talbot's law to the special case of field sequential colour television, the apparent brilliance (I) of the colour television image will be

$$I = \frac{1}{T_c}\left[aY_G \int_0^{T_G} P_G(t)\,dt + bY_R \int_0^{T_R} P_R(t)\,dt + cY_B \int_0^{T_B} P_B(t)\,dt \right] \ldots\ldots\ldots\ldots\ldots(1)$$

where T_c is the duration of the complete colour cycle or colour frame period;

T_G, T_R, T_B are the durations of the green, red and blue colour field periods respectively;

Y_G is the luminosity (or Y component of the tri-stimulus values) of the green colour filter for unity electrical excitation;

Y_R and Y_B are the luminosities of the red and blue colour filters respectively, for unity electrical excitation;

$P_G(t)$, $P_R(t)$, $P_B(t)$ are the luminosity vs. time characteristics (decay curves) of the green, red and blue phosphor components, respectively;

a, b and c are the relative electrical amplitudes during the green, red and blue fields.

In order to obtain optimum utilization of transmitter power, the electrical amplitudes of the three colour field periods should be equal when transmitting white; that is, $a = b = c$. If one were to assume that the apparent luminosities of Y_B, Y_R and Y_G were equal, the colour field frequency, rather than the colour frame repetition rate, would be the determining factor as far as flicker is concerned. However, for adequate colour reproduction, the apparent luminosities of the three primaries cannot be equal. The amount by which they differ from each other controls the extent to which threshold flicker brightness for white subject matter is a function of the colour frame frequency or of the colour field frequency. Mathematically, the luminosity envelope during a colour frame period, and thus the flicker characteristics of a given set of colour primaries, can be expressed as follows:

For primaries " A " (see Fig. 2) the ratios of the luminosities of the three primaries are:

$$Y_B : Y_R : Y_G = 1 : 1{\cdot}5 : 2{\cdot}4 \ldots\ldots\ldots(2)$$

For primaries " B" (see Fig. 2), the ratios are:

$$Y_B : Y_R : Y_G = 1 : 5{\cdot}2 : 14{\cdot}4 \ldots\ldots\ldots(3)$$

From the aforesaid, it follows that colour frame flicker will be most evident with those primaries which display the largest ratio between the green and blue luminosities. For primaries " A," this will be 2·4 and for primaries " B," 14·4.

It also follows that flicker inherent in a set of primaries can be expressed in terms of the ratio of the apparent luminosities for a white and for a green picture, or I_W/I_G. The larger this ratio, the less flicker there will be for a given apparent illumination.

It is reasonable to assume that the persistence characteristics for the three phosphor components can be made equal [$P(t)$].

From equation (1), the apparent luminosity for white will be

$$I_W = \frac{Y_G + Y_R + Y_B}{T_c} \int_0^T P(t)\,dt \quad \ldots\ldots(4)$$

and the apparent luminosity for a green picture will be

$$I_G = \frac{Y_G}{T_c} \int_0^T P(t)\,dt \quad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The ratio of the white and green luminosities then will be

$$\frac{I_W}{I_G} = \frac{Y_G + Y_R + Y_B}{Y_G} \quad \ldots\ldots\ldots\ldots\ldots(6)$$

When substituting values for primaries " A,"

$$\frac{I_W}{I_G} = 2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

and for primaries " B,"

$$\frac{I_W}{I_G} = 1{\cdot}43 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

The larger ratio (7) corresponding to primaries " A " indicates greater freedom from flicker, whereas equation (8) shows that with primaries " B " the reverse is true.

As pointed out before, if the luminosities of the three primary colour fields were equal, the critical fusion frequency would be lower than for either primaries " A " or primaries " B " Equation (6) then would be

$$\frac{Y_G + Y_R + Y_B}{Y_G} = \frac{3Y_G}{Y_G} = 3$$

This is another way of expressing that the increase in ratio of white to green luminosities indicates greater freedom from flicker. It should be kept in mind that the average or apparent brightness of the white images [I_W from equation (4)], obtained with these various sets of primaries, remains constant.

Fig. 2 shows the relative brightness of the two sets of primaries (" A " and " B "). The relative luminosities of the two sets of primaries have been given in their proper magnitudes. Thus, the ratio of the sum of the individual primaries will indicate which set (" A " or " B ") is capable of furnishing a more luminous white (for equal electrical excitation of the two sets). Therefore, the luminosity sum of primaries " A " is $\sum Y_A = 19{\cdot}6$; and for primaries " B," $\sum Y_B = 20{\cdot}6$. The ratio of the luminosity sums of primaries " A " and primaries " B " is $Y_A/Y_B = 0{\cdot}98$. Thus, while the two sets of primaries (Fig. 2) yield substantially the same luminosity, from a flicker standpoint their performances are appreciably different.

When using with the field sequential system a rotating colour disc or drum in front of a cathode-ray tube, the function $P(t)$ in equation (5) must be such that at the end of each colour field period the brightness of a given area on the cathode-ray tube is no more than approximately 1/20th of the initial excitation intensity. This is necessary in order to avoid colour contamination due to colour carry-over from one field to the next.

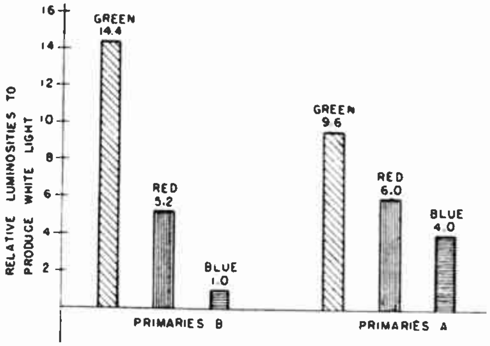


Fig. 2.—Relative luminosities to produce white light at a colour television receiver using primaries B and primaries A.

There are a number of additional factors which also influence the perception of flicker. Independent of the relative values of the maximum and minimum field brightness occurring during a colour cycle, flicker will increase as the viewing angle increases; that is, as the ratio of the viewing distance to picture size decreases. As a corollary of this, flicker will be more noticeable in pictures containing large, unbroken areas of white. As a matter of fact, large, unbroken areas in green (the primary with the highest luminosity) would be even more likely to enhance the sensation of flicker.

Experience has shown, however, that rarely does a condition occur where any one of the primary colours occupies a large unbroken area.

Flicker becomes much more apparent when one searches for it ; on the other hand, when there is sufficient entertainment value in a picture, a great deal more flicker will be tolerated unconsciously. Flicker is also influenced by the amount of surrounding room illumination. The influence of this ambient illumination on flicker will be shown later. It has also been found that flicker will be less apparent when there is action in the picture (even in the form of random noise). This is an important factor since television involves almost entirely the transmission of action rather than of stills.

Extensive investigations have been carried out in the CBS laboratories on the subject of flicker as related to colour television. Before describing the experiments, two important terms should be defined. The first is " threshold flicker," which is noticeable only when scrutinizing the picture under test. This type of flicker makes many observers doubt whether they actually noticed it. Another term for threshold flicker might be " just noticeable flicker." Threshold flicker can be found on the screen in most motion picture theatres. In order to perceive such flicker, however, one would have to search for it.

The second term, " maximum tolerable flicker," is flicker which is noticeable but not yet disturbing. Bio-physicists[1] have found that such flicker has no cumulative effect and is harmless to the observer even after long exposure. In some motion picture theatres which are equipped with especially powerful arcs or highly efficient screens, this type of flicker is almost constantly apparent in large solid white areas.

During the series of flicker tests, two experimental measuring arrangements were used : one was an actual television system ; the other, a simulated system which permitted measurements outside the range of the available frame frequencies and brightness values of the television system, as well as a more precise means of maintaining a given brightness level.

One of the colour television systems utilized during the tests comprised a CBS colour television receiver and a colour slide transmitter, operating at 525 lines per picture and 120 colour fields per second (corresponding to 40 colour frames per second). A 5-in. projection tube with a P-6 phosphor was used in a direct-viewing arrangement, capable of producing a colour picture with a maximum highlight brightness of 50 foot-lamberts. The picture was surrounded by a white masking board measuring 3·5 ft. by 5 ft. A colour disc using filters corresponding to primaries " B " rotated between the tube and the masking board.

