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What is Engineering?

ENGINEERING is today one of the professions in which the need for precision of statement is almost an article of faith. It is therefore surprising that there have recently been so many imprecise statements purporting to define 'Engineering'.

It may be significant that the imprecision usually consists of over-generalization about the scope of Engineering. Consider for example the statement that 'Engineering is the application of science to increase the material prosperity of mankind.' Such a definition would include agriculture, medicine, psychology, sociology (and could include both economics and education if the applications of science in these fields had been more fruitful).

The above statement becomes a little less grossly imprecise if, for '*science*', we write '*the physical sciences*', thereby excluding the biological and social sciences. Yet it still covers a great deal more than is commonly understood by the description, 'Engineering'.

Ask many metallurgists, industrial physicists or applied mathematicians why their respective professional associations are not directly interested in the Council of Engineering Institutions. The answer will be that they do not consider themselves to be 'Engineers'—though most of them will agree that they are, in the widest sense of the word, 'Technologists'.

The man of action tends to dismiss these considerations as 'hair-splitting', and identifies the semantic with the pedantic. But later he may find that his own actions are circumscribed by other people's interpretation of words. Thus even if we cannot agree on precise definitions of 'Technology' and 'Engineering', it will pay us to ask whether there is any significance in the fact that we have a Ministry of the first but a Council of Institutions of the second. Should it be conceded that 'Engineering', the field covered by the C.E.I., is only a part of 'Technology'?

There are undoubtedly corporate members of our own Institution and other constituent Institutions of the C.E.I. who could more aptly be described as applied physicists than as engineers. The borderline between engineering and the remainder of technology is necessarily blurred and is still negotiable. The rapid developments which are to be expected in applied science (and particularly in applied electronics) in the remaining decades of the twentieth century will give birth to new major technologies which will breed professional associations that demand and deserve separate recognition. Can they be accommodated within the C.E.I.? The answer will depend upon whether they lie inside or outside the blurred boundaries of 'Engineering'.

This means that the answer lies with the C.E.I. itself, for two reasons. First, because Government and other official bodies will undoubtedly regard the C.E.I. as the authority on the question: 'What is Engineering?' Secondly, because the C.E.I. by the very act of prescribing the routes to professional engineering qualification, will have staked out the boundaries of its own territory and conceded the remaining lands to 'Technology'.

We can then wait and see on which side of the fence the flowers will grow.

E. W.

INSTITUTION NOTICES

I.E.R.E.–I.E.E. Collaboration in India

The Indian Division of the I.E.R.E. was formed as a result of a visit to that country of the Secretary, Mr. G. D. Clifford in 1951. A headquarters office was established in Bangalore and in the ensuing years it has become the strongest and most flourishing of the Institution's Overseas Divisions. With a view to furthering technological development in India, discussions were initiated recently between the Institution and the Institution of Electrical Engineers on possible collaboration in that country.

The Council of the I.E.R.E. is pleased to announce that the I.E.E. has now accepted an invitation to share the I.E.R.E. office facilities in India. The headquarters office will remain in Bangalore at 7 Nandidurg Road, Bangalore 6. (Telephone Bangalore 29640.)

Electronics and Open Heart Surgery

Through its Medical and Biological Electronics Group, the Institution is associated with a Collaborate Meeting on 'Interdisciplinary Problems Associated with Open Heart Surgery and After Care', which is being organized by the U.K. Liaison Committee for Sciences Allied to Medicine and Biology, at Oxford from 27th to 29th March 1968. The four main sessions will deal with, respectively: diagnostic procedures, open heart surgery, after care, and respiratory problems. Short papers by electronic engineers intended to provide answers to some of the clinical problems which will be posed by cardiac surgeons will be welcomed.

Further information on the meeting, which will be supported by a scientific and technical exhibition, may be obtained from Mr. G. S. Innes, B.Sc., C.Eng., St. Bartholomew's Hospital, London, E.C.1, to whom offers of papers should also be sent.

'MOGA 68'

The 7th International Conference on Microwave and Optical Generation and Amplification will be held in Hamburg, from 16th to 20th September 1968. The Conference is sponsored by the Communication Engineering Group of the V.D.E. in co-operation with the Hamburg Section of the V.D.E., and the German Section of the I.E.E.E.

The scientific programme will be co-ordinated by a committee under the chairmanship of Professor Dr. Ing. F. W. Gundlach. The object of the Conference will be to report and discuss further scientific knowledge achieved in this particular field, thus continuing the tradition established by previous international conferences on Microwave Tubes (Paris 1956, London 1958, Munich 1960, The Hague 1962, Paris 1964, and Cambridge 1966). Since 1966 the original scope of the Conference has been extended to include the application of solid state devices, plasma and other systems for the generation and amplification of oscillation in the optical and microwave ranges.

Requests for fuller information, which will be circulated in January 1968 to previous participants in these Conferences, should be addressed to the Conference Office, 'MOGA 68', c/o Valvo GmbH., Burchardstrasse 19, D-2 Hamburg 1, Germany.

Noise in Electronic Devices

A Conference on Physical Aspects of Noise in Electronic Devices is being arranged by the Institute of Physics and the Physical Society, in collaboration with the Institution of Electrical Engineers. The Conference will be held at the University of Nottingham from 11th to 13th September, 1968.

Review papers will be presented on: noise aspects of grid controlled valves at very low frequencies; microwave tubes; measurement techniques; semiconductor devices; flicker, $1/f$ and other very low frequency noise; oscillators; radiation statistics; lasers, masers and parametric amplifiers; particle detectors and photodetectors.

Contributions on these or related subjects are invited. Summaries (in triplicate) should be submitted not later than 31st May 1968 to: Conference Secretary, I. Snowden, The M-O Valve Co. Ltd., Research Laboratories, First Way, Exhibition Grounds, Wembley, Middlesex.

Further information and registration details will be available early in the new year, and may be obtained from The Meetings Officer, Institute of Physics and the Physical Society, 47 Belgrave Square, London, S.W.1.

Ceylon Public Service Commission

Advice has been received from the Council's representative in Ceylon, Mr. D. F. Edirisinghe, that the Ceylon Public Service Commission now recognizes corporate membership of the I.E.R.E. as a complete qualification for recruitment to appropriate professional engineering posts. This recognition is irrespective of the date at which exemption from the Graduate Examination was obtained. (In 1964 the ruling required applicants to have satisfied the Examination syllabus of September 1962.)

Ceylon thus joins the growing number of governments which have accepted Institution corporate membership as a full qualification for professional engineering posts. A leaflet giving details of such recognition of the Institution in Great Britain and other countries throughout the world is available on request from the Membership Secretary, at 9 Bedford Square, London, W.C.1.

U.D.C.621-52

Coefficient Plane Synthesis of Zero Velocity Lag Servomechanisms

By

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Summary: The basic coefficient plane technique is extended to cover the synthesis of zero velocity lag servomechanisms, thus offering the facility of a rapid and exact design philosophy for this class of feedback control systems. An important application of the technique to the direct evaluation of sensitivity of system performance to changes in load dynamics is discussed in detail.

Because certain standard compensation methods result in a high, rather than infinite, velocity constant, a brief study has been made to determine the allowable drift of the system zero such that the performance criteria of interest are not significantly affected. For the type of servomechanism studied, it is concluded that the order of drift met in practice when using these compensation methods is not normally sufficient to invalidate the use of the coefficient plane technique at the synthesis stage.

List of Symbols

a_n	denominator coefficient of s^n
b_n	numerator coefficient of s^n
θ_{ss}	steady state displacement error
Ω	coefficient of ramp function input
$[\alpha/2]$	coefficient of acceleration input
C_v	velocity error constant
C_a	acceleration error constant
θ_0	controlled variable
θ_i	command variable
θ, E,	general displacement error
s	true Laplace operator
$S = s/\omega_0$	normalized Laplace operator
ω_0	normalization angular frequency
b	coefficient of S^2 in normalized transfer function
c	coefficient of S in normalized transfer function
ω_B	system bandwidth
$[\omega_B/\omega_0]_{b,c}$	normalized bandwidth at the point (b, c)
J	load moment of inertia
f	load viscous damping coefficient
K_g	servo feedforward gain adjustment
K_m	servomotor gain
T_i	input derivative time-constant
T_r	rate feedback time-constant
T_r'	minor loop rate feedback time-constant
T_n	integrator time-constant
T_p	transient velocity feedback network time-constant
T_1, T_2	passive network time-constants
M_p	peak amplitude ratio
ζ	damping ratio of complex poles

1. Introduction

Servomechanisms required to follow accurately a ramp function input are considered to be of sufficient importance to warrant a special place in the control engineering literature.[1,2] It is shown in this paper that such servomechanisms are amenable to the coefficient plane technique, thus offering the facility of a rapid and exact synthesis tool. The fundamental principles and philosophy of this technique have been outlined in a previous paper.[3] An important advance to be described herein is the use of the coefficient plane to produce a subjective comparison of various designs based on the insensitivity of performance to changes in load dynamics. This subjective comparison directly assesses a most fundamental reason for using feedback control, and is an alternative approach to the use of classical sensitivity functions as defined by Horowitz.[4]

Zero velocity lag servomechanisms are often part of much larger control systems whose overall effectiveness is only measurable in statistical terms. Nevertheless it is normally possible and sufficient to write the performance specification of the servomechanism in terms of criteria related to deterministic inputs only. This procedure is likely to continue, and is well

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understood. Truxal[5] has stated that the three most commonly used independent performance criteria are maximum percentage overshoot, bandwidth, and velocity constant. For the servomechanisms considered here, velocity constant is very high, bandwidth is a judicious choice between command signal following and noise signal rejection, whilst maximum percentage overshoot crystallizes the form of transient response. If disturbance torques are significant, feed-forward gain may be included in addition to, or instead of, the more common criteria,[6] whilst other criteria of interest in specific applications are acceleration constant, peak amplitude ratio, and the insensitivity of performance to load changes mentioned previously. Generalized synthesis via the coefficient plane requires that the foregoing performance criteria are determined as functions of the normalized coefficients of the servomechanism so that the relationships may be presented in graphical form.

2. Some Servomechanisms Exactly or Approximately Meeting the Zero Velocity Lag Requirement

It is assumed that the inertia load to be controlled can be adequately described by an inertia J and a viscous damping coefficient f referred to the output shaft, whilst the feedforward gain from the comparator to the motor terminals is K_g and includes all signal amplification terms. Figure 1 shows four possible ways of achieving a negligible velocity lag. With one exception the type of compensation required to achieve high value of velocity error constant (C_v) will increase the order of the system, resulting in three system poles and one system zero. It is therefore convenient to define the servomechanism to have the following transfer function,

$$\frac{\theta_o}{\theta_i}(s) = \frac{1+b_1 s}{1+a_1 s+a_2 s^2+a_3 s^3} \qquad \ldots\ldots(1)$$

The corresponding error transfer function is,

$$\frac{\theta}{\theta_i}(s) = \frac{(a_1-b_1)s+a_2 s^2+a_3 s^3}{1+a_1 s+a_2 s^2+a_3 s^3} \qquad \ldots\ldots(2)$$

For a ramp function input,

$$\theta_i = \Omega t$$

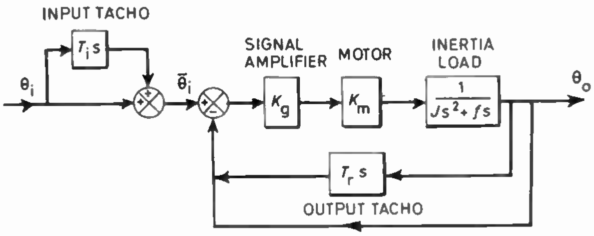
it may be shown that

$$\theta_{ss} = \Omega(a_1-b_1)$$

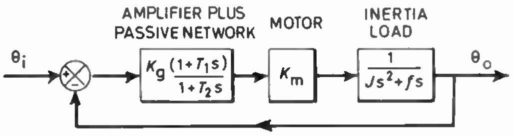
and hence the velocity constant is given by

$$C_v = \frac{1}{(a_1-b_1)} \qquad \ldots\ldots(3)$$

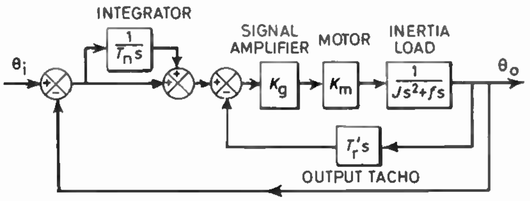
Table 1 summarizes the transfer function coefficients and velocity constants for the designs shown in Fig. 1. Three adjustable design parameters are provided for each design, and therefore in general three independent performance criteria can be met simultaneously. C_v will always be infinite for the design of Fig. 1(c), resulting in a true velocity lag servomechanism, whilst the design of Fig. 1(a) will have an infinite C_v if the servomechanism is carefully tuned at the post production stage. Designs of Figs. 1(b) and (d) will have high C_v only if the term $\left[\frac{K_g K_m}{f}\right]$ is relatively high. Since C_v is so sensitive to load friction in designs of Figs. 1(b) and (d), the designer must ensure that C_v is high enough even with the maximum expected value



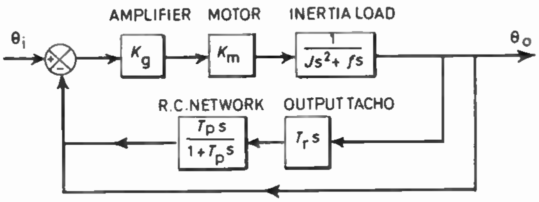
(a) Pure input and pure output derivative signal shaping.



(b) Passive network compensation.



(c) Integral control plus minor loop rate feedback compensation.



(d) Transient velocity feedback compensation.

Fig. 1. Some servomechanisms with potentially small velocity lag.