The simulated system employed a slide projector and a translucent screen on which the images to be viewed were projected from the rear. A standard colour disc intercepted the light near the projector lens. Various values of colour frame frequencies were obtained by changing the speed of the motor driving the colour disc. All brightness measurements were made with a Macbeth Illuminometer. The ambient surface brightness which surrounded the picture under examination was determined by the average of four readings taken around the picture area.

Flicker measurements made with the simulated system of 40 colour frames per second were, on the average, within 15 per cent. of those made with the actual television system. Most of the flicker measurements at 40 frames per second were made with the actual television system. Measurements requiring high picture brightness values at 40 frames per second, and all frame frequencies over 40, were made with the simulated system. Measurements made later with the 48 and also the 50 colour frames per second television systems, using larger screens, checked with previous values determined on the simulated system.

The close correspondence between threshold flicker values obtained with the simulated system and with the actual television system was somewhat unexpected. In the function $\int_0^T P(t)\,dt$, appearing in equation (4), the picture brightness values for a given colour at any time period (t) of the colour field period (T) are different. With the simulated system, such as described before, the picture brightness in all parts of the picture will remain substantially constant during a colour field period. In the actual television system, any particular area of the picture will be illuminated only during a small fraction of the colour field period (T); after initial excitation, the brightness at that particular area will decay exponentially and must assume a negligible value at the end of T. The maximum persistence any portion of the screen may have is the colour picture duration, or 6T. Only the electronic colour tube receiver, described elsewhere, presents such a large variance from the short persistence (T) required in receivers using a colour disc. Hence, differences in the function $\int_0^T P(t)\,dt$, such as between the simulated and the actual colour television systems, would cause changes small enough to be lost in the complex measurements of the flicker threshold illumination. Repeated cross-checks between the simulated and actual systems warranted the use of either system interchangeably. The numerical effects of the brightness versus time function as a factor affecting flicker will be discussed later.

All threshold flicker measurements were made using the same picture material; this was a slide containing areas of white highlights large enough to represent a severe test object. Technical as well as non-technical persons were used as observers. The various readings obtained indicated that the observations of both groups could be weighed equally. It was to be expected that sizeable variations would be found in the readings of different individuals. To minimize dispersion and facilitate the reading of the curves, plots were made using average threshold flicker illumination readings.

In Fig. 3, colour frame repetition rates versus picture highlight brightness in foot-lamberts are plotted. Two sets of curves have been drawn; one set corresponds to "threshold flicker" and the other to "maximum tolerable flicker." Both curves have been taken under low as well as high ambient light conditions. The low ambient illumination, corresponding to 0·01 foot-lambert surface brightness, is that occurring in a fairly dark room. The high ambient illumination corresponding to 20 foot-lamberts is more than adequate for reading and writing. An average of all observations showed that "maximum tolerable flicker" occurs at a brightness which is about three times that at which "threshold flicker" becomes apparent. However, the "maximum tolerable flicker" curves have been plotted with a ratio of only slightly over 2 : 1 in order to provide conservative data for actual design considerations. Earlier investigators[4] found a similar relationship between the two types of flicker and refer to "threshold flicker" as "just noticeable flicker" and to "maximum tolerable flicker" as "noticeable but satisfactory flicker." The curves published show that the illumination ratios which correspond to these two types of flicker,

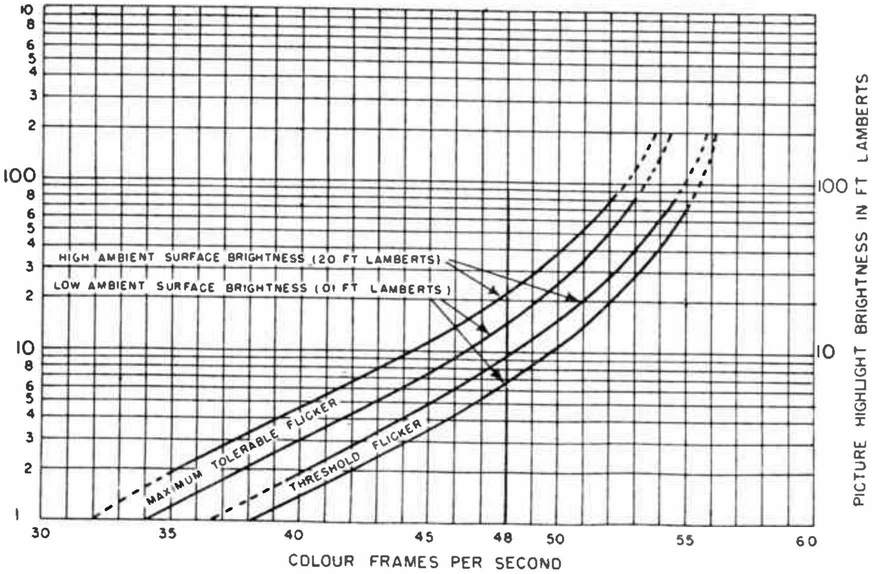


Fig. 3—Observations were made from a distance of seven times picture height. Wratten Filters 26, 27 and 58 (Primaries B) were used in the colour disc. The measurements at high intensity were made using a simulated system employing a slide projector.

average approximately three, which checks closely with the CBS value.

The use of a still picture instead of a subject in motion introduces an additional safety factor. As pointed out earlier, moving subjects or random noise tend to decrease the critical flicker frequency or, inversely, make it possible to tolerate a higher threshold flicker illumination.

In the flicker tests as indicated in Fig. 3, the receiver colour primaries " B " were employed. The relative luminosities of primaries " B " and those of primaries " A " have been shown in Fig. 2, with the latter showing appreciably smaller variations in luminosity from one colour field to another. Development of primaries " A " was undertaken at the suggestion of R. D. Kell.[5] A new set of flicker threshold curves, employing the primaries " A " has been derived, and is shown in Fig. 4, where the increase of the threshold flicker illumination values by a factor of approximately 2·5 becomes evident. Threshold as well as maximum tolerable flicker for low and high ambient light conditions are plotted. The viewing distance for all threshold and tolerable flicker determinations corresponded to seven times the picture height.

Measurements were made to determine threshold flicker illumination as a function of the viewing angle. It was found that if the picture size remained constant, threshold flicker illumination varied approximately in proportion to the viewing distance. In carrying out these measurements, the viewing distance varied from three to twelve times the picture height. Actually, when reducing the viewing distance from six times picture height to three times picture height, the threshold flicker illumination was reduced by a factor of 1·85 instead of 2; doubling the viewing distance to picture height ratio increased the threshold flicker brightness by a factor of 2·12.

Tests were also carried out to determine the relationship between the threshold flicker brightness for an actual scene as compared with that of a plain white raster. It was found that with a still picture, such as employed in the tests, the threshold flicker brightness increased by a factor of approximately 2 over that of an unmodulated, uniform white picture field.