Table 1

Some servomechanisms with potentially small velocity lag

Servo	Description	Infinitely adjustable design variables	b_1	a_1	a_2	a_3	$\frac{1}{C_v} = \frac{\theta_{ss}}{\Omega}$
Fig. 1(a)	Pure input and pure output derivative signal shaping	T_1, T_r, K_g	T_1	$T_r + \frac{f}{K_g K_m}$	$\frac{J}{K_g K_m}$	0	$T_r + \frac{f}{K_g K_m} - T_1$
Fig. 1(b)	Passive network compensation	T_1, T_2, K_g	T_1	$T_1 + \frac{f}{K_g K_m}$	$\frac{J + T_2 f}{K_g K_m}$	$\frac{T_2 J}{K_g K_m}$	$\frac{f}{K_g K_m}$
Fig. 1(c)	Integral control plus minor loop rate feedback compensation	T_n, T_r', K_g	T_n	T_n	$T_n T_r' + \frac{T_n f}{K_g K_m}$	$\frac{T_n J}{K_g K_m}$	0
Fig. 1(d)	Transient velocity feedback compensation	T_p, T_r, K_g	T_p	$T_p + \frac{f}{K_g K_m}$	$T_p T_r + \frac{J + f T_p}{K_g K_m}$	$\frac{J T_p}{K_g K_m}$	$\frac{f}{K_g K_m}$

of load friction. Figure 1(a) is a special case resulting in a one-zero, two-pole system which has been completely synthesized *en passant* elsewhere.[7] The practical disadvantages of this design are, firstly, the input signal may not be available as a shaft rotation so that a tachogenerator cannot be used to generate a pure input derivative signal, and secondly, even if the input shaft rotation exists, the provision of the second tachogenerator may make the servomechanism unnecessarily expensive.

3. Normalization Technique Applied to Third-order Zero Velocity Lag Servomechanisms

Provided $a_1 \simeq b_1$, eqn. (1) may be written as follows,

$$\frac{\theta_0}{\theta_i}(S) = \frac{1 + cS}{1 + cS + bS^2 + S^3} \qquad \ldots\ldots(4)$$

where $\omega_0^3 = 1/a_3$

$b = \omega_0^2 a_2$

$c = \omega_0 a_1 \simeq \omega_0 b_1$

$S = s/\omega_0$

True poles and zeros for the servomechanism will be the poles and zeros of eqn. (4) multiplied by the normalization frequency ω_0. True time is normalized time divided by ω_0, whilst true frequency for harmonic response will be the excitation frequency multiplied by ω_0. b and c are the normalized coefficients forming the axes of the coefficient plane.

4. Optimum Forms of the Zero Velocity Lag Servomechanism Transfer Function

Standard forms of system transfer functions have appeared extensively in control engineering literature in an attempt to crystallize mathematically the designer's intuition in selecting an acceptable form of system response.[1,8,9] Some standard forms applicable to the zero velocity lag servomechanism are given in Table 2, and the corresponding transient and frequency responses are shown in Fig. 2.

Porter[10] has shown that if zero velocity lag is required, at least one overshoot must be present in the step function response, and furthermore it is not possible to achieve a low percentage overshoot without introducing a long 'tail' to the response, a principle clearly observable in the Whiteley transient response of Fig. 2(a). Lathrop and Graham[1] used the i.t.a.e.† performance index $\left(\int_0^\infty t|E|\mathrm{d}t\right)$ to establish optimum forms for the zero velocity lag servomechanism transfer function, and these are quoted in Table 2 for the two cases when, respectively, the index is minimized following a ramp function input and minimized following a step function input. In the first case the 52% maximum overshoot is rather high; in the second case the 40% maximum overshoot is still high by most standards but the 95% normalized settling time is much lower than for any of the other standard forms. From Fig. 2(a) it is interesting to note that this fairly reliable performance index, faced with the problem of balancing large overshoot against the long-tail, has preferred the large overshoot. When comparing proposed designs, it is important to remember the effect of the normalization frequency ω_0. For example, in a specific situation, it may be possible to make ω_0 sufficiently high for the Whiteley standard form to have an acceptable settling time if this form is considered most suitable for the situation.

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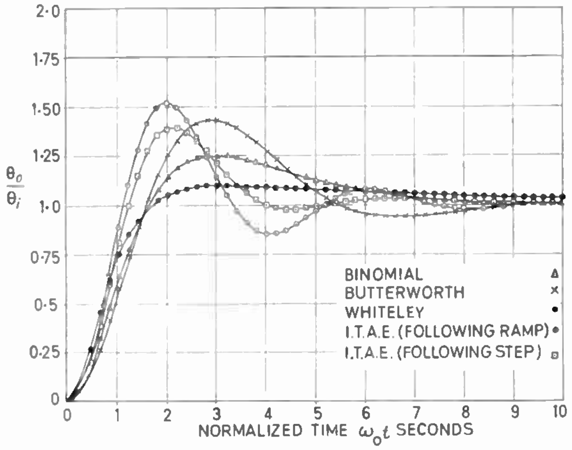
† i.t.a.e. = integral of time × absolute error.

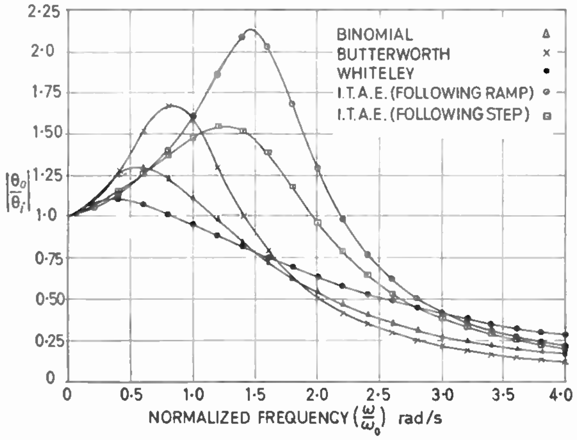
Table 2

Standard forms of the third-order zero velocity lag servomechanism

Form	b	c	Normalized 95% settling time	Percentage overshoot	M_p	Normalized bandwidth
Binomial	3·0	3·0	6·52	25%	1·30	1·64
Butterworth	2·0	2·0	7·32	44%	1·68	1·70
Whiteley	5·1	6·3	7·40	10%	1·10	1·77
i.t.a.e. optimum (following ramp)	1·3	2·94	6·76	52%	2·12	2·48
i.t.a.e. optimum (following step)	1·75	⩾3·0	3·65	∼40%	∼1·55	⩾2·30



(a) Transient response of standard forms of the third-order zero velocity lag servomechanism.



(b) Frequency response of standard forms of the third-order zero velocity lag servomechanism.

Fig. 2.

Whilst accepting that these standard forms are a useful guide, the compromise nature of servo design does mean that it is often advisable to depart from these standard forms in order to avoid the introduction of extra compensation terms to achieve a satisfactory trade-off between performance criteria of interest. For example, if we are allowed only two design variables, it would be wrong to use these variables to obtain the Whiteley optimum values of b and c, letting ω_0 take whatever value is forced upon it with consequent low bandwidth without first seeing whether, by a suitable movement in the coefficient plane we might not obtain a different, but still satisfactory form of transient response coupled with a more useful bandwidth.

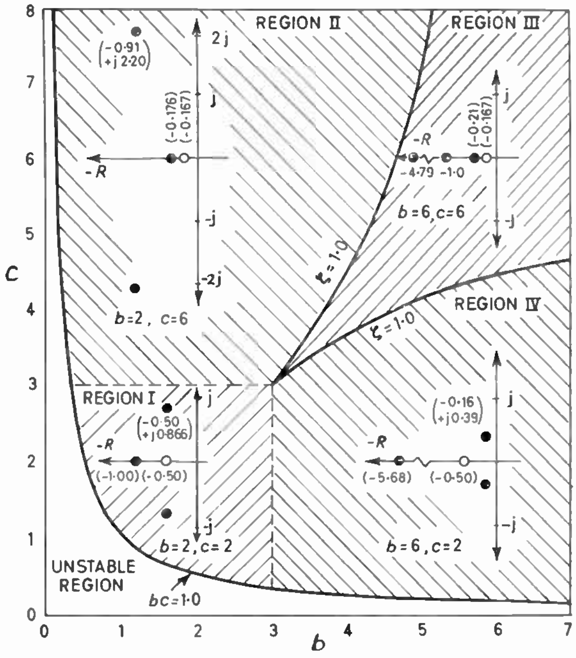


Fig. 3. Division of the coefficient plane on the basis of trends in system pole zero geometry.

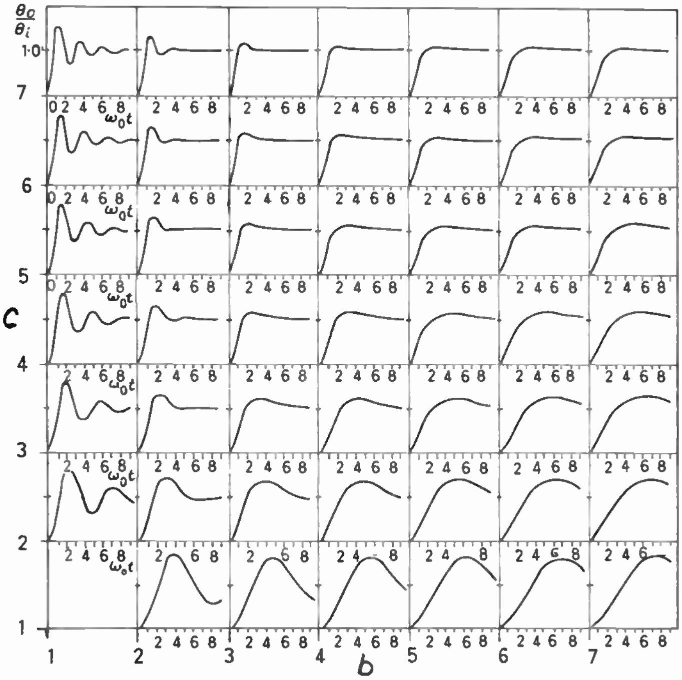


Fig. 4. Sample transient responses plotted in the coefficient plane.

5. Trends in System Pole Zero Geometry

Arbitrary limits of $b = c = 7{\cdot}0$ have been imposed in this coefficient plane study of zero velocity lag servomechanisms; all practical servos so far met have been found to lie comfortably in this region. The transient response will either consist of an exponential term plus a damped sinusoid, or three exponential terms depending on whether or not complex poles are present in the system pole zero array. $bc = 1{\cdot}0$ defines the absolute stability contour in the coefficient plane.[3] For $bc > 1{\cdot}0$ it is possible to split up the coefficient plane into four regions based on trends in system pole zero geometry as shown in Fig. 3. In region I all poles and zeros are (relatively) near the origin, whilst in region II the real pole and zero are close to the origin compared with the complex poles. All poles are real in region III whilst in region IV the real pole is so far to the left that all performance criteria (except C_v) are dominated by the remnant one zero, two-pole array. This remark also applies to the lower part of region III. There is a pole at $S = -1$ along the line $b = c$, and a double pole on the real axis along the lines $\zeta = 1{\cdot}0$. Interchanging b and c will invert the system poles.

6. Time Domain Properties

Sample transient responses are shown in Fig. 4, the long tail–low percentage overshoot coupling being evident in a large part of the coefficient plane.

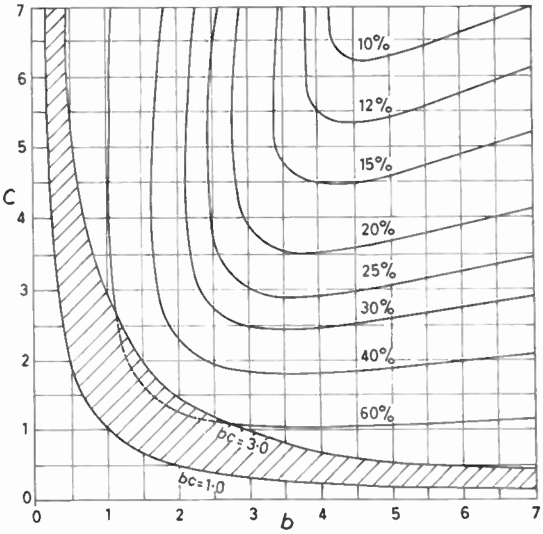


Fig. 5. Maximum percentage overshoot contours for the third-order zero velocity lag servomechanism.

These responses are provided as an aid to understanding the effect of coefficients on the transient response so that if a point in the coefficient plane meets various performance criteria, an immediate check on the form of transient response is available. Using samples and interpolation techniques, the maximum percentage overshoot contours shown in Fig. 5 were constructed. A digital computer was used to evaluate the transients in order to improve resolution in the region of maximum percentage overshoot.

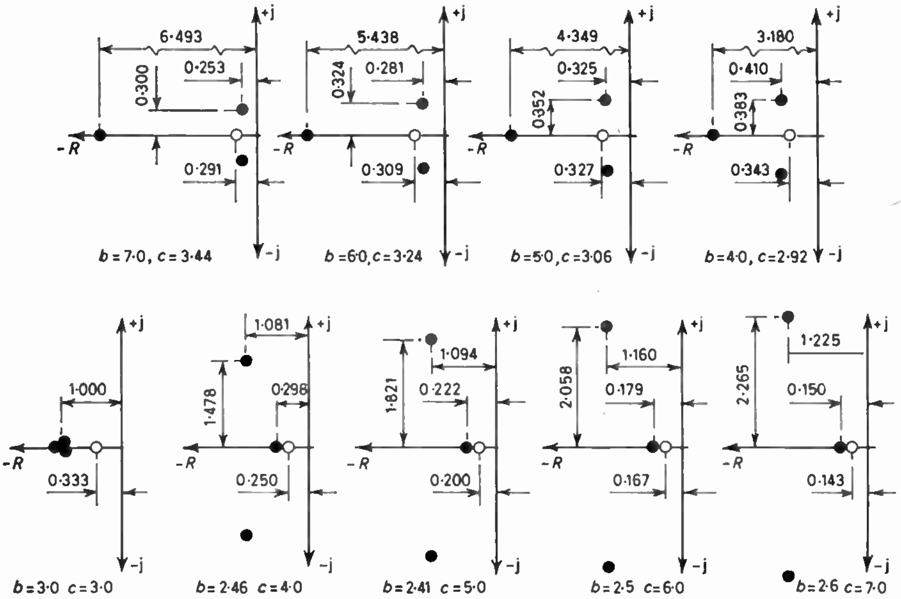
Having determined such contours, it is instructive to evaluate the system pole-zero arrays as a particular contour is transversed in the coefficient plane. Results are shown in Fig. 6 for 25% and 15% contours, and emphasize the wide variety of pole-zero configurations capable of meeting this specification. It should be noted that many of these pole zero arrays are difficult to interpret in the time domain without recourse to further computation, whereas the coefficient plane yields the required information by inspection.

If a parabolic input $\theta_i = [\alpha/2]t^2$ is applied to the zero velocity lag servomechanism defined by eqn. (4), the steady state error is $\theta_{ss} = \alpha \, . \, a_2$. Under these circumstances the acceleration constant is truly meaningful and is defined by $\theta_{ss} = [\alpha/2]/C_a$, hence

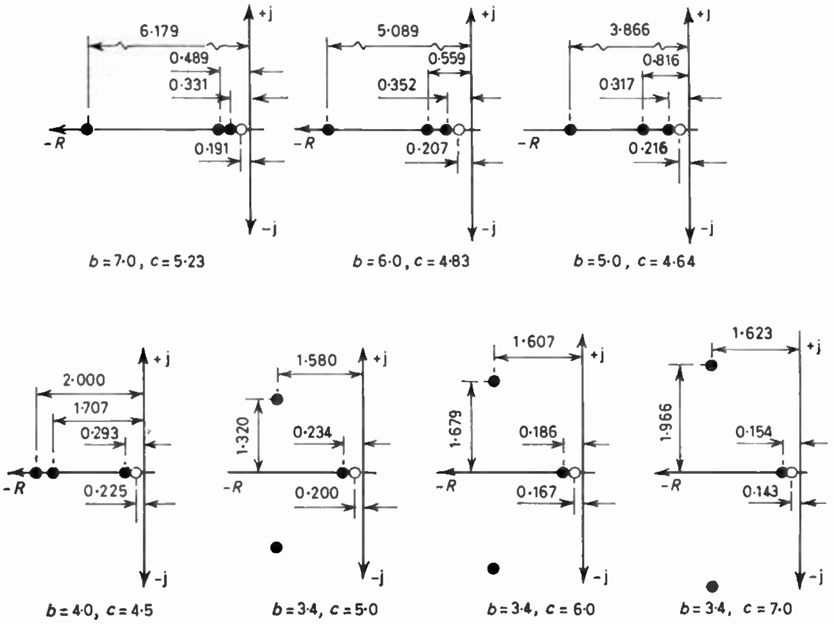
$$C_a = \frac{1}{2a_2} \qquad \ldots\ldots(5)$$

Applying the normalization procedure,

$$C_a = \frac{\omega_0^2}{2b} \qquad \ldots\ldots(6)$$



(a) System pole-zero arrays resulting in 25% maximum percentage overshoot for third-order zero velocity lag servomechanism.



(b) System pole-zero arrays resulting in 15% maximum percentage overshoot for the third-order zero velocity lag servomechanism.

Fig. 6.

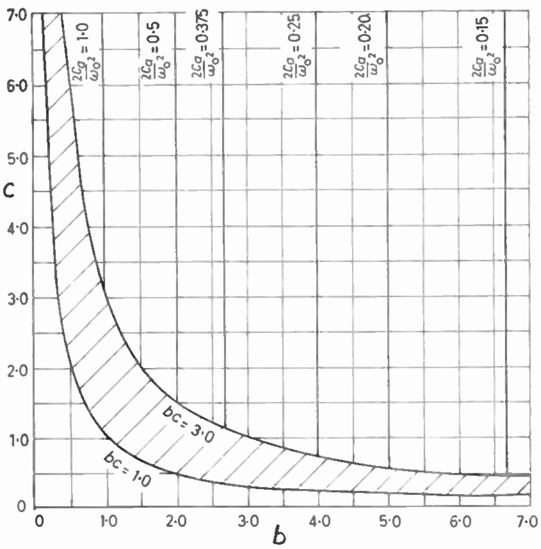


Fig. 7. C_a contours for the third-order zero velocity lag servomechanism.

Clearly from eqn. (6), acceleration constant contours are simply vertical straight lines when plotted in the coefficient plane as shown in Fig. 7. If C_v is not infinite, the acceleration constant must be modified and eqn. (5) is no longer valid.

7. Frequency Domain Properties

The amplitude ratio of the system defined by eqn. (4) is,

$$\frac{\theta_0}{\theta_i}(j\omega) = \sqrt{\frac{1+c^2\omega^2}{(1-b\omega^2)^2+(c\omega-\omega^3)^2}} \quad \ldots\ldots(7)$$

and sample responses are shown in Fig. 8. There is only one form of frequency response of importance, unlike the simple three-pole system which can have four different forms of response;[3,11] nevertheless the shape geometry for this unique form changes considerably, as can be seen by comparison of the responses for (b = 3, c = 7) with (b = 3, c = 2).

Bandwidth contours are obtained by equating steady state amplitude ratio to $1/\sqrt{2}$, and are shown in Fig. 9. At any point in the coefficient plane, the normalized bandwidth is increased by increasing c and decreasing b. M_p contours are shown in Fig. 10, and have been obtained by digital computation of M_p for many sample points in the coefficient plane and then using suitable interpolation techniques to determine the required contours.

8. Synthesis of Servomechanisms with Only Two Adjustable Design Parameters

Many synthesis techniques can be developed via the coefficient plane. A typical example is the study of servo performance when only two design para-

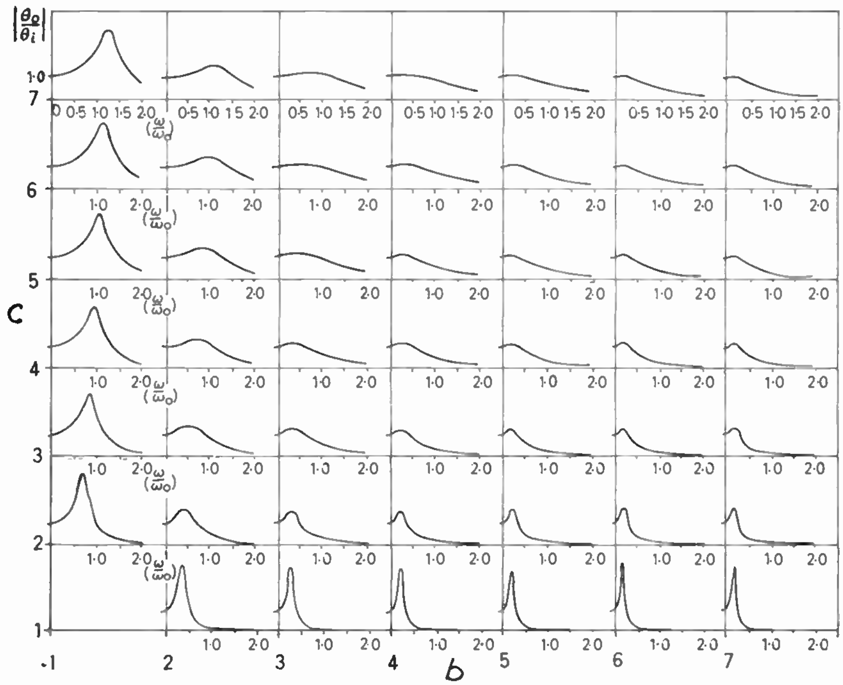


Fig. 8. Sample frequency responses plotted in the coefficient plane.

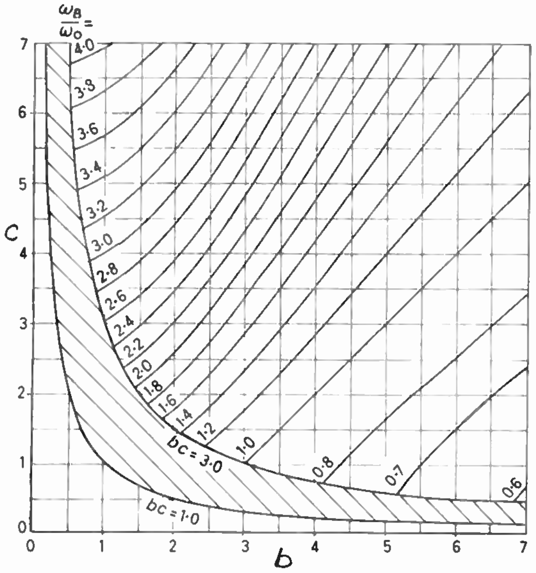


Fig. 9. Normalized bandwidth contours for the third-order zero velocity lag servomechanisms.

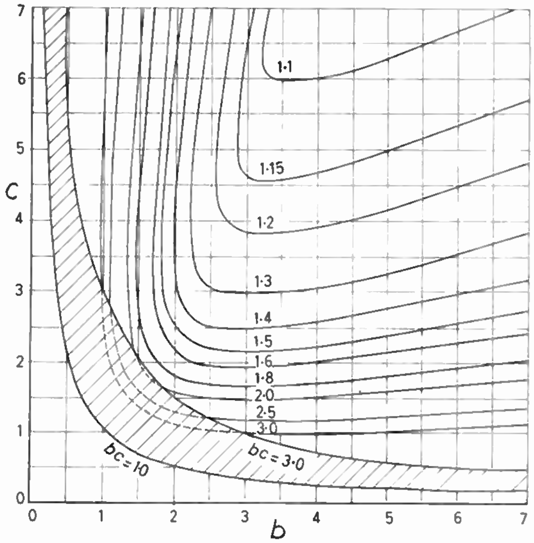


Fig. 10. M_p contours for the third-order zero velocity lag servomechanism.

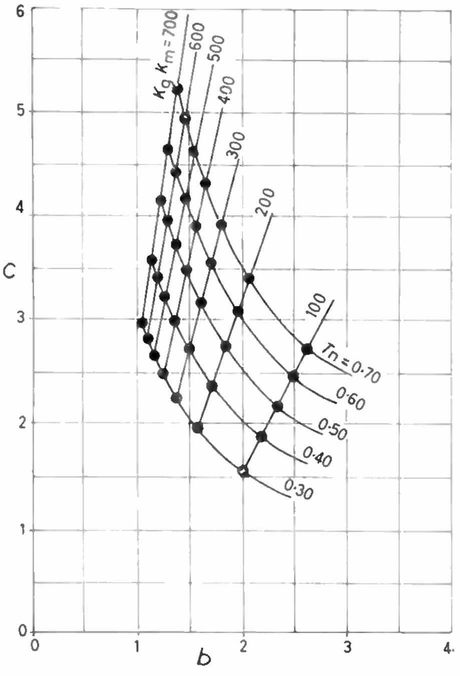


Fig. 11. Tracking coefficient plane movements due to variation of the design variables T_n and $K_g K_m$ for the integral compensation third-order zero velocity lag servomechanism ($T_r' = 0$).

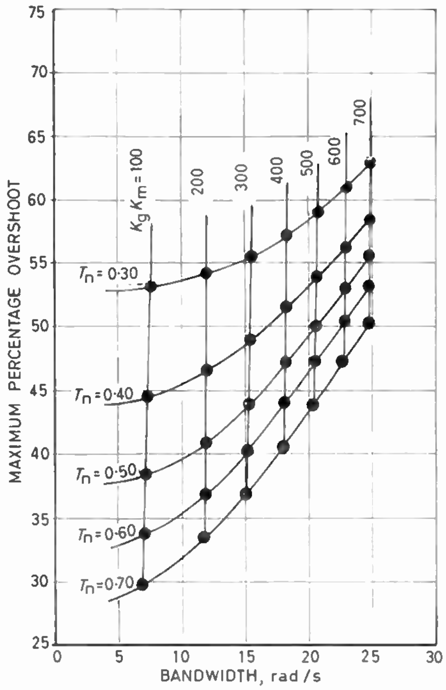


Fig. 12. Maximum percentage overshoot and bandwidth as a function of the design variables T_n and $K_g K_m$ for the integral compensation third-order zero velocity lag servomechanism ($T_r' = 0$).

meters are available. Consider the servomechanism shown in Fig. 1(c), which is a true zero velocity lag servo. If the minor loop rate feedback is not allowed due to space or economic reasons we are left with the two design variables $K_g K_m$ and T_n. As a consequence of the omission of minor loop rate feedback, stability is heavily dependent on the presence of adequate load friction. With these two degrees of design freedom we can fix any two of the normalized parameters b, c and ω_0, at the same time guaranteeing zero velocity lag. If b and c are fixed to give a specific form of response, say Whiteley or i.t.a.e. optimum, ω_0 will be constrained to a particular value by the physics of the system. This value of bandwidth is often low, and the problem now facing the designer is to increase bandwidth by making some concession on the form of response. Suppose that the concession is to be decided by a study of the compromise between bandwidth and maximum percentage overshoot as the design variables $K_g K_m$ and T_n are sampled. For the sampled values, b, c and ω_0 are evaluated as follows.

$$\omega_0 = \left[\frac{K_g K_m}{T_n J}\right]^{1/3} \qquad \text{......(8)}$$

$$c = \omega_0 T_n \qquad \text{......(9)}$$

$$b = \frac{\omega_0^2 f T_n}{K_g K_m} \qquad \text{......(10)}$$

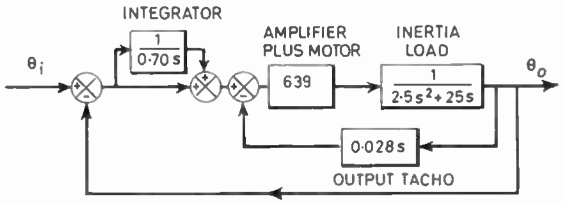
Figure 11 shows the corresponding coefficient plane movements for a medium servo with $J = 2{\cdot}5$ slug . ft^2 and $f = 25$ lb . ft/rad/s as $K_g K_m$ is varied from 100 to 700 lb . ft/rad and as T_n is simultaneously varied from 0·30 to 0·70 s. Superimposing Fig. 11 on Fig. 5 determines percentage overshoot as a function of $K_g K_m$ and T_n, whilst superimposing Fig. 11 on Fig. 9 determines $[\omega_B/\omega_0]_{b,c}$, and hence ω_B as ω_0 is already known. The compromise between bandwidth and overshoot is shown in Fig. 12. To a first approximation, within the range considered, bandwidth is a linear function of feedforward gain, whilst increasing the integrator time-constant dampens the peak overshoot. As an example of the kind of choice now available to the designer faced with these comprehensive (and comprehensible) trends in system behaviour, consider the point $K_g K_m = 300$, $T_n = 0{\cdot}50$, giving percentage overshoot = 44% and $\omega_B = 15$ rad/s. To increase the bandwidth to 20 rad/s, we can keep percentage overshoot constant by increasing $K_g K_m$ to 500 and increasing T_n to 0·70, or alternatively we can keep T_n at the original value, increase $K_g K_m$ to 500 and accept that the percentage overshoot will thereby increase to 50%. The final choice will be influenced by component considerations, presence of nonlinearities, and sensitivity to changes in load dynamics.