The information contained in Figs. 3 and 4 has been condensed in Fig. 5, where other reference brightnesses, such as usually encountered on 35-mm. professional and 16-mm. home motion picture screens, are indicated. The threshold and maximum tolerable flicker illumination values for primaries " A " and primaries " B " at the colour frame frequencies of 40, 48 and 60 are plotted. For example, when using primaries " A " and a direct-viewing tube, combined with a colour disc, the field sequential colour television

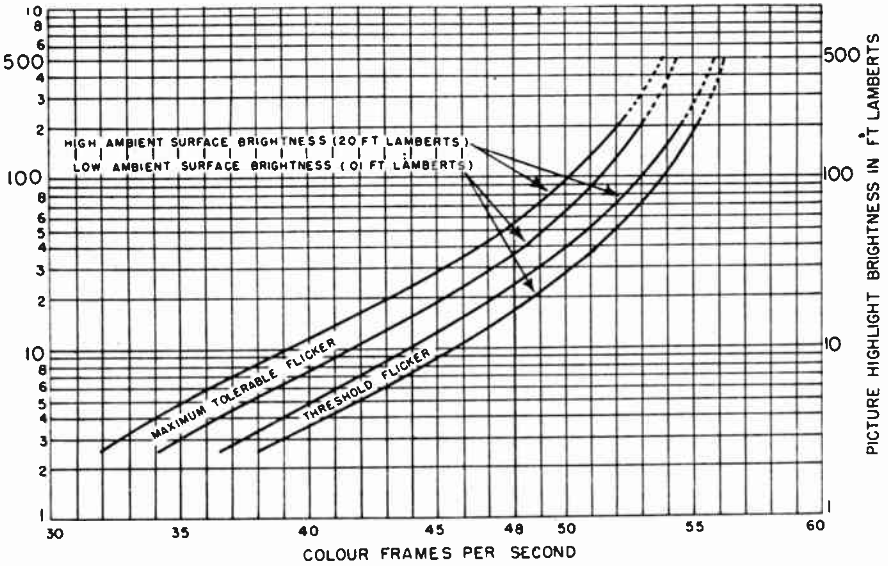
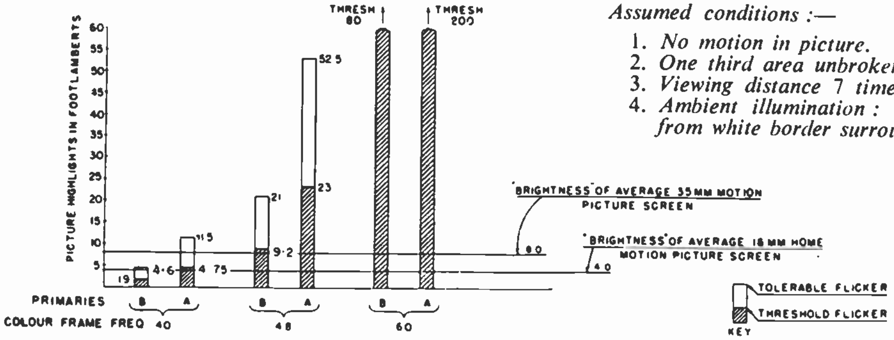


Fig. 4.—Flicker characteristics of CBS colour television receiver primaries A (derived from curves for primaries B). Observation distance—seven times picture height.



Assumed conditions :—

1. *No motion in picture.*
2. *One third area unbroken white.*
3. *Viewing distance 7 times picture height.*
4. *Ambient illumination : 20 foot-lamberts reflected from white border surrounding screen.*

Fig. 5.—Picture brightness for threshold and tolerable flicker with sequential colour receiver using primaries B and primaries A at various colour frame frequencies.

system with 48 colour frames per second permits a picture highlight brightness of 23 foot-lamberts for threshold flicker and at least 50 foot-lamberts for maximum tolerable flicker.

Further tests have been made to determine the threshold flicker values for a colour frame repetition rate of 50 per second, corresponding to a colour field frequency of 150 per second. These represent logical values for the field sequential colour television system when used with a 50-cycle power supply such as is found in most European countries. The measurements have shown that the threshold flicker values plotted for 48 colour frames per second in Fig. 4 increased by approximately 70 per cent. Thus, when using primaries " A," the threshold flicker illumination at 50 colour frames per second was approximately 40 foot-lamberts, as compared with 23 foot-lamberts at 48 frames. This increase from 48 colour frames to 50 represents an increase in required video bandwidth of only 4 per cent.

The question of flicker would be of no consequence in the field sequential television system if a colour frame frequency of 60 per second were used. However, increasing the colour frame rate from 48 to 60 would necessarily increase the required video bandwidth by 25 per cent. ; conversely, keeping that bandwidth constant would reduce the definition by that amount. In view of the scarcity of space in the radio spectrum and in the interest of keeping the transmitter and receiver bandwidth to an absolute minimum, a colour frame repetition rate of 48 or 50 per second represents an optimum.

It is important to point out that these illumination levels do not represent a ceiling for all types of colour television receivers operating within the field sequential system. Thus far, only relatively fast decaying phosphors have been considered ; these showed negligible luminosity at the end of a colour field period. One form of projection-type colour receiver utilizes long persistence phosphors and does not require moving colour filters. Three strips of screen material, each fluorescing in a colour which approximates one of the primaries, are deposited on the flat screen of the colour projection tube. In one version of the receiver, the vertical scanning frequency is 48 per second, but the vertical scanning amplitude is three times that which would correspond to the normal aspect ratio. In another version, three identical scanning patterns with a standard U.S.A. 3 : 4 aspect ratio are reproduced sequentially on each one of the phosphor strips. The three vertically displaced strips are then superimposed on a viewing screen by means of three projection lenses.

With this tube, the only limitation imposed on phosphor persistence is that no smear should appear when rapidly moving objects are shown. Thus, it is necessary that after one colour picture period (lasting 1/24th of a second), the residual brightness of any picture element be no more than about 3 per cent. of the initial excitation brilliance. The triphosphor tube just described employs Willemite for green. Willemite (zinc orthosilicate) decays to approximately 1 per cent. of its initial brightness 1/24th of a second after excitation. It is less important for the red and blue phosphors to have long persistence, because the luminosity ratio of the green primary to the red primary, in accordance with primaries " B," is 4 : 1. Thus, green, which has the longest persistence, also becomes the chief source of luminosity.

At present, primaries " B " are used in the electronic triphosphor tube in order to take advantage of the appreciable difference in luminous efficiency between the green Willemite and the red phosphor. When more efficient red phosphors become available, primaries " A " may also be employed in such a tube.

Further tests carried out by E. W. Engstrom[6] related to threshold flicker illumination for screens with varying persistence. Using a simulated system based on curves 6, 8, 9 and 10 of his paper, the threshold flicker illumination, for a persistence characteristic corresponding to Willemite, shows approximately a five-fold increase over a screen which decays to 1 per cent. of its initial value after 1/144th of a second. These tests encompassed a repetition-rate of 48 frames per second, which is the same as the colour frame frequency rate of the field sequential system under discussion.

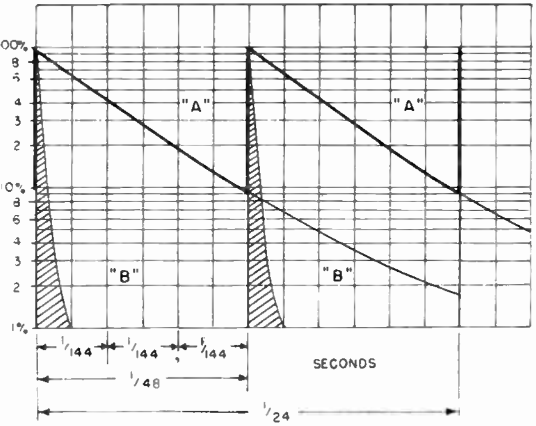


Fig. 6.—Pure colour transmitted once every $\frac{1}{48}$ sec. " A " Flicker component with long persistent phosphor. " B " Flicker component with present short persistent phosphor.

(Published data shows that the use of long persistence phosphors as shown at A gives a five-fold increase in the flicker threshold illumination over the short persistence phosphors as shown at "B.")

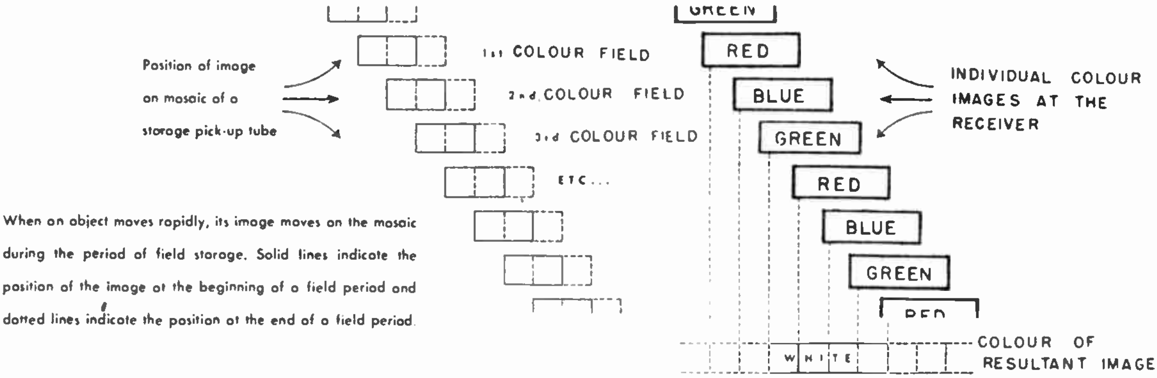
The decay characteristics of the short persistence white phosphor (zinc sulphide) used for direct viewing, and of zinc orthosilicate (Willemite) used in the triphosphor projection colour tube, were measured in the CBS laboratories. Ten-inch tubes were used and operated at 12 kV anode voltage. In Fig. 6, both characteristics are shown schematically. The area under curve A (drawn with thick lines) shows the light output when only the green field is excited, using Willemite as screen material. The shaded area under B shows the relatively short duration light impulses which correspond to the persistence characteristic of the white P-6 type phosphor used in the direct-viewing colour tubes.

In order to determine independently the quantitative influence of the long persistence phosphors on threshold flicker illumination, comparative tests were carried out, using the 10-in. tube with sulphide screen and the 10-in. tube with a Willemite screen. A group of observers were subjected to flicker tests. The colour frame rate was 48 per second, and the screens were excited only during the green colour field period, that is, every third 1/144th of a second. The average of all readings has indicated that the threshold flicker illumination for the long persistence Willemite screen was approximately four times that of the short persistence white screen used for direct-view colour pictures.

Applying the factor of 4 to the threshold flicker illumination values used in Fig. 5 for primaries " B " at 48 colour frames per second, threshold flicker would appear at a picture brightness of 37 foot-lamberts and maximum tolerable flicker at approximately 80 foot-lamberts. With primaries "A," long persistence phosphors permit a maximum threshold flicker highlight brightness of approximately 90 foot-lamberts, and for tolerable flicker at least 200 foot-lamberts. The values mentioned above are sufficiently conservative since the factor of 4, to which reference was made, was arrived at for green only. This factor would, no doubt, be greater if tests had been made on the basis of a white field, using long persistence phosphors for red and blue as well.

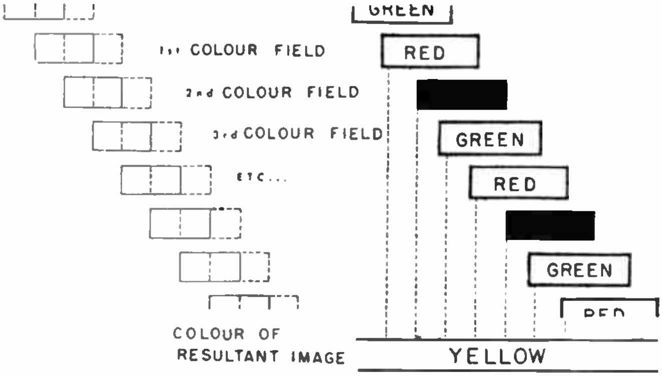
Colour Fringing

When the image of an object moves across the storage surface of a television camera, it will leave behind a trail of electric charges. When that storage surface is scanned, the electric charges representing the trail of the moving object are partially or completely wiped off. In certain types of pickup tubes, such as the orthicon or the image-orthicon, the geometrical and electrical constants of the tube can be so adjusted that the electrical charges which are produced on the storage surface by a stationary or moving image are almost completely erased with a single scansion.



When an object moves rapidly, its image moves on the mosaic during the period of field storage. Solid lines indicate the position of the image at the beginning of a field period and dotted lines indicate the position at the end of a field period.

A. WHITE OBJECT MOVING ONE-HALF ITS WIDTH DURING A COLOUR FIELD (1/144 SEC)



B. YELLOW OBJECT MOVING ONE-HALF ITS WIDTH DURING A COLOUR FIELD (1/144 SEC)

Fig. 7.

If the storage surface (in the orthicon this is a photosensitive mosaic and in the image-orthicon a semi-conductive glass surface) is charged up in a linear fashion, an object moving at a substantially uniform velocity would not be transmitted as individual stationary images, but as a contiguous succession of uniform streaks. These are composed of sections which correspond to the distance which the object has travelled during the vertical scanning interval.

In a simultaneous colour television system where three cameras pick up the object at the same time, a moving object at the transmitting end will be reproduced on the receiving screen in its original colour during all phases of its travel. Assuming that perfect registration is maintained with the three cameras and the three receiving tubes, the final image will not show colour fringes, leading or trailing the moving object, regardless of its speed.

In a sequential colour television system, the possibility of colour fringing exists if the colour switching rate is such that between two successive colour changes a moving object at the pickup has progressed a sufficient amount to show a succession of leading and trailing colour fringes. It is the intensity of these colour fringes and their magnitude in relation to a picture element which determine the subjective effect of colour fringing.

Only when the colour switching rate corresponds to the field repetition frequency is it feasible that an object could move rapidly enough to show colour fringes. However, it is not difficult to see that the important consideration is not the absolute speed of the object, but the relationship of the distance travelled during one colour field period to the size of the object, measured in the direction of its travel.

Figure 7 (*a*) shows a white object moving in a horizontal direction at a specific rate of speed so chosen that during a colour field period the object will have progressed a distance equal to half of its own width measured along its trajectory. The moving object, in the form of an oblong whose length is twice its height, is shown on the left side of Fig. 7 (*a*) in successive positions corresponding to progressive colour field periods; the object itself is drawn with solid lines. The dotted outlines to the right of the moving object indicate the actual displacement. On the right side of Fig. 7 (*a*), the individual colour images, which correspond to primaries red, blue and green are shown in succession. Here again, the object has moved forward during a colour field period an amount equal to half its own length.

Underneath the displaced colour images, a colour summation is carried out in view of the fact that the colour repetition rate is sufficiently fast to cause complete colour fusion in the observer's eyes. It is well to note that along each column (drawn with dotted lines on the right side of Fig. 7 (*a*)) all three primary colours appear. The resultant impression will be white, as indicated at the bottom of the dotted columns in the form of white squares. Thus, the colour of a white moving object will always be solid white and void of colour fringes as long as the distance traversed during one colour field period does not exceed half its own width measured in the direction of travel. This establishes what may be called a limiting velocity. Simple calculation shows that this limiting velocity is very high. For example, an automobile travelling at the rate of 800 miles per hour could progress half its length (or about 8 ft.) in 1/144th of a second without showing colour fringing. A white object which extends 1 ft. in the direction of motion has a fringe limiting velocity of 50 miles per hour. As the length increases, this velocity will increase in the same proportion. In practice, this relationship has significance only if the moving object on the screen is larger than a few picture elements.

A tennis ball, for instance, can travel as fast as 60 m.p.h. and, therefore, will move about three-and-a-half times its own diameter in 1/144th of a second. Thus theoretically, the tennis ball would appear on the receiving screen as individual red, blue and green dots. Actually, however, when the object is small in relation to the picture size, the individual colours will fuse, and the ball will tend to appear as a grey streak. It is important to point out that in a monochromatic system a normally white tennis ball when travelling at 60 m.p.h. will appear to be grey, unless it is followed by the lens of the camera. This is because the image of the ball rests only for a brief period on any given portion of the storage surface of the television camera. Thus, the corresponding signal amplitude will be lower than if the ball were stationary. As a matter of fact, the apparent brightness of the tennis ball travelling at 60 m.p.h. will be approximately one-third that of a stationary ball. When the flight of the tennis ball is transmitted through the field sequential colour television system, it appears on the receiving screen in the following manner. Until it reaches a speed of approximately 10 m.p.h., the ball will show no fringings. Then, as the ball gathers speed, the amount of fringing will increase in proportion to the velocity. However, the apparent intensity of the ball's image at the receiver will diminish at the same rate due to the decreasing charging time at the camera. As a result, the individual colours constituting the colour fringes will tend to fade out against the background.