In this example the use of the coefficient plane has avoided the construction and calibration of five root loci, and the detailed consideration of the meaning of thirty-five system pole-zero arrays.

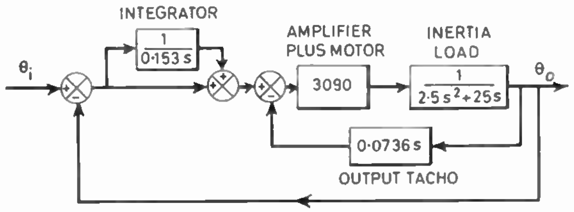
9. Sensitivity of System Performance to Changes in Load Dynamics

Load characteristics are rarely accurately known, and vary between servos in the same production batch, and in an individual servo the characteristics may drift with time. Relative insensitivity of feedback control system performance to changes in load characteristics is a reason for using this mode of control, but it is easily possible to lose this insensitivity by poor design even if desired requirements in bandwidth, percentage overshoot, etc., are met in the nominal case. Usually sensitivity is checked by evaluating the sensitivity transfer function in the frequency domain, a tedious procedure involving certain approximations.[4] Using the coefficient plane we simply evaluate b, c, and ω_0 as the load characteristics change, and plot changes in performance criteria directly against changes in load dynamics.

As an example, consider the servomechanism shown in Fig. 1(c), provided this time with three infinitely adjustable design parameters $K_g K_m$, T_n, and T'_r. It is required that the nominal percentage overshoot should be 25% and the nominal bandwidth is to be 20 rad/s. Nominal load conditions are those considered in Section 8, i.e. $J = 2{\cdot}5$ slug ft^2 and $f = 25$ lb ft/rad/s, but the friction coefficient is doubtfully known, and the wide variations are expected. Clearly, subject to the form of response, M_p, C_a and settling time being satisfactory, any combination of b and c lying on the 25% contour of Fig. 5 would be sufficient for meeting the specification when controlling the nominal load. Choosing the two points $b = 2{\cdot}41$, $c = 5{\cdot}0$ (design point I, $\omega_B/\omega_0 = 2{\cdot}8$),



Design point I: $b = 2{\cdot}41$, $c = 5{\cdot}0$, $\omega_0 = 7{\cdot}15$.



Design point II: $b = 5$, $c = 3{\cdot}06$, $\omega_0 = 20$.

Fig. 13. Two servomechanisms with integral control plus minor loop rate feedback compensation both meeting the 25% maximum percentage overshoot, 20 rad/s bandwidth and infinite velocity constant requirements simultaneously.

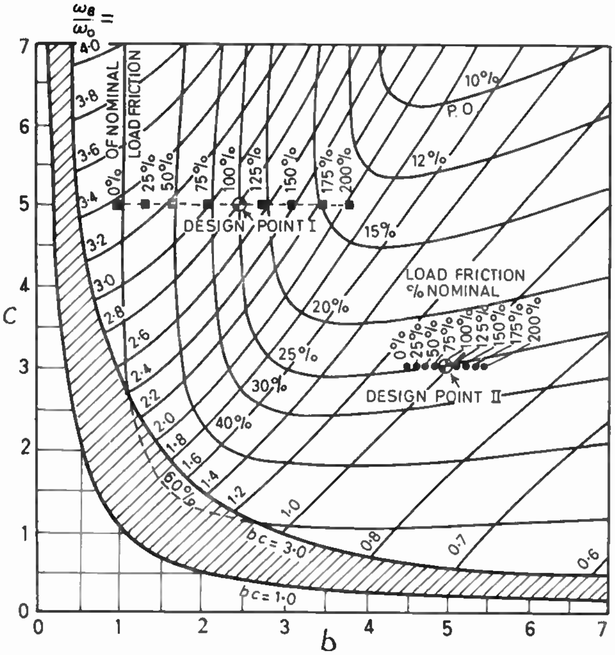


Fig. 14. Coefficient plane movement due to variation of load friction in two servomechanisms with integral control plus minor loop rate feedback compensation, both nominally meeting the 25% maximum percentage overshoot, 20 rad/s bandwidth, and infinite velocity constant requirements simultaneously.

and $b = 5{\cdot}0$, $c = 3{\cdot}06$ (design point II, $\omega_B/\omega_0 = 1{\cdot}0$), the required values of $K_g K_m$ and T_r' are determined, and are shown in Fig. 13. Some idea of the respective forms of response can be obtained from Figs. 4 and 8.

The most likely source of deviation in the load dynamics is the load friction coefficient. Let us investigate the change in percentage overshoot and bandwidth as the load friction varies from 0% to 200% of the nominal value. Inspection of Table 1 shows that for Fig. 1(c), only a_2 is affected by changes in load friction, hence in this particular application ω_0 and c remain constant, whilst b is defined from the a_2 equation,

$$b = \omega_0^2 \left[T_n T_r' + \frac{f . T_n}{K_g K_m} \right] \qquad ......(11)$$

where $\omega_0{}^2$, T_n, T_r' and $K_g K_m$ are known from Fig. 13. Equation (11) has been evaluated for both design points for 9 values of friction coefficient between the limits of 0% nominal and 200% nominal and the movements in the coefficient plane are shown in Fig. 14, on which the normalized bandwidth and percentage overshoot contours have been superimposed. The comparison is startlingly clear. Movement about design point I is orthogonal to percentage overshoot contours in that region and therefore a large change in percentage overshoot results from the change in load friction whilst movement about design point II is almost parallel to percentage overshoot contours in that region and consequently there will be an insignificant change in percentage overshoot due to the change in load friction. ω_0 remains constant, so changes in true bandwidth are also available directly from Fig. 14, showing that bandwidth change is more than double at design point I. This much information is available from inspection, and on a basis of insensitivity to load changes we would reject design point I in favour of design point II. The exact relationship between bandwidth, percentage overshoot, and load friction is shown in Fig. 15.

Insensitivity to load friction is therefore a sound reason for isolating the region around $b = 5{\cdot}0$, $c = 3{\cdot}06$. Reference to Fig. 6(a) shows that the third pole in this region is a long way to the left leaving one dominant system zero and two dominant system poles. In fact the third pole is so far to the left that a reasonable approximation to system performance is obtained simply by ignoring the s^3 term in the system transfer function.

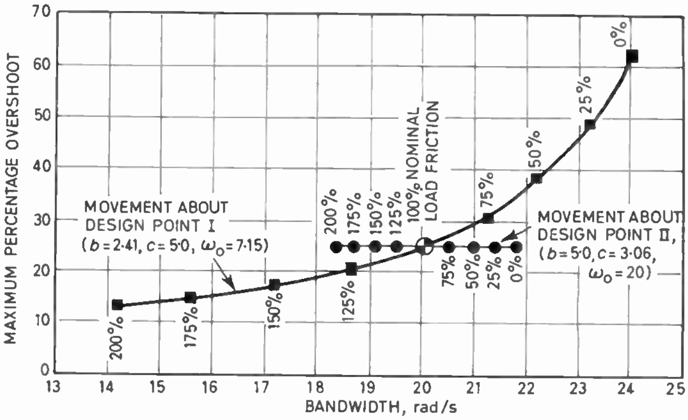


Fig. 15. Changes in bandwidth and maximum percentage overshoot due to variation of load friction in two servomechanisms with integral control plus minor loop rate feedback compensation, both nominally meeting the 25% maximum percentage overshoot, 20 rad/s bandwidth, and infinite velocity constant requirements simultaneously.

Thus the coefficient plane has indicated that in this case a dominant Type (1, 2) system pole-zero array is justifiable on the basis of lower sensitivity to load friction changes, not because we cannot readily understand the significance of the third pole and would necessarily wish to drive it well to the left as an inherent part of alternative design techniques.

It is coincidental that c and ω_0 are constant for this particular example. In the general case where the moment of inertia, and the compensation terms themselves can be subject to change, b, c, and ω_0 will change from nominal values, but the coefficient plane technique is equally valid and straightforward.

10. Accuracy of the Technique in the Presence of Small but Finite Velocity Lags

Reference to Table 1, shows that Figs. 1(b) and (d) will only have zero velocity lag if the load viscous friction is zero. In practice it is often sufficient to ensure that C_v is relatively high, i.e. C_v/ω_B is high. The design of Fig. 1(d) is commonly found in instrument servos used in fire control systems and it is fairly easy to ensure at the design stage the relationship $a_1 \leqslant 1{\cdot}02b_1$, i.e. the load friction dependent term in a_1 is about 2% of the total coefficient. Are the charts in this paper seriously in error when applied to a servo in which $a_1 \neq b_1$ but wherein these coefficients are within 2%?

Let us consider design points I and II, and assume that the servo under consideration is of design 1(b) or (d) rather than Fig. 1(c). For the purpose of this investigation it is convenient to assume that due to the presence of load friction, the pole positions are unchanged. The system zero has therefore moved to the left relative to the poles because since b_1 is less than $a_1 = c/\omega_0$, Z_1 must be further to the left than $(-1/c)$. Design points I and II have quite dissimilar pole-zero arrays as shown in Fig. 6(a), and therefore a different approach must be used in each case when establishing the effect of small changes in the zero position on performance criteria of interest.

For design point I, if the system zero is superimposed on the real pole (a large drift of 10% is required to accomplish this), the transient response is that of a simple two-pole system with $\zeta = 0{\cdot}515$, giving a maximum percentage overshoot of 15%. For the true servo velocity lag servomechanism, the percentage overshoot will be 25% as design point I is on this particular contour. Using residue theory it may be shown that the change in percentage overshoot is approximately linear as the system zero is drifted between these two positions. Thus we can say that if a 10% drift in the zero decreases percentage overshoot from 25% to 15%, a 2% drift (the maximum expected in practice) will decrease the percentage overshoot to 23%. There will be a negligible change in bandwidth due to the drift in the system zero.

At design point II, the third pole may be truly neglected, as it is thirteen times further to the left than the real part of the complex poles, leaving a dominant two-pole, one zero array. This remnant array can be synthesized completely using Reference 7. Thus a 2% drift in system zero position will decrease percentage overshoot to about 24% compared with the nominal value of 25% and the bandwidth will be reduced to 0·98 of the nominal value.

We can therefore summarize by saying that in realistic present-day servo designs wherein a high C_v is required, but C_v is not infinite because of the presence of load friction, the coefficient plane technique is still highly applicable although the accuracy of the performance criteria will obviously depend on the design point chosen. The technique has already met with a great deal of success in the rapid synthesis of transient velocity feedback servos required for instrument applications.

11. Conclusions

Many dissimilar system pole-zero arrays satisfy the performance specifications for zero velocity lag servomechanisms controlling known dynamic loads. Using the coefficient plane it is possible to evaluate and compare the many possible designs without recourse to these system pole-zero arrays, or even to the root-locus technique. Besides generating a visual understanding of the changes in system response due to changes in design parameters and load dynamics, the coefficient plane has three outstanding features as a synthesis technique. Firstly, performance criteria are evaluated directly, there is no rounding off required. Secondly, any number of design or load variables can be varied simultaneously, thus rendering many *sets* of root loci and system pole-zero arrays redundant. Finally, sensitivity of performance to changes in load dynamics is evaluated quickly and accurately.

In practice, many servomechanisms only approximate to the zero velocity lag requirement as the compensation techniques used do not allow C_v to be infinite in the presence of load friction. It is shown that realistic practical designs in this group approximate sufficiently well to allow the coefficient plane to be used in their analysis and synthesis.

12. Acknowledgments

The author acknowledges with pleasure the assistance of Messrs. J. D. Lamb and V. Windsor.

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Joint Conference on 'R.F. Measurements and Standards'

Organized by the Institution with the collaboration of the Institution of Electrical Engineers, a Conference on R.F. Measurements and Standards was held in the Glazebrook Hall at the National Physical Laboratory, Teddington, from 14th–16th November, 1967. The Conference, the first of its kind to be held in Great Britain on this particular subject, follows shortly after the inauguration of the British Calibration Service; this Service has the object of co-ordinating and improving standards of calibration in all fields of measurement including high frequency electrical parameters. Opened by Major-General Sir Leonard Atkinson, K.B.E., President Elect of the I.E.R.E., the Conference comprised 18 scientific papers read by authors from Government establishments and Industrial and University laboratories. The main theme of the papers was the British contribution to the science of r.f. measurement in the range 100 kHz–3 GHz.

Development of techniques, comparable with the best available internationally, was the keynote of two contributions from the Electrical Inspection Directorate of the Ministry of Technology.[1,2] The work described covered the design of a precision r.f. bridge and the outline of methods for carrying out both attenuation and power measurement to a high degree of accuracy. A paper entitled 'Noise Source Calibration in the Decimetre Band' described work carried out in the Services Valve Test Laboratory[3] which, when coupled with a complementary paper from Ferranti on a noise source primary standard,[4] sets new and improved standards for noise measurement.