A large variety of tests with the field sequential colour television system have proved that colour fringing is a rare phenomenon and occurs far less frequently, for instance, than stroboscopic effects in motion pictures.

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C.C.I.R.

The International Consultative Committee on Radio Communications, of which the B.B.C. is a member, held its first post-war meeting in Stockholm in 1948, at which questions relating to all technical activities in radio communications were discussed. Amongst these was the question of standards for television to assist the development of television services throughout the world, and to facilitate the manufacture of equipment and the interchange of programmes between different countries. These subjects involve very complicated and difficult technical issues, and in an attempt to resolve then an International Study Group was set up under the chairmanship of Mr. Erik Esping, of Sweden.

It was arranged that the Study Group should make a tour of inspection which started at the end of March in the United States of America. The Group then went to Paris and Holland.

On April 26th it arrived in the United Kingdom. The first part of the inspections in this country were devoted to laboratory and service demonstrations of the B.B.C. television system.

The delegates visited Birmingham and, after visits to the Post Office television radio link installations, were taken out to Sutton Coldfield to inspect the transmitter there. It was explained that the transmitter at Holme Moss, which is now under construction, will be generally similar in design and layout to the Sutton Coldfield installation, and with the high aerial and the high site which has been chosen, will mean that the Holme Moss transmitter will have a service range considerably greater than that of any other television station yet built, or likely to be built in the near future.

Demonstrations were also given to the CCIR delegates at the B.B.C. Research Station at Kingswood Warren in Surrey. These were generally arranged to show the interdependence between television standards adopted and the performance obtained, the wavelengths available, the cost and many other important factors affecting a television service.

One demonstration showed the effect of passing a 405-line picture and a 625-line picture through an electrical network which would simulate the effect of a reasonably priced receiver and the already internationally agreed line distribution system. The comparative tests were carried out with and without the small distortions inevitably present in such a practical system. It was shown that, while the 405-line and the 625-line picture generated by the camera varied but little in initial appearance without this distortion, after both pictures had been passed through the simulating network, the 405-line picture was only very slightly distorted, but the 625-line picture was considerably distorted. The net result was that as far as the viewer was concerned the 405-line picture was considerably better. The effect of spot broadcasting, which makes the line structure of the picture invisible, was also demonstrated.

The delegates were also shown a map giving the location of the ten television transmitters at present projected for the ultimate development of the present television standards in this country, and it was demonstrated that in the wavelength space available just sufficient " ether channels " to enable this to be done could be found.

A further problem, which was of great interest to the delegates, was a demonstration of the effects of sharing wavelengths for television purposes. Several means by which this might be done were shown, and the limitations on each method outlined.

A demonstration was given of the testing of the scale model of the Sutton Coldfield aerial, from which the aerial at that station and the aerials to be used at other stations have been designed. By a specially developed technique it is possible conveniently to make models one-seventh the size of the final model, and to carry out precise measurements at seven times the frequency to determine the best design for the final structure.

A demonstration of colour television was also given. It was explained to the delegates that at this demonstration they would see one particular form of colour television, but that no significance could be attached to the fact that a particular method of producing a colour television picture was being employed. In due course, the B.B.C. will consider all possible methods of producing a coloured picture before any decision is taken. It was emphasized that, as far as the United Kingdom is concerned, the B.B.C. will for several years concentrate on the widespread diffusion of the present monochrome picture on 405-lines, and that it is hoped to complete the whole television distribution system as now planned by the end of 1954.

BRIGHTNESS AND CONTRAST IN TELEVISION*

by

P. C. Goldmark†

How bright does a television picture need to be? The American Standard Association's recommendation for motion picture screen brightness is 10 foot-lamberts without film in the gate. With clear film this value would drop to approximately eight foot-lamberts. The highlight brightness of the average 16-mm. home colour film is approximately one-half of this value, or four foot-lamberts as measured on a screen 3 ft. wide. Thus, if television were to be viewed only in darkened rooms, these brightness values, based on motion picture experience, would be adequate.

There is, however, an important factor which, in most instances, prevents both motion picture and television images from being satisfactorily viewed in a well-lighted room—the loss of contrast range. Since motion picture and television screens freely reflect the surrounding light, a lower limit is set automatically to the darkest shades reproducible.

A good picture, whether film, television, painting, or engraving, should appear to the eye to have a contrast range of approximately 30 : 1. This means that the highlights of such pictures, when viewed with surrounding illumination, should be about 30 times brighter than the darkest shade obtainable under such conditions.

Paintings, drawings and photographs usually display deep satisfactory shades of blacks since the dyes, paints or printing inks employed for black are extremely light absorbent, thus ensuring adequate contrast range. Usually, it is taken for granted, therefore, that regardless of the amount of light directed on to a photograph or painting, the contrast range remains the same.

However, motion pictures and television, two media which derive their blacks from an absence of light, cannot present darker shades than those determined by the surrounding light. Thus, in order to approximate the contrast range of the original scene, the highlights of these images, as a rule, would have to be many times brighter than the ambient room illumination. Motion picture projectors, whether in the theatre or at home, are unable to furnish this extra brightness and, therefore, the pictures must be viewed in the dark. Television pictures, whether black-and-white or in colour, unquestionably will be viewed during times when darkening the room would be inconvenient. Let us examine what happens to television images under such conditions.

The light reflected from the walls of the average artificially-lighted room is seldom in excess of five foot-lamberts. Allowing for reflection loss, this also represents the maximum highlight brightness of the pictures and photographs on the walls of such a room. During the day, with natural illumination, the brightness values are higher. It is safe to assume that television rarely would be viewed in rooms where the illumination of the area surrounding the receiver is more than 20 foot-lamberts.

The majority of the current black-and-white direct-viewing television receivers, when located in rooms where the ambient illumination is 20 foot-lamberts, reflect approximately 15 foot-lamberts from their screens. In order to obtain a contrast range of 30 : 1 in pictures produced by these receivers, the necessary high-light brightness would have to be 15 × 30, or 450 foot-lamberts.

Actually, many receivers do not furnish more than 30 foot-lamberts measured on a blank raster. Thus, with an ambient illumination of 20 foot-lamberts, the maximum contrast range will not be in excess of 3 : 1 (the ratio of the maximum highlight brightness of 30 plus 15 foot-lamberts to the reflected ambient room light of 15 foot-lamberts). If one wished to

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† Columbia Broadcasting System Inc.
Dr. Goldmark presented a similar paper to the A.I.E.E. in March 1949.

obtain a contrast range of 30 : 1 with these receivers, the reflected illumination from the screens would have to be not more than 1/30th of the maximum highlight brightness, or one foot-lambert. Correspondingly, the surrounding illumination could be only 25 per cent. higher, or 1·25 foot-lamberts—a dark room, indeed.

The conclusion one draws from this is that many present day black-and-white receivers should not be viewed in rooms where the surrounding illumination is much in excess of one foot-lambert ; otherwise, the picture will suffer from inadequate contrast range. Let us suppose that one wished to view television pictures with an ambient illumination as high as 20 foot-lamberts and the blank screen of the receiver were still to reflect 75 per cent. of the ambient illumination, or 15 foot-lamberts. In order to produce the desired maximum contrast range of 30 : 1, the highlight brightness of the television images would have to be increased to a total of 450 foot-lamberts.

It is quite conceivable that commercial direct-view type receivers some day will be capable of furnishing a highlight brightness of 450 foot-lamberts. It is doubtful, however, that this would be a satisfactory solution, since viewing such a bright image without a correspondingly bright surrounding would be uncomfortable. Assuming that the presently used field repetition rate of 60 per second were employed, such a picture would, in addition, display objectionable flicker.

Thus, it is evident from the examples cited that for adequate image recognition, contrast range is more important than mere brilliance. This leads us into certain considerations regarding the human eye.

One of the most important capacities of the eye is its ability to discriminate brightness in space. This often is called contrast recognition. It is measured as the relative brilliance of nearby areas with an incremental difference in brightness.

Under the best conditions, the human eye can discriminate between adjacent areas only when the contrast difference is not less than 1 per cent. This should not be confused with the ability of the eye to adapt itself to different light levels without appreciably impairing visual acuity. During a single day, our eyes may be exposed to a range of illumination of the order of one billion to one—from bright sunlight to dim starlight. For our purposes, we need only consider illumination levels which are in excess of approximately one-tenth foot-lambert.

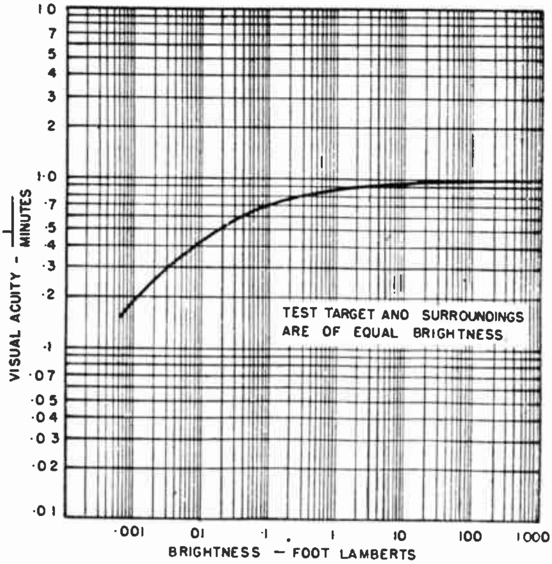

Fig. 1.—Visual acuity versus brightness.

It is commonly known that the capacity for visual acuity will vary with brightness. Other factors, such as contrast discrimination, flicker recognition and colour discrimination, also grow with brightness.

Fig. 1 illustrates how visual acuity varies with brightness. On the ordinate, visual acuity is plotted in terms of the reciprocal of the visual angle (measured in minutes). Thus, the visual acuity of 1·0 represents the capacity of the eye just barely to resolve detail which occupies one minute of the visual angle. In the same way, for the eye to distinguish a certain detail which corresponds to a visual angle of 10 minutes, a visual acuity of only 0·1 would be required, and so on. A visual acuity of 1·0 corresponds to a resolving power of 20/20. The maximum visual acuity which the human eye normally achieves is a little over 2·0.

The test object used to determine Fig. 1 consisted of a grating composed of black and white bars. It is evident from this diagram that for brightnesses up to about one-tenth of one foot-lambert, the visual acuity increases fairly rapidly. Between two and 1,000 foot-lamberts, however, the visual acuity rises only a negligible amount—from 0·9 to 1·0. Thus, from the point of view of resolution, it hardly pays to increase the brightness of pictures above two foot-lamberts highlight brightness. It is important to note that the measurements represented in Fig. 1 were made with a surrounding of the same brightness as the test target. If the brightness of the surrounding were much different from that of the target, the visual acuity would not only cease increasing, but would actually decrease, even if the brightness of the test object should be raised above five foot-lamberts.

The same holds true for the faculty of contrast discrimination. Fig. 2 indicates the smallest contrast the eye can see at different brightnesses as applied to three different sized test areas. Even for such a small area as corresponds to a diameter of 10 minutes, brightness is advantageous only up to about two foot-lamberts, just as in the case of acuity. Beyond that, contrast recognition increases at a very slow rate with increasing brightness.

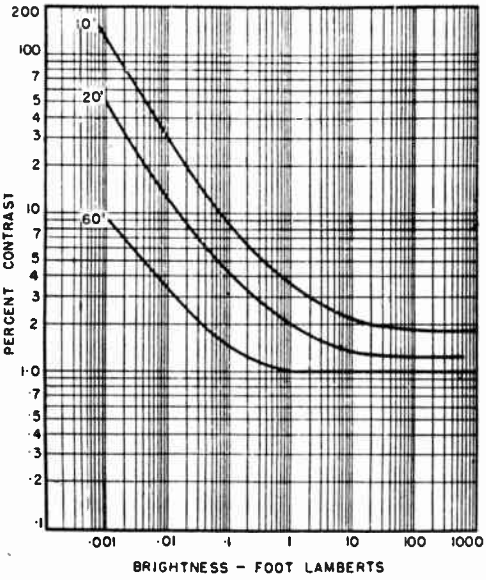

Fig. 2.—Contrast discrimination versus brightness.

Contrast values for the three test target areas indicate that for a given brightness, the necessary contrast for barely perceiving a detail varies approximately as the inverse of the size of that detail; in other words, the larger the object, the smaller need be the required contrast, and vice versa. Increased brightness is of use to the eye only if it brings with it increased contrast. It is this increased contrast which assists the eye to see fine detail. Thus, if one wishes to see greater detail in a picture or a scene, one may increase the contrast, if possible, or else move closer to the scene or picture for a more detailed examination. The limit is set by the maximum possible picture brightness and then by the resolving power of the eye.

Several inherent properties of television make it difficult either to increase the brightness or view the picture from a closer range. The most basic limitation is that television pictures are made up of approximately 500 horizontal scanning lines. Each line can show no detail along its height, but can show variations along its length. No matter how closely one looks at a television screen, or how bright it is, no detail smaller than a square area, whose height is roughly that of a line, can be perceived.

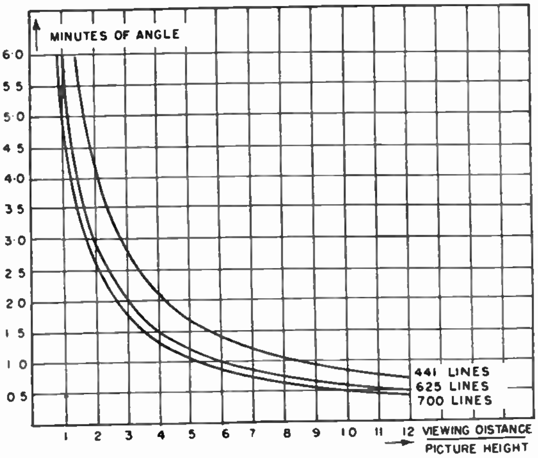

Fig. 3.—Visual acuity versus $\frac{\textit{viewing distance}}{\textit{picture height}}$ *ratio.*

Applying a visual acuity of approximately 1·0, a television picture with 500 active scanning lines would have to be viewed at a distance of about seven times the picture height, in order that the available detail be resolved. Viewing it closer would not yield additional detail to the normal eye. At a greater viewing distance, however, the apparent resolution would decrease.

Fig. 3 shows this relationship between visual acuity and optimum viewing distance.

We can use Fig. 1 to determine the optimum brightness with which it is possible to resolve a 525-line television picture. As pointed out before a visual acuity of approximately 20/20, or nearly 1·0, corresponding to a visual angle of one minute, represents the resolving power of a normal eye, and, according to Fig. 1, is achieved at a brightness of about one foot-lambert. This, however, represents unusually favourable conditions since the test target in Fig. 1 has a high contrast range (black and white bars). In television, both fine and coarse detail often occur when the contrast is less than would correspond to the full range between black and maximum white. Therefore, one has to consider the influence of the picture illumination level on the resolving power of the eye for finer gradations.

It was shown earlier that a certain reciprocity existed in the relationship represented in Fig. 2 ; namely, that for a given brightness, the minimum contrast discrimination and the test object size are, in the first approximation, interchangeable. Applying this to the specific television problem under discussion, we find that for a test object corresponding to a visual angle of roughly one minute, a picture highlight illumination of 10 foot-lamberts would allow a minimum recognizable contrast step of about 20 per cent.