Novel solutions to a number of problems were a feature of contributions from Industry. A design of coaxial thermocouple and associated r.f. load using thin-film techniques, whereby r.f. power can be measured to an accuracy of 5% from d.c. to 1 GHz, was put forward by Marconi Instruments as the basis for a new range of commercial absorption power meters.[5] In the measurement of lumped immittance, Wayne Kerr outlined their 'crevasse entry' technique and showed its corresponding impact on design of r.f. bridges.[6]

In describing a technique for measurement of impedances within a micro-circuit module, authors from the University of Southampton showed how they had been able to achieve a satisfactory connection between circuit and measuring bridge by use of a micro-strip line.[7]

Several authors supported their papers by practical demonstrations of relevant equipment. It was interesting after a paper on attenuation measurement[8] to be able to compare British, Russian and American standard attenuation measuring equipment side by side.

The Proceedings of the Conference, incorporating all the papers and reports of the discussions, will be published as a separate volume by the I.E.R.E. early in 1968, price £5. A full list of the papers presented was published in the September issue of *The Radio and Electronic Engineer*.

A. G. WRAY

1. I. A. Harris, 'Standards for Electrical Circuit Properties at Radio Frequencies'.
2. R. W. A. Siddle and I. A. Harris, 'A C.W. Comparator for Precision R.F. Attenuators'.
3. G. J. Halford and E. G. Robus, 'Noise Source Calibration in the Decimetre Band'.
4. R. W. Murray, 'A Coaxial Primary Standard for Noise Source Calibration'.
5. A. A. Luskow, 'Thermocouple Power Meters for Microwave Frequencies.'
6. T. McCartney, 'The Measurement of Lumped Immittance at R.F.'
7. H. A. Kemhadjian, A. Negandhi and B. J. Lewis, 'Measurements on Microcircuits in the Range 100–1000 MHz'.
8. J. McHattie, 'The Measurement of Attenuation at Radio Frequencies'.

U.D.C.658.5:621.97

Quality Failure Cost Analysis

By

D. C. STONE†

Reprinted from the Proceedings of the Joint I.E.R.E.–I.Prod.E.–I.E.E. Conference on 'The Integration of Design and Production in the Electronics Industry', held at the University of Nottingham on 10th–13th July 1967.

Summary: Faults occur during the assembly of apparatus, as a result of weakness of design, faulty materials, errors in process methods, and human mistakes. Each fault costs money to repair, the cost appearing in the final price of the product. A method of organizing production/inspection, fault information analysis, and costing to discover and control the quality failure costs arising during assembly of television receivers is given.

Detailed information, not only of the reject percentages, but also of the related costs resulting from faults occurring during manufacture, is produced and made available to designers, production engineers, suppliers, and factory management. The main causes are located and permissible expenditure to produce an improvement in quality and reliability without increasing the price is derived. Experience shows that there is a correlation between assembly failures in the factory and service costs in the field.

1. Introduction

During the manufacture of an electronic product it is common experience that not all newly-assembled products will function correctly the first time they are switched on. In fact, if the product is complex there is a high probability that the reject level will be large. A low level of faulty functioning can only be achieved if the design is inherently suitable for manufacture to its specification, using materials which are sufficiently free from faults, employing processes and methods which fulfil their purpose without introducing or leaving faults, operated by people attending to the correctness of their work.

Any failure of a product to function correctly costs money in fault tracing, repair, re-testing and scrap material. The reliability of a product which has an unusually large reject level during manufacture is usually low; high field-service costs may be anticipated and customers' unfavourable attitudes are inevitable.

In order to achieve optimum functioning, reliability and cost it is necessary to supply the designer, the production engineer, and the operator with facts concerning the troubles which occur during manufacture so that corrective remedies may be introduced.

The most effective method of indicating the relative importance of faults is to use the terms understood by everybody—money.

This analysis therefore produces its final information in such a manner as to show those troubles costing the most money. It relates to the quality failure costs arising during final assembly and testing of domestic television receivers.

2. Sources of Information

2.1. *Inspection Plan*

Every fault which occurs is due to a quality failure. It is necessary to know what faults occur, at which stage of manufacture they are found, and why they occur. It is customary to inspect a product at various stages during manufacture. Very often inspection is considered to be an unavoidable nuisance which sorts out the bad from the good products and could be eliminated if all products were good. By correct planning, inspection can be used as a tool in controlling quality and costs *during the process of manufacture*.

A diagram may be drawn which shows the flow of materials through the assembly department (Fig. 1). This can conveniently be in the form of a block diagram in which each block is a process and the lines represent material flow. At appropriate stages an inspection may be inserted as a part of the manufacturing procedure; this may be visual, electrical or functional. The whole quality and performance requirement of the product is planned to be checked by a suitable distribution of the inspection functions along the process line.

The types of fault which may be expected are listed in standardized abbreviations and have a code number (Table 1). The number of faults will vary with the product but about 120 would give adequate coverage for a television receiver. Record forms are designed

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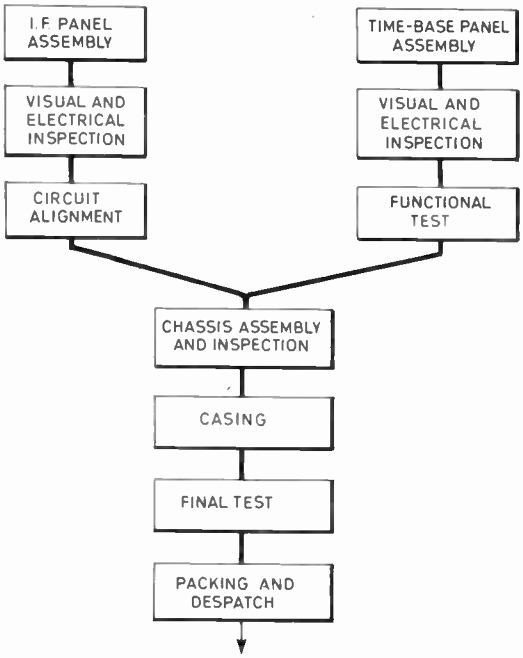


Fig. 1. Simplified production flow diagram of television assembly.

Table 1

Example of fault code numbers with abbreviations.

Code	fault	Abbreviations
1	Unsoldered joint. (Process)	U.J. Process
2	Unsoldered joint. (Operator)	U.J. Op.
3	Dry joint. (Process)	D.J. Process
4	Dry joint. (Operator)	D.J. Op.
5	Wrongly wired leads (Panel)	W/W Leads Panel
6	Solder short-circuit (Process)	S.S/C Process
7	Solder short-circuit (Operator)	S.S/C Op.
8	Wiring short-circuit	W/S/C
9	Short-circuit print	S/C Print
10	Open-circuit print	O/C Print
12	Wrong value capacitor	W/Value Cap.
15	Wrongly wired components	W/W Components
18	Badly fitted coils	B/Fitted Coil
20	Damaged components	Dam. Components
21	Missing resistors & capacitors	Missing Res-Cap
25	Faulty valves	Faulty Valve
27	Faulty resistors & capacitors	Faulty Res-Cap
31	Reversed diodes	Rev. Diodes
33	No fault found	N.F.F.
41	Faulty mechanical action switch	Faulty Sw. Mech.

to be used at inspection or repair stages where information will exist concerning faults. The facts are usually marked on the form by the inspector by a simple stroke, showing very simply the types and quantities of faults. Supervision can see from these self-analysis forms which faults require immediate action. In fact, it is essential that the local supervision are informed both verbally, and by looking at the records regularly throughout the day in order that they will initiate the first steps in correcting quality failures. A new record form is used by the inspector each day.

There are eleven main information gathering stages in the assembly of television receivers; for the purpose of this description several of these will be considered in more detail.

2.2. *Panel Viewing*

After component insertion and machine soldering each panel is viewed for correctness of soldering and associated faults. Any suspect joints, short circuits etc. are corrected by the viewer who counts up the number of joints retouched on the panel (Fig. 2), and records the number on a form. A tally is therefore built up showing the distribution of number of suspect joints per panel and indicating any trend of change in soldering performance. It is to be realized that there are hundreds of joints per panel, so a factual record of numbers is better information than an inspector's estimate that soldering quality is changing.

2.3. *Fault Tracing*

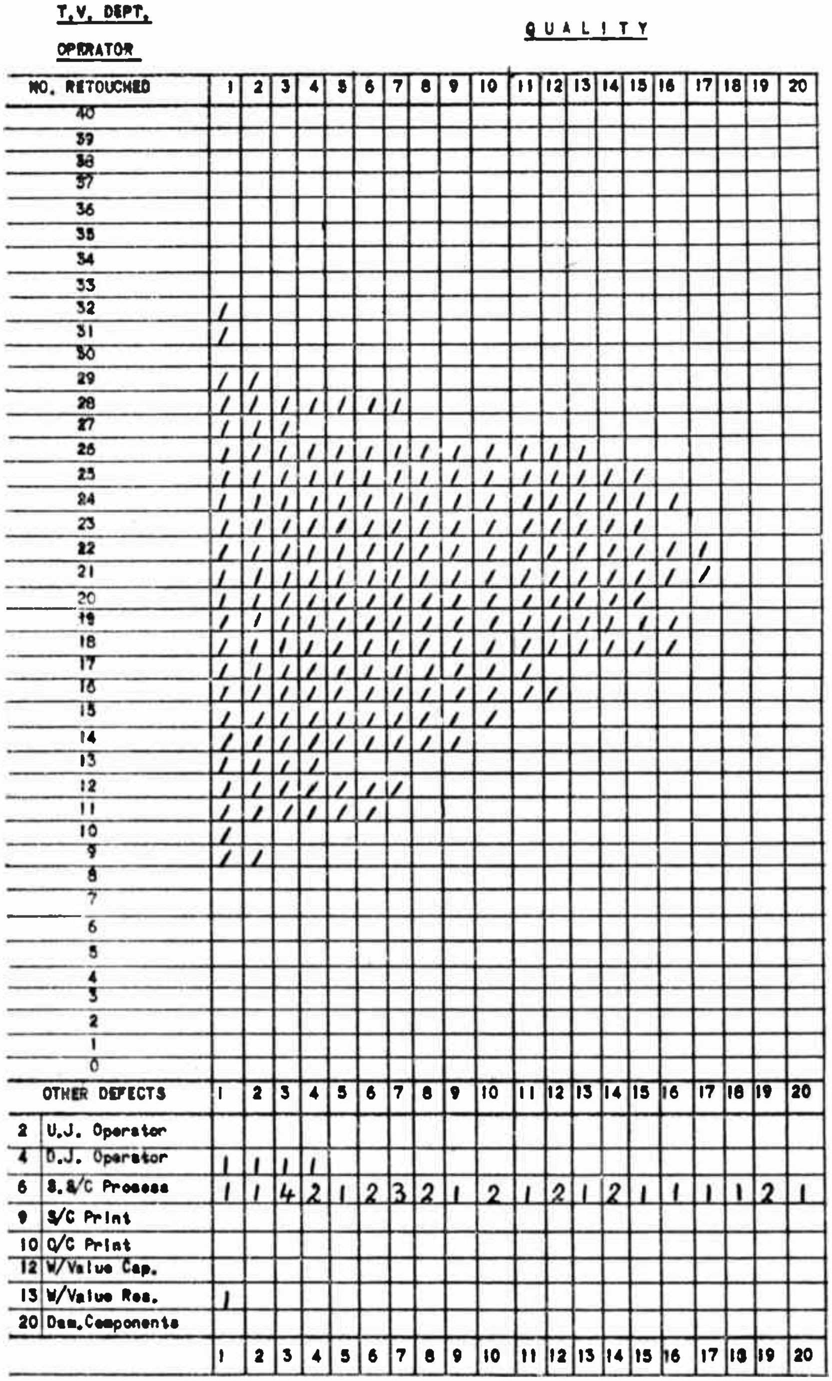
There are various stages at which measurements or electrical function tests are made, namely, point-to-point voltage check, circuit alignment, time-base tests; in these cases the operator records the numbers of good and bad panels. The faulty panels are passed to a fault-finder who records the cause of faulty functioning (Fig. 3), on a suitable form. Any unusual build-up of faults can be seen quite readily by the supervision who will then investigate the exact details. For example, an excessive number of faults 12 (wrong value capacitor), would be checked in detail with the fault-finder and subsequently the work in progress may be checked in full to locate, for example, a quantity of incorrectly marked components.

It has not been possible to design a simple form for the analysis of faults in completed receivers; the diversity of faults is so extensive that a simple form does not give enough information. The fault-finder writes the cause of fault in standard wording on (Fig. 4) a sheet of paper; the causes are grouped into suitable categories by an analysis clerk as explained later.

3. Analysis of Information

There are at least three advantages in producing faults information in a standard manner. These are:

(*a*) Each inspector can give reasonably accurate information to local supervision concerning important faults; examples of faults are referred back to the operation responsible for the fault, through the supervision, thus ensuring immediate action at local level.



T.V. DEPT.