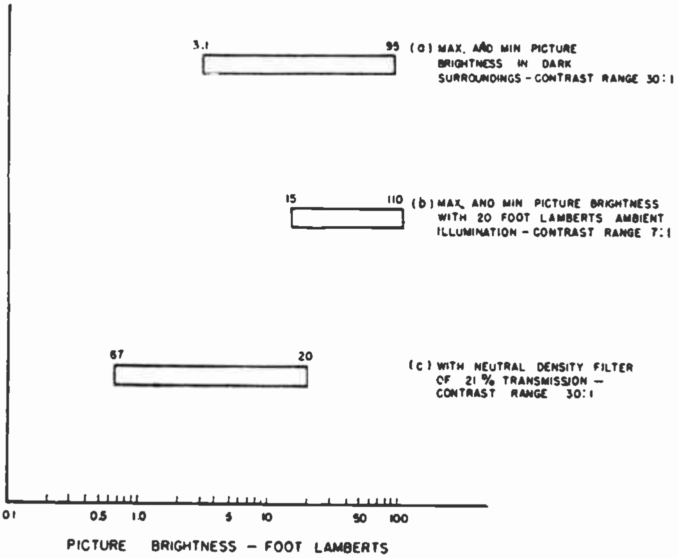

Fig. 4.—Effect of neutral density filter on contrast range.
(*Direct vie wtube*).

Television pictures which contain a maximum contrast range of 30 : 1 are considered entirely adequate, although the present state of the art does not yet permit such a range to be maintained in fine detail. Accordingly, the 20 per cent. minimum contrast discrimination for the finest picture detail in a 525-line system with a highlight brightness of 10 foot-lamberts, corresponds to a maximum of $\frac{\log 30}{\log 1{\cdot}2}$ or roughly 19 discernible shades between black and maximum white.

It is thus evident that 10 foot-lamberts highlight brightness is adequate from the point of view of resolution and contrast discrimination. It was this value which was quoted earlier as recommended for motion picture screen illumination by the American Standards Association.

One of the proposed solutions for producing adequate contrast range in television pictures suggested increasing the picture highlight brightness to a value many times above that of the surrounding brightness. This solution does not solve the problem because local illumination, which is much higher than the general ambient illumination, produces a sensation of glare, and glare reduces visual effectiveness. Experiments with visual acuity and contrast recognition have shown that both reach their optimum for a given brightness when the surrounding illumination is about the same as the locally illuminated area. A surrounding too bright or too dim tends to decrease effectiveness of the visual functions.

When we gaze through a window at an outdoor scene, the window through which we look will be a source of glare to us. Not only will it produce discomfort, but our visual functions actually will be impaired, and our eyesight will be less perfect than if we viewed the scene surrounded by the same over-all brightness. This fact has become so important in visual studies that it is an accepted practice to provide a large surrounding area of the same brightness as the test area under observation.

Quite aside from these considerations, it is not economical to produce television receivers capable of extreme picture brightnesses. Yet a way has to be found to maintain adequate contrast range with normal ambient illumination.

A simple solution, which does not entail undue cost and yet is effective, is illustrated in Fig. 4. Column "a" shows a picture tube illumination of 95 foot-lamberts plotted against a minimum brightness of 3·1 foot-lamberts. Viewed in a darkened room the resulting maximum contrast range would be 95 divided by 3·1, or about 30.

Different conditions arise when the same picture is viewed in a well-lighted room with an ambient illumination of 20 foot-lamberts (as read on a white surface surrounding the picture tube). These are illustrated in Column "b," Fig. 4. The maximum highlight brightness is now 110 foot-lamberts, which is the sum of the reflected ambient light, or about 15 foot-lamberts plus the original maximum picture highlight brightness of 95 foot-lamberts. Because the minimum possible picture brightness is 15 foot-lamberts, it follows that the resulting maximum contrast range is 95 divided by 15, or about 7 : 1. This would produce a picture of rather poor quality.

Column "c" illustrates what happens if a neutral density filter of 21 per cent. light transmission were to be placed against the front of the cathode-ray tube. This filter could be a thin layer of grey cellophane, or any other suitable light absorbing material. The original high-light brightness of 95 foot-lamberts is now reduced to $\frac{95 \times 21}{100}$, or 20 foot-lamberts. On the other hand, the reflected ambient light of 15 foot-lamberts is reduced by the square of the filter attenuation factor, resulting in a minimum possible picture brightness of 15 divided by 22·6, or 0·67 foot-lambert. The peak highlight brightness was 20 foot-lamberts, and thus, the maximum contrast range for this condition is $\frac{20}{0 \cdot 67}$, or 30. It is important to keep in mind that this is possible with an ambient illumination of 20 foot-lamberts and a picture tube highlight brightness of only 95 foot-lamberts.

The following is a mathematical analysis of the effect of the neutral density filter on contrast and brightness. If the contrast range is limited by ambient illumination, then

$$I_A \gg B_{min}$$

where I_A is the surrounding light reflected from the picture screen and B_{min} is the least possible brightness (corresponding to black) when the television receiver is viewed in complete darkness ($I_A = 0$). Under the same conditions, B_{max} shall be the maximum picture highlight brightness. The contrast range then will be no greater than

$$\frac{B_{max}}{B_{min}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

When the ambient light I_A is not zero, the picture highlight brightness becomes $B_{max} + I_A$ and the minimum brightness I_A; the contrast range will be

$$\frac{B_{max} + I_A}{I_A} \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

When a neutral density filter with transmission factor "a" (where $0 < a < 1$) is placed in front of the picture screen so that ambient light can penetrate to the screen only through the neutral density filter, then the picture highlight brightness will be reduced to

$$(B_{max} + I_A \, . \, a)\, a$$

and the minimum brilliance to

$$I_A \, . \, a^2$$

The contrast range then will be

$$\frac{a\,(B_{max} + I_A \, . \, a)}{I_A \, . \, a^2} = \frac{B_{max} + I_A \, . \, a}{I_A \, . \, a} \quad \ldots . (11)$$

The increase in contrast range due to the use of the neutral density filter is (11) divided by (10), or

$$\frac{(B_{max} + I_A \, . \, a)\, I_A}{I_A \, . \, a\,(B_{max} + I_A)} = \frac{B_{max} + I_A \, . \, a}{a\,(B_{max} + I_A)} \quad \ldots . (12)$$

In the first approximation, $(B_{max} + I_A \, . \, a)$ equals $(B_{max} + I_A)$ so that the increase in contrast becomes roughly $1/a$. If, for instance, a neutral density filter is used with $a = 0 \cdot 33$ (33 per cent. transmission), and the ambient illumination were such that without the filter the contrast range were 10 : 1, then, through the use of the filter, the contrast range would increase threefold or to about 30 : 1.

It was naturally desirable to find out what effect this trading of higher brightness and low-contrast range against lower brightness and high-contrast range would have on a group of observers. Actual tests were carried out in the Columbia Broadcasting System's laboratories late in 1946. The method used is illustrated in Fig. 5.

A simulated test was utilized, representing a television projection set capable of high initial brightness. A neutral density filter of 33 per cent. transmission was placed in front of the projection receiver so that the surrounding illumination, incident on the screen, had to pass through the neutral density filter twice before reaching the observer's eye, while the picture brightness was reduced only once. The slide projector produced a 15 by 20 in. picture on a ground-glass screen. Around the screen was a large white border, and both were externally illuminated by the same source. The light reflected from the border measured 20 foot-lamberts, and the light reflected from the projection screen was 4·5 foot-lamberts. Without the neutral density filter, the picture had a highlight brightness of 60 foot-lamberts, and thus, with a minimum screen brightness of 4·5 foot-lamberts, the contrast range was about 13 : 1 (Fig. 5, Column a). With the neutral density filter in front of the projection screen, the highlight brightness was reduced to about 20 foot-lamberts, whereas the minimum screen brightness was reduced to one-tenth of its original value, or, roughly, one-half foot-lambert. As a result, the contrast range was trebled and became 40 : 1 (Fig. 5, Column b).