OPERATOR

QUALITY

NO. RETOUCHED	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
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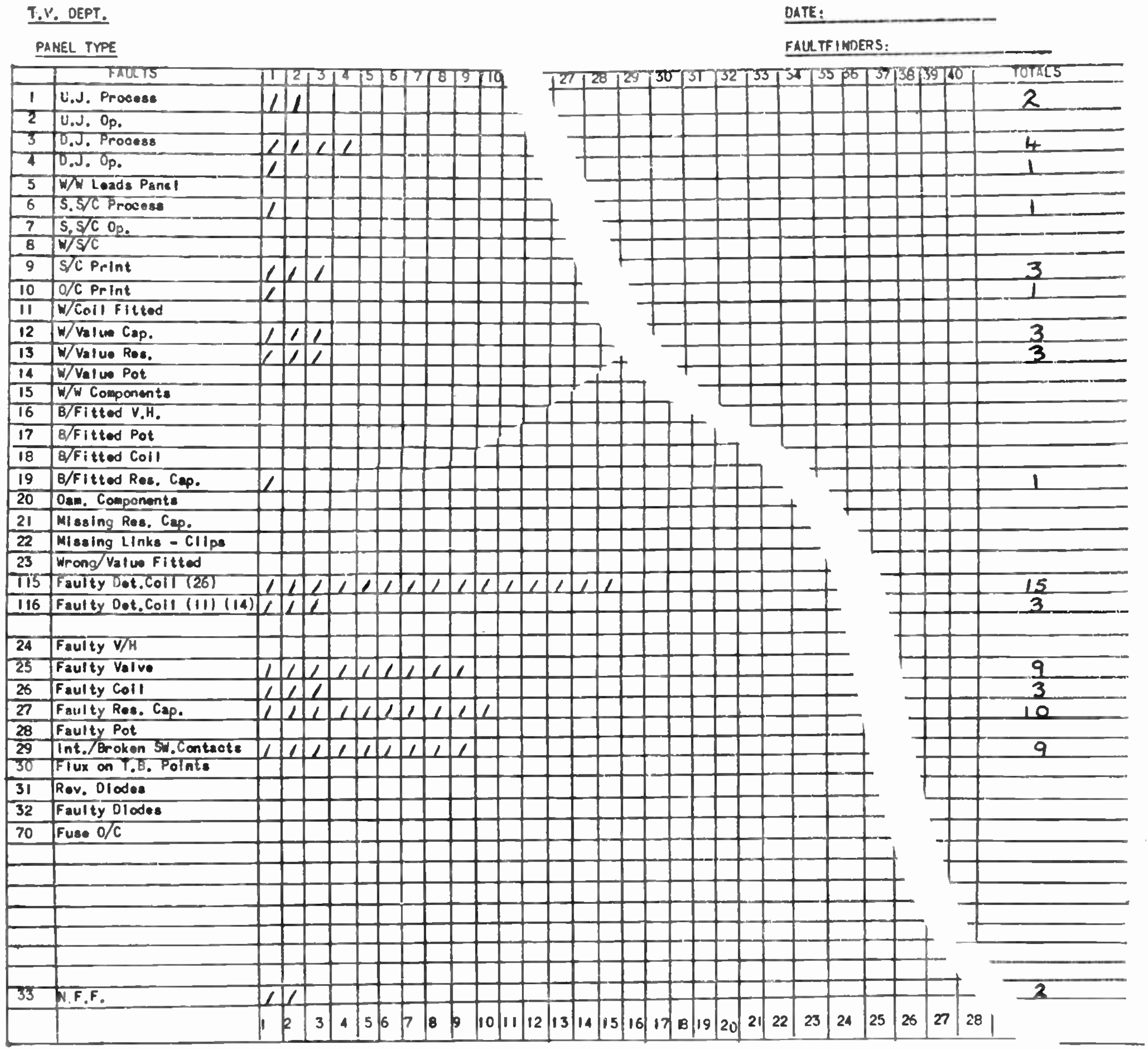
4																				
3																				
2																				
1																				
0																				

OTHER DEFECTS		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	U.J. Operator																				
4	D.J. Operator	1	1	1	1																
6	S.S/C Process	1	1	4	2	1	2	3	2	1	2	1	2	1	2	1	1	1	1	2	1
9	S/C Print																				
10	O/C Print																				
12	W/Value Cap.																				
13	W/Value Res.	1																			
20	Dam.Components																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Fig. 2. Soldering viewing record.



T.V. DEPT.

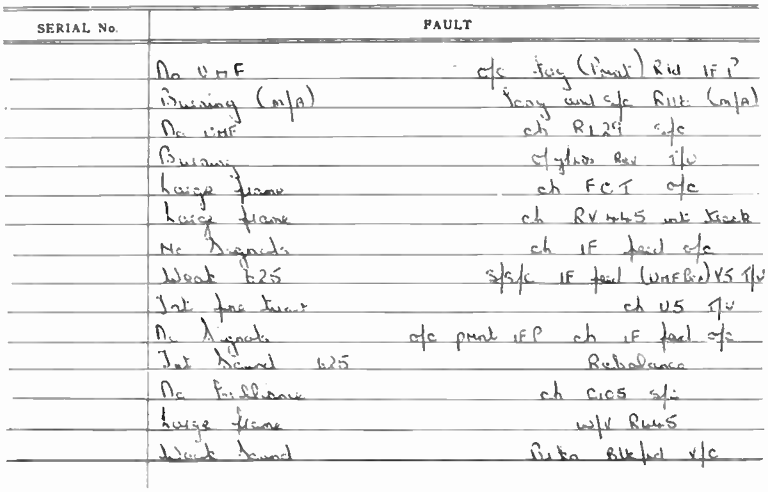
PANEL TYPE

DATE:

FAULTFINDERS:

	FAULTS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	TOTALS
1	U.J. Process	/	/														2
2	U.J. Op.																
3	D.J. Process	/	/	/	/												4
4	D.J. Op.	/															1
5	W/W Leads Panel																
6	S.S/C Process	/															1
7	S.S/C Op.																
8	W/S/C																
9	S/C Print	/	/	/													3
10	O/C Print	/															1
11	W/Coil Fitted																
12	W/Value Cap.	/	/	/													3
13	W/Value Res.	/	/	/													3
14	W/Value Pot																
15	W/W Components																
16	B/Fitted V.H.																
17	B/Fitted Pot																
18	B/Fitted Coil																
19	B/Fitted Res. Cap.	/															1
20	Om. Components																
21	Missing Res. Cap.																
22	Missing Links - Clips																
23	Wrong/Value Fitted																
115	Faulty Det.Coil (26)	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	15
116	Faulty Det.Coil (11) (14)	/	/	/													3
24	Faulty V/H																
25	Faulty Valve	/	/	/	/	/	/	/	/	/							9
26	Faulty Coil	/	/	/													3
27	Faulty Res. Cap.	/	/	/	/	/	/	/	/	/	/						10
28	Faulty Pot																
29	Int./Broken SW.Contacts	/	/	/	/	/	/	/	/	/							9
30	Flux on T.B. Points																
31	Rev. Diodes																
32	Faulty Diodes																
70	Fuse O/C																
33	N.F.F.	/	/														2

Fig. 3. Faultfinder's record.



SERIAL No.	FAULT	
	No UHF	o/c tag (Front) R14 IF ?
	Buzzing (m/a)	Tag and s/c R114 (m/a)
	No UHF	ch R129 s/c
	Buzzing	[illegible] Rev T/V
	Large frame	ch FCT o/c
	Large frame	ch RV445 not track
	No signals	ch IF feed o/c
	Weak 625	s/s/c IF feed (UHF Box) V5 T/V
	Int frame tear	ch V5 T/V
	No signals	o/c print IFP ch IF feed o/c
	Int sound 625	Rebalance
	No brilliance	ch C105 s/c
	Large frame	w/v R445
	Weak sound	[illegible] Blk lead v/c

Fig. 4. Final-test faultfinder's record.

(*b*) A clerk may make a daily analysis showing accurately the fault trend at each main process stage. This is presented to intermediate management in the form of graphical displays (Fig. 5).

(*c*) All information on fault types may be gathered together from the whole manufacturing process.

4. Costing of Faults

Each fault costs money. For each standard fault code an estimate is made of the cost resulting from that fault at each stage of manufacture. Examples are given in an arbitrary currency, designated 'ducats', for the purpose of this explanation.

The cost includes: fault tracing, repair work, material scrapped and cost of re-inspection or re-test.

Average costs are used, i.e. average times for fault tracing, repairing, and re-testing. The weighted average cost is used for specific types of components (e.g. capacitors, resistors or coils). The cost of a fault will differ between stages of manufacture according to the degree of skill involved. For example, a wrong value resistor will have the following differing failure cost:

(*a*) At Panel Assembly, 5·6 ducats, being the cost of the component plus insertion (unsoldered).

(*b*) At Panel Viewing, 9·6 ducats, being the cost of the original component, the cost of labour to unsolder and remove original component, the insertion and soldering of new component.

(*c*) At Point-to-Point, 31·6 ducats, being the cost of fault tracing, material, labour and re-testing.

(*d*) At Final Test, 76 ducats, being the cost of fault tracing, material, labour, re-testing of completed receivers.

For each fault code there is a failure cost at each stage of manufacture. These costs are built into a computer program.

5. Computing Costs

The analysis clerk, having made daily entries of faults on the foreman's display charts, counts up the number of each fault type after five working days. The appropriate quantity is mark-sensed on to a computer card (Fig. 6) which has been pre-punched with the fault code number, the cost of the fault, the previous cumulative total quantity of that fault. There are 112 punched cards used in this analysis.

Two runs may be made on an I.B.M. 1401 computer. The first run calculates and prints the failure cost in each of the eleven information-gathering stages of production, listing each fault under its code number and name. The cost is expressed as an average for each set made and in Table 2 the quantity of faults is shown as a percentage of the sets made. At the side of the week's results, the computer prints the cumulative quantities of faults, the total cumulative costs per fault and the cumulative percentage of sets made with that fault. New cumulative punched cards are produced for the start of the next week's analysis.

The second computer run combines together the quantities of each fault code from all inspection points. This analysis summary lists the cost of that week's faults in descending cost order (Table 3). Cumulative quantities are also given; the total quantity/failure cost incurred from the start of production is printed on the last page of the summary.

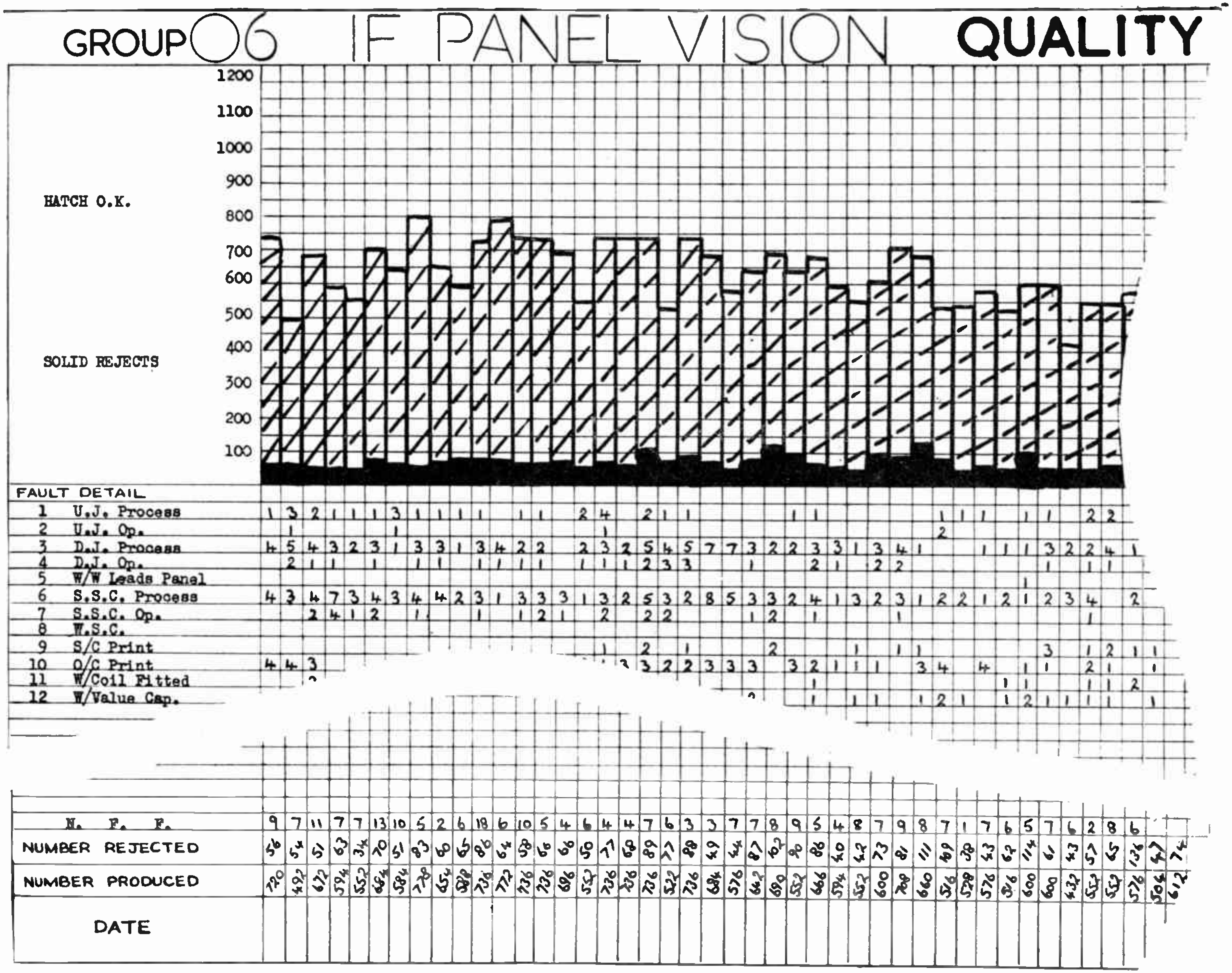


Fig. 5. Part of display chart in foreman's office.

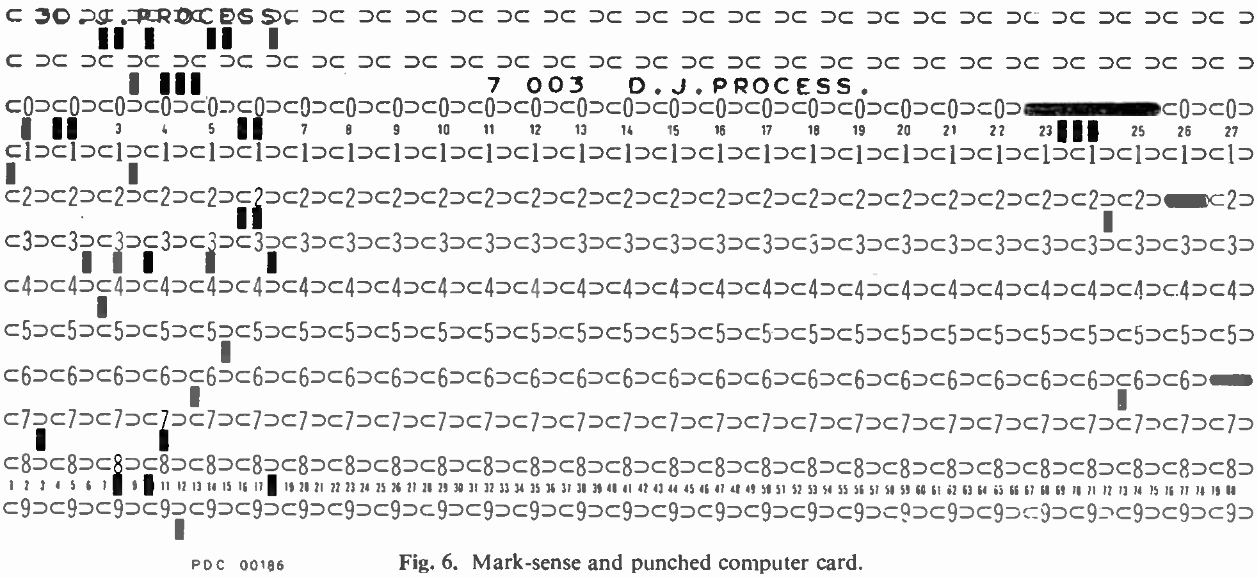


Fig. 6. Mark-sense and punched computer card.

Table 2

Computer sheet for one inspection group.

			Television fault analysis					
Set type			Qty. produced this week 2000			Cumulative qty. 14500 W/E		
Section header one		01	This week			Cumulative		
Code	Description		Qty.	Cost	%	Qty.	Cost	%
01 001	Fault type-one		27	5·63	1·35	177	36·88	1·22
01 002	Fault type-two		3	1·25	0·15	28	11·66	0·19
01 004	Fault type-four		101	4·17	5·05	510	21·04	3·52
01 007	Fault type-seven		460	47·92	23·00	787	81·98	5·43
	Total		591	58·97		1502	151·56	

Table 3

Computer analysis summary.

			Television fault analysis summary					
Set type 19 inch		Qty. produced this week 4550				Cumulative qty. 59151 W/E		
			This week				Cumulative	
Code	Description	Qty.	Cost	Cost/set	Cost %	Qty.	Cost	Cost/set
042	Faulty action p/buttons	269	185·27	9·77	15·88	4964	3253·77	13·20
029	Int/broken sw./contacts	551	118·39	6·24	10·14	6090	1264·17	5·13
049	Faulty det. coil	393	108·82	5·74	9·32	4689	1270·22	5·15
025	Faulty valve	359	56·13	2·96	4·81	6266	942·87	3·83
034	Broken leads	560	45·04	2·38	3·86	5115	575·92	2·34
026	Faulty coil	267	42·11	2·22	3·61	6084	1018·51	4·13
053	Def. coil assembly	73	38·81	2·05	3·33	1170	622·05	2·52
027	Faulty res/cap	311	35·85	1·89	3·07	7187	742·93	3·01
048	Tuner	166	34·51	1·82	2·96	2455	510·44	2·07
028	Faulty pot	248	31·64	1·67	2·71	1543	209·47	0·85
055	F.O.T.							
074	Damaged cabinet							
071	Retouch							

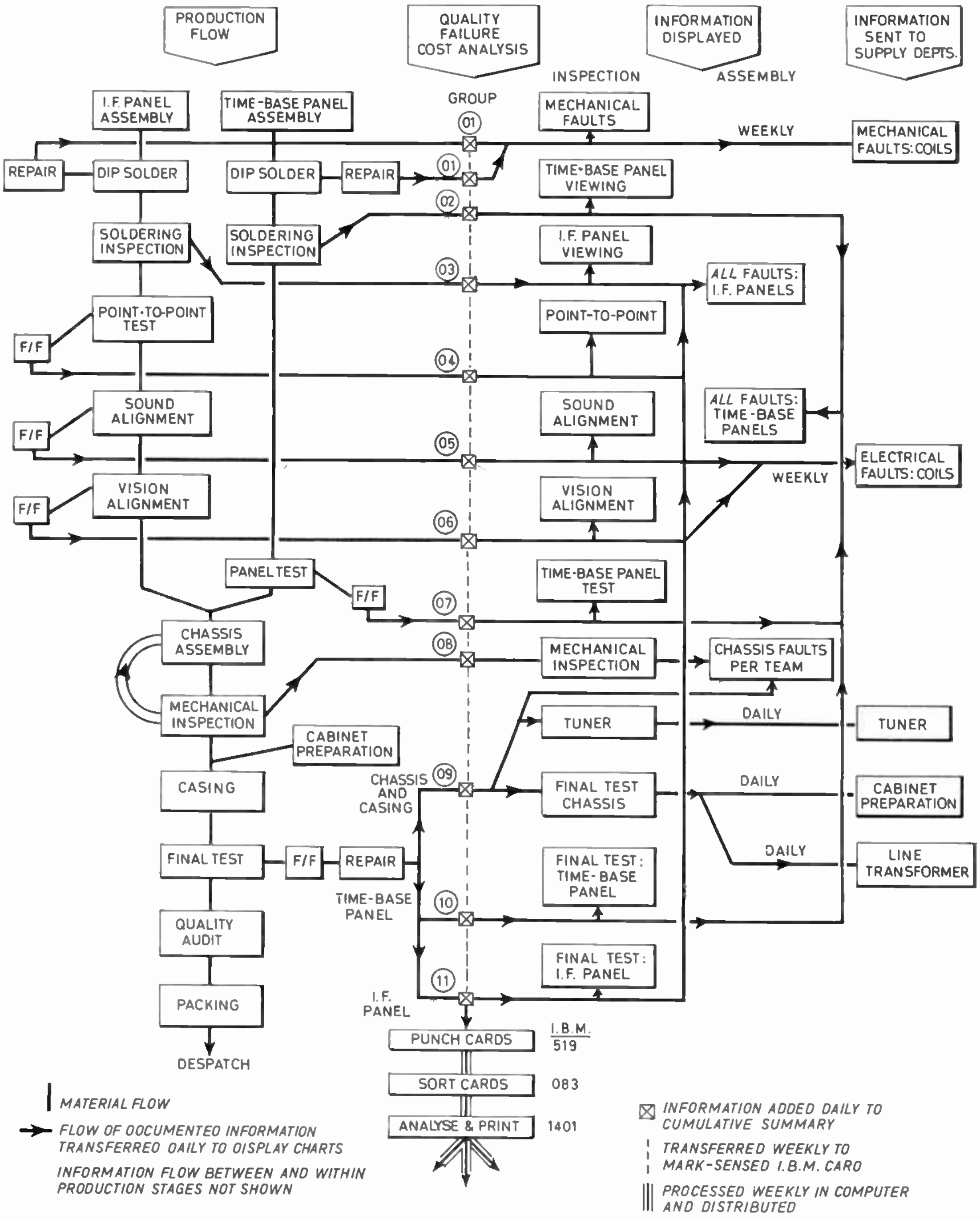


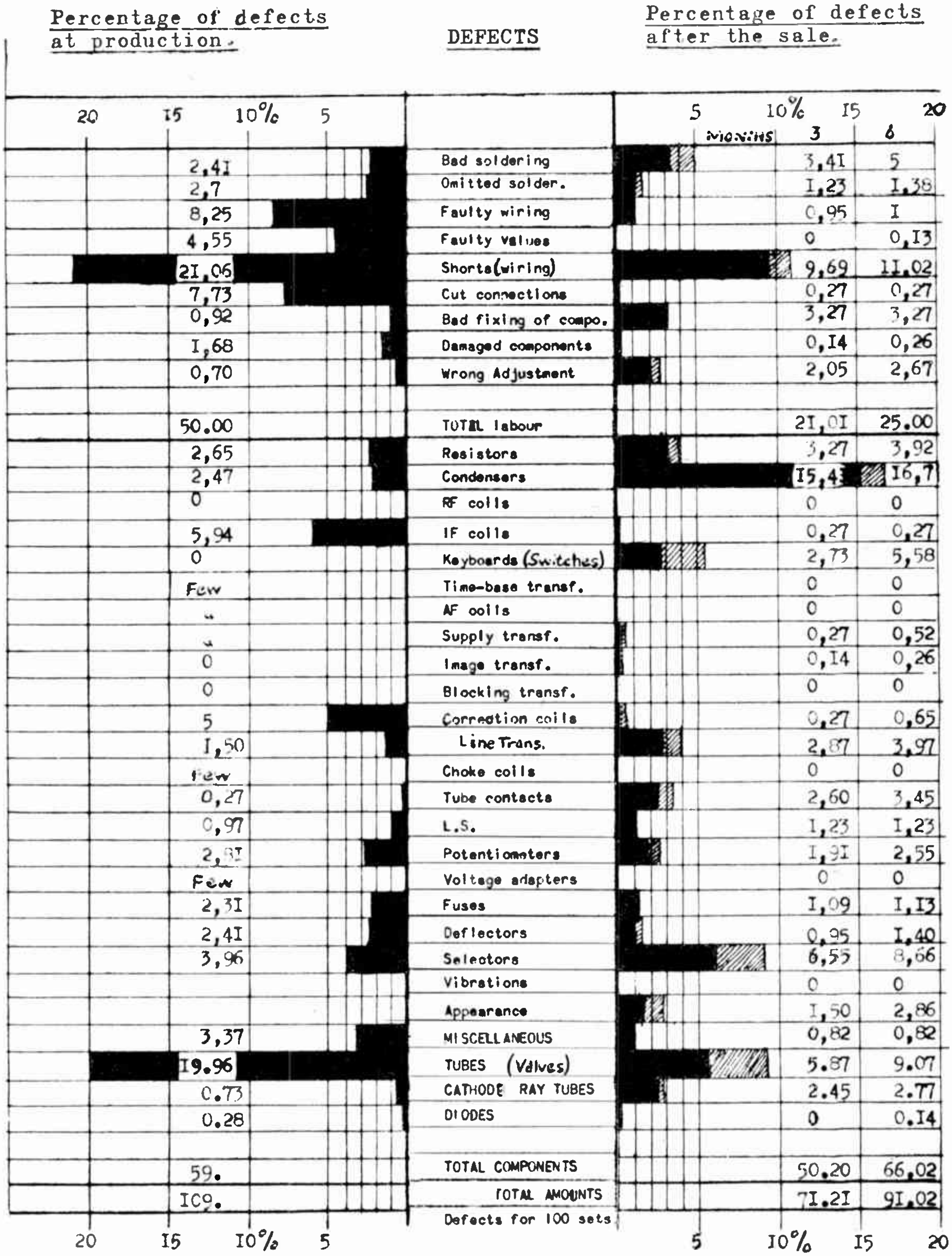
Fig. 7. Extended flow-diagram of television assembly.

6. Use of Quality Failure Cost Analysis

The second computer run is a Pareto analysis. The first ten fault codes usually account for 50% to 60% of the total cost. The production manager calls together temporary working groups to study ways in which each major zone of costs may be reduced. Each working group will contain the specialists appropriate to the particular problem, and may include representation from the following functions:

Design, production engineering, production and inspection, electronics engineering, purchasing, and others.

DEFECT CHART FOR I00 SETS



Percentage of defects at production.	DEFECTS	Percentage of defects after the sale. MONTHS 3	6
2,4I	Bad soldering	3,4I	5
2,7	Omitted solder.	I,23	I,38
8,25	Faulty wiring	0,95	I
4,55	Faulty Values	0	0,I3
2I,06	Shorts(wiring)	9,69	11,02
7,73	Cut connections	0,27	0,27
0,92	Bad fixing of compo.	3,27	3,27
I,68	Damaged components	0,I4	0,26
0,70	Wrong Adjustment	2,05	2,67
50.00	TOTAL labour	2I,0I	25.00
2,65	Resistors	3,27	3,92
2,47	Condensers	I5,4	16,7
0	RF coils	0	0
5,94	IF coils	0,27	0,27
0	Keyboards (Switches)	2,73	5,58
Few	Time-base transf.	0	0
〃	AF coils	0	0
〃	Supply transf.	0,27	0,52
0	Image transf.	0,I4	0,26
0	Blocking transf.	0	0
5	Correction coils	0,27	0,65
I,50	Line Trans.	2,87	3,97
Few	Choke coils	0	0
0,27	Tube contacts	2,60	3,45
0,97	L.S.	1,23	I,23
2,8I	Potentiometers	I,9I	2,55
Few	Voltage adapters	0	0
2,3I	Fuses	I,09	I,I3
2,4I	Deflectors	0,95	I,40
3,96	Selectors	6,55	8,66
	Vibrations	0	0
	Appearance	I,50	2,86
3,37	MISCELLANEOUS	0,82	0,82
I9.96	TUBES (Valves)	5.87	9.07
0.73	CATHODE RAY TUBES	2.45	2.77
0.28	DIODES	0	0.I4
59.	TOTAL COMPONENTS	50.20	66,02
IC9.	TOTAL AMOUNTS	7I.2I	9I,02
	Defects for 100 sets		

Fig. 8. Correlation between failure rate in factory and service.

(by courtesy of La Radiotechnique.)

The working group will devise ways of preventing the fault. It will use all technical resources available, and will be guided by the cost involved. For example, a mechanical fault such as faulty action of push buttons may be avoided by a minor redesign costing 10 ducats per set in re-tooling, more expensive process, better and dearer material, more labour, etc. However, if the previous failure cost of 30 ducats per set is reduced to one third of this value by the redesign, i.e. a new failure cost of 10 ducats, an operation profit of 10 ducats per set is gained together with a reduction of the reject level to one third of its previous level.

The quality failure costs analysis (q.f.c.a.) and the records of the working groups form permanent records which may enable various faults to be avoided in future designs. Inevitably new techniques bring new problems which are not avoided because of lack of previous experience; however, the q.f.c.a. assists in locating the troubles and bringing about more rapid action to achieve cost reduction.