For the test, a number of different colour slides were projected on to a screen from the rear. The picture highlight brightness, in each instance, was adjusted to measure 60 foot-lamberts without the neutral density filter. Seven observers participated in the tests, and each observer viewed seven different slides. Out of a total of 49 observations, in 43 instances the observers indicated preference for the picture with the neutral density filter (conditions as indicated in Fig. 5, Column b). In the other six observations, the individuals specified no preference. In no instance was there preference indicated when pictures were shown with greater brightness but less contrast (Fig. 5, Column a).

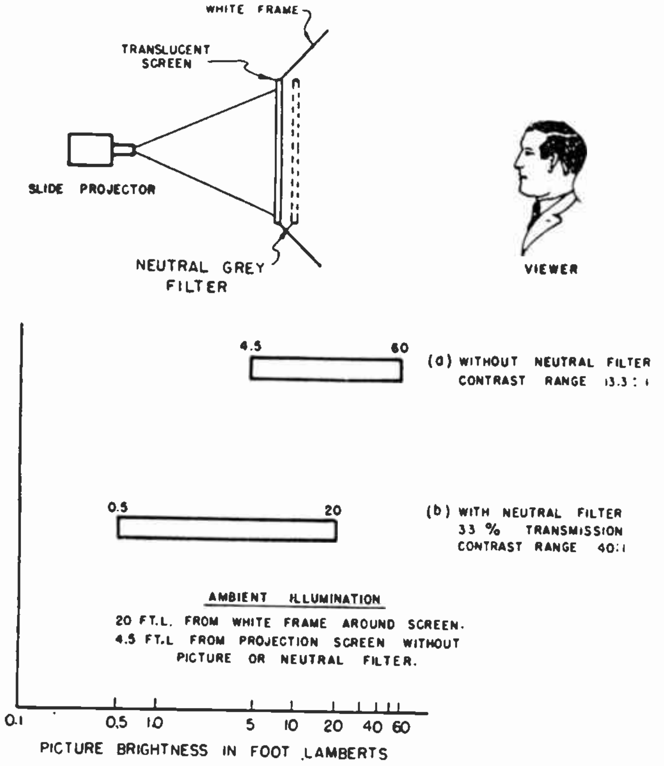

Fig. 5.—Contrast range of projected pictures in the presence of ambient illumination when viewed with and without neutral filters.

During these tests, the observers found, almost without exception, that a certain three-dimensional effect, originally present in some of the colour slides, disappeared when they viewed the projection pictures without the neutral density filter. They found, however, that it was present again when the contrast range was re-established, even though the highlight brightness was reduced to one-third of its original value.

In the colour television system developed by CBS, the direct-viewing receivers employ rotating colour discs in front of the cathode-ray tube. The colour discs necessarily absorb an appreciable amount of light from the visible spectrum, and the average light loss of the red, blue and green filters is between eight and ten. This means that if the cathode-ray tube behind the filters had a highlight brightness of 200 foot-lamberts, the observer would see between 20 and 25 foot-lamberts.

This apparent loss of light, however, is compensated for to a large degree by greatly improved contrast range in the presence of ambient illumination. This, again, is due to the fact that the surrounding light has to pass through the colour filters before being reflected back by the white screen of the cathode-ray tube, and then has to pass through the colour filters again before reaching the observer's eye. As a result, colour television receivers with colour discs can be viewed in well-lighted rooms without loss of contrast range.

This process, taking place within the colour television receiver, has been re-created in two projectors placed side by side, and the results are shown in Fig. 6. Fig 6*a* shows diagrammatically how a picture screen, with a highlight brightness of 20 foot-lamberts, suffers from poor contrast range (2·7 : 1). To simulate the conditions created by the colour filters, Fig. 6*b* shows a resultant highlight brightness of 20 foot-lamberts, but with a potential contrast range of 160 : 1.

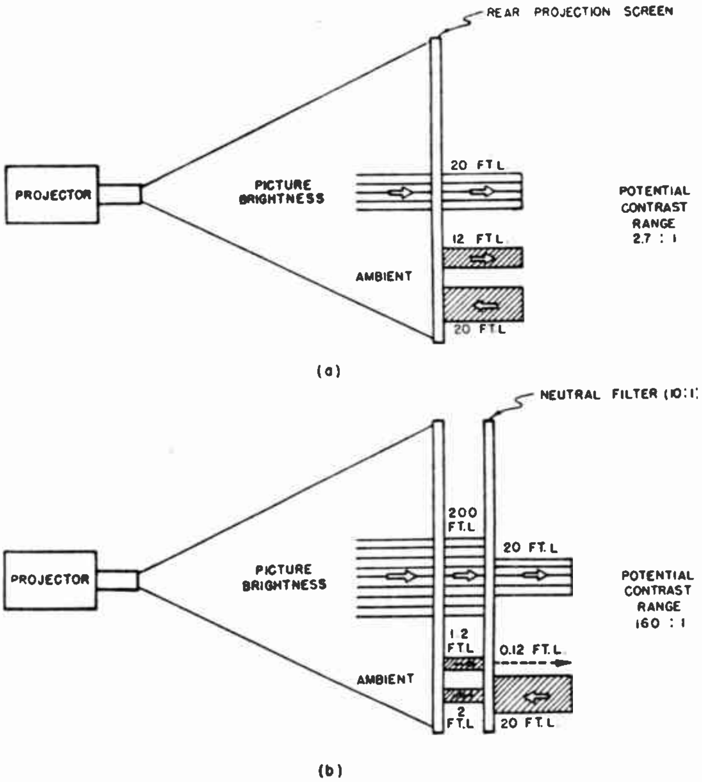

Fig. 6.—Effect of neutral grey filter in preserving contrast.

Reference

1. Goldmark, P. C. "Brightness and Contrast in Television." *Electrical Engineering*, pp. 237-242 (March 1949).

TRANSFERS AND ELECTIONS TO MEMBERSHIP

Subsequent to the publication of elections to membership which appeared in the May issue of the Journal, a meeting of the Membership Committee was held on June 6th, 1950. Seventeen proposals for direct election to Graduateship or higher grade of membership were considered, and eighteen proposals for transfer to Graduate or higher grade of membership.

The following list of elections was approved by the General Council : Thirteen for direct election to Graduate or higher grade of membership, and fourteen for transfer to Graduate or higher grade of membership.

Direct Election to Associate Member

Butterworth, Robert Anderson, Sqd./Ldr.	Emsworth, Hants.
Williams, Robert Wesley, Wing/Cmdr.	Winchester, Hants.

Direct Election to Companion

Harris, William Jackson	Glasgow

Direct Election to Associate

Bird, Henry George	Manchester
Boddington, Derrick	Bedford
Brierley, Ronald	Derby
Das, Daleep Bruce, Flt./Lt.	Rajpur
George, George Naguib	Heliopolis, Egypt
Laurence, Roger Frederic	Guildford, Surrey
Luscombe, Leslie	London, N.8
Russell, William Albert, Flt./Lt., B.Sc.	Cranwell, Lincs.
Skelton, Peter, Flt./Lt.	Kenya, E. Africa
Tully, Alexander	Kenya, E. Africa

Direct Election to Graduate

Thompson, Philip Martin	Liverpool

Transfer from Associate Member to Full Member

Ahmad, Riaz, M.Sc.	Karachi, Pakistan
Keen, Arthur William	Twickenham, Middlesex

Transfer from Associate to Associate Member

Batchellor, John Robert, M.A.(Cantab.)	Romford, Essex
Croft, Roy Thomas	Malvern, Worcs
Malloy, John James, Lieut(L)	Kenton, Middlesex
Tomlinson, Terence Bernard, B.Sc.	Hedge End, Hants.

Transfer from Student to Associate

Brown, William Charles, Flt./Lt.	Singapore, Malaya
Charlton, Leslie	Johannesburg, S. Africa
Hansen, Hans Adolf Brodersen	Calais, France
Ryland, Arnold	Wellington, N. Zealand

Transfer from Student to Graduate

Francis, Idris Alan	Manchester
Korczynski, Wladyslaw	London, W.9
Seshachary, Veeravalli, B.Sc.	Madras, India
Smith, Frederick, George	Cardiff