7. Future Developments

Experience gained with the q.f.c.a. indicates that the material flow diagram may be expanded to contain the information feedback loops and the document analysis route needed to control quality costs. This is indicated in Fig. 7. This is now a normal part of the quality/production engineering activity. Studies carried out by our associates in La Radiotechnique of Paris have shown an interesting correlation between faults during manufacture and failures in service (Fig. 8). Unusual departures from correlation have sometimes been traced to the increased failure rate in service of components operating nearer to limit rating than is customary.

Analysis of the causes, quantities, and cost of failures, during service in the field may yield a useful contribution towards a reduction in overall cost of manufacture and service, and an improvement in reliability.

8. Acknowledgments

Appreciation is expressed for the assistance given by members of study teams who over a period of four years, have developed the various systems of information collecting, analysis, flow, and costing which have led to this quality failure cost analysis. Acknowledgment is also made to Philips Electrical Ltd. for permission to present this paper, and to La Radiotechnique, Paris, for use of Fig. 8.

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U.D.C. 535.3/5

A Review of Electro-optic Beam Deflection Techniques

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Based on a paper given at the B.S.I.R.A. Conference on 'New Developments in Optics and their Applications in Industry', held at Eastbourne in April 1967.

Summary: Electro-optic beam deflectors are of two basic types. The digital beam deflector produces a range of quantized beam output positions by the use of an assembly of electro-optic polarization switches coupled through birefringent elements. The analogue light deflector produces a continuously variable range of beam output positions by electro-optic variation of the refractive index of a deflecting element. In each case the number of resolvable output positions is determined by the diffraction angle of the light beam, the amount of background light generated, and the aberrations of the system.

Electro-optic beam deflectors may in future be applied to data reading and storage in computers, as well as in information displays, optical printers, and in multiple switching arrays. Using the electro-optic materials at present available, the maximum number of resolvable output positions in a two-dimensional deflector system is of the order of 10^6/cm^2. Limitations of switching speed arise through power dissipation in the electro-optic material and the large reactive energy storage in the switches. However, using existing materials and those which should be available in the near future, switching speeds in excess of 10^6 random addresses per second should be possible in deflectors of this capacity.

List of Symbols

A	prism aperture
B	prism base
b	beam displacement
C	capacitance of electro-optic switch
D	aperture of system
d	beam diameter
E	electric field strength
g_{mm}	quadratic electro-optic coefficient
h	total internal reflection (t.i.r.) mirror spacing
I	beam intensity
L	crystal length
n_i	refractive index
P	dielectric polarization
R	quadratic electro-optic coefficient
r_{mn}	linear electro-optic coefficient
R_s	surface resistivity of electrode
α_i	beam deflection angle
β_0	convergence angle of ray pencil
γ	Wollaston prism angle
Γ	optical phase delay
δ	diameter of Airy disk
ε	beam splitting angle
ζ	prism angle
θ_c	critical reflection angle
θ_1'	refraction angle
λ	optical wave length
ϕ	total deflection angle of beam
ψ	prism deflection angle

1. Introduction

The development of the laser has produced a new interest in techniques for light beam deflection since many applications can be foreseen for rapidly scanned beams of light. It is, of course, possible to do this by electro-mechanical methods involving the actual movement of a reflecting or refracting surface. Devices such as rotating or oscillating mirrors or prisms driven by motors or piezo-electric transducers could be used for this. However, these methods are limited to low speeds of operation and are only suited to systems requiring scanning at a regular rate. To control a light beam by non-mechanical methods it is necessary to vary the refractive index of a transparent medium through which the light passes. Such a change may be produced by electric fields, either through the linear electro-optic effect or the quadratic (Kerr) electro-optic effect. The applications of these effects in

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crystalline materials to the problem of optical beam deflection are reviewed in this paper. Similar changes are possible through magneto-optic effects.[1, 2] The elasto-optic effect may also be used in which strain in the medium produces the change. This may be produced thermally or by the transmission of acoustic waves through the medium.[3] All these approaches to the problem of high-speed light deflection are being studied at present with different types of application in mind. These include television projection systems or other large screen displays, scanned optical radars, optical printers, optical scanning systems for reading and writing of data into memory stores of computers, and optical switching arrays.

By using lasers in beam deflection systems rather than beams of incoherent light it will, in principle, be possible to obtain the maximum resolution in the deflection pattern. This is due to the spatial coherence of the laser light which propagates through the deflector system essentially as a plane wave front with the minimum possible beam divergence. This is determined by diffraction effects that are extremely small for beams of the usual size.[4] If the optics of the system do not introduce appreciable distortion of the phase-front then the resolution is set by the beam divergence angle alone. Correspondingly, it would be possible to focus the energy of the beam at the output of the optical system into the minimum 'diffraction-limited' spot area and hence maximize its brightness.[5]

Two basic types of optical beam deflection exist; the first is termed digital beam deflection in which a range of quantized beam deflections or transverse beam displacements is produced; the second is termed analogue deflection in which a continuous range of output deflections is produced. The digital beam deflector is particularly relevant in the proposed computer applications since it can convert digital voltage pulses in binary code directly into optical displacement. The deflected light beam can thus address a memory store to read in or read out data. It could also be used to carry out switching processes over large arrays of possible output positions.

2. Fundamentals of the Electro-optic Effect

The variations in refractive index that can be produced in available electro-optic materials are usually less than 1 part in 10^3, and to make use of such a weak effect for digital beam deflection the same phase modulation techniques developed in electro-optic modulators are employed. In analogue deflection the refractive index change is used directly.

A brief review of the electro-optic modulation effects is given. A more comprehensive treatment can be found elsewhere.[1, 6]

The electro-optic effect produces a change in the refractive index on applying a field to the medium which is written schematically as:

$$\frac{1}{n^2} = \frac{1}{n_0^2} + rE + RE^2 \qquad \ldots\ldots(1)$$

where r and R represent the linear and quadratic effects. There are also secondary elasto-optic effects as a result of the mechanical stress in the medium produced by the field, either through the converse piezo-electric effect or through electro-striction. These stress effects depend on crystal symmetry in the same way as the electro-optic effects, although at sufficiently high field frequencies only the primary effect is important. In general the optical properties of crystals depend on the polarization and direction of the light relative to the crystal axes. This is described in terms of the refractive index ellipsoid

$$\frac{x_1^2}{n_1^2} + \frac{x_2^2}{n_2^2} + \frac{x_3^2}{n_3^2} = 1 \qquad \ldots\ldots(2)$$

where x_i are a set of co-ordinates in the crystal and n_i are the principle refractive indices. In isotropic crystals $n_1 = n_2 = n_3$; in uniaxial crystals $n_1 = n_2 \neq n_3$; and in biaxial crystals $n_1 \neq n_2 \neq n_3$. Since the applied field E is a vector and the components of r and R depend on crystal symmetries, the effect of applying a field is to change and re-orientate the index ellipsoid. Thus the principal refractive indices which determine the propagating velocity of orthogonally polarized waves in the medium are field dependent.

Figure 1 illustrates the change in the cross section of the index ellipsoid in the case of a uniaxial linear electro-optic material such as potassium di-hydrogen phosphate (KDP) in which the field is applied along the optic axis. The index ellipse changes from its circular field-free cross section and rotates to principal axes at 45° with respect to the original crystal axes. The refractive indices along these new axes are

$$n'_{x1,2} \simeq n_1 \mp \tfrac{1}{2} n_1^3 r_{63} E_3 \qquad \ldots\ldots(3)$$

Thus two light beams polarized along these directions and travelling along the optic axis over a length L experienced a relative retardation

$$\Gamma_{x_1'} - \Gamma_{x_2'} = \frac{2\pi n_1^3 r_{63} E_3 L}{\lambda}$$

In some types of crystals electro-optic coefficients exist which allow modulating fields to be applied transverse to the direction of propagation. For example, when the modulating field is normal to a 110 face and the incident light is normal to a $\bar{1}10$ face of a cubic crystal, then again the principal axes are rotated through 45° with respect to the crystal axes (see Fig. 2), and a differential phase change is produced of

$$\Gamma_{x_1'} - \Gamma_{x_2'} = \frac{2\pi n_1^3 r_{41} EL}{\lambda}$$

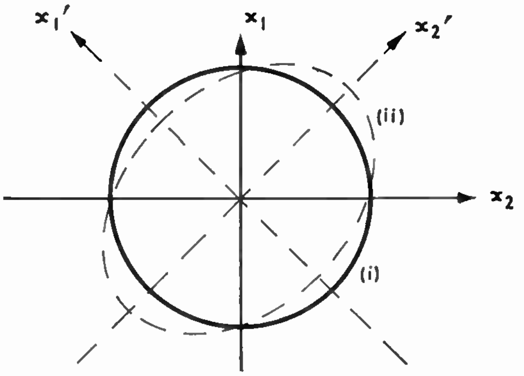


Fig. 1. Intercept of index ellipsoid with x_{12} plane in uniaxial material. x_3 is optic axis. (i) field off (ii) field applied along x_3.

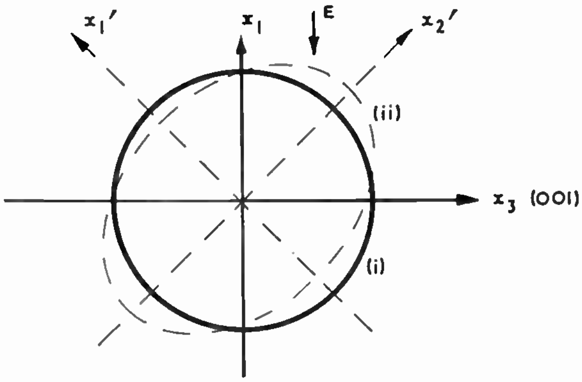


Fig. 2. Intercept of index ellipsoid with x_{12} plane (110 face) in cubic material. (i) field off (ii) field applied.

Numerous other orientations are possible for the direction of the electric field and light propagation with respect to the crystal axes. However, the two conditions discussed are most commonly used.

In quadratic effect (Kerr effect) materials, the relative phase change is a quadratic function of the applied field or polarization in the medium (P), although the quadratic electro-optic constants are not the same for the two principal refractive indices. For a field applied along the 100 axis of cubic material such as potassium tantalate-niobate (KTN) the relative phase delay for light propagating normal to the axis may be written.

$$\Gamma_o - \Gamma_e = \frac{2\pi n^3 (g_{11} - g_{12}) P^2 L}{\lambda}$$

Thus, by producing a relative electro-optic half-wave phase delay of π between two orthogonally polarized waves we have the equivalent of an electrically controlled half-wave plate. It is well known that such a plate produces a $\pi/2$ change in the direction of polarization of a light beam when the principal axes of the plate are at an angle of $\pi/4$ to the direction of the incoming light beam as shown in Fig. 3. The switching of a light beam between two orthogonal directions of polarization is the operating principle of the digital beam deflector.

The materials most widely used at present in electro-optic modulators are potassium di-hydrogen phosphate (KDP) and ammonium di-hydrogen phosphate (ADP). These can be obtained in excellent optical quality, and can be cut and polished without difficulty. Other linear electro-optic materials are lithium niobate, lithium tantalate, barium titanate. These are ferro-electric materials and, as such, the dielectric constants and electro-optic constants can be strongly temperature dependent as the Curie temperature is approached.

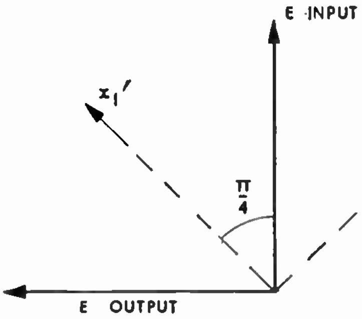


Fig. 3. Polarization change in passing through half-wave plate.

Temperature stabilization of these materials is important in practical modulators. Linear electro-optic materials with cubic crystal structure are especially useful in modulators since there is no natural birefringence to complicate the design of modulators using convergent light beams. At present there exist gallium arsenide, cadmium sulphide and zinc telluride of reasonable quality in this category, although gallium arsenide is only transparent at infra-red wavelengths. The mixed crystal KTN ($KTa_xNb_{1-x}O_3$), is a centrosymmetric cubic material showing large quadratic electro-optic effects at room temperatures since its Curie temperature is about 0°C. However, it has not so far been possible to grow this material in sizes and qualities sufficient to be of practical use. The temperature stabilization ($<0{\cdot}01°$) which would be necessary in a modulator using this material is also a major problem. New materials, such as strontium-barium niobate,[8] are being developed, but at present the ideal material with a low half-wave voltage, low r.f. losses, with good optical and electrical homogeneity, and absence of field-induced laser damage effects[9] is a long way off.

3. Digital Beam Deflection

Figure 4 shows the basic digital light deflection system. It consists of a number of stages each comprising an electro-optic switch and a birefringent element.[10, 11] Each electro-optic switch is used to produce two possible orthogonal states of the direction of polarization of the light beam passing through it. The birefringent elements may be of different types and, as a first example, a birefringent crystal, such as calcite, aligned with its optic axis in the $x-z$ plane will be considered. Then, if an electro-optic switch produces a beam at its output which is polarized in the ordinary ray direction for the following calcite crystal, the beam will pass unrefracted normally through the crystal. If, however, the beam is polarized orthogonally as an extraordinary ray, then the beam is refracted away from the normal. It leaves the crystal with a parallel displacement (b) which is proportional to the thickness of the crystal through the relation

$$b = L \tan \varepsilon$$

where ε is the splitting angle between the beams. The maximum value of this is

$$\tan \varepsilon_{\max} = \frac{n_e^2 - n_o^2}{2 n_o n_e}$$

at which the corresponding orientation of the optic axis is

$$\tan \nu = n_e / n_o$$

In calcite at 6328 Å the maximum splitting angle is 5·9°, and in sodium nitrate it is 9·17°.

Thus if a beam passes through a sequence of such deflecting units, a maximum of 2^n different beam position can be produced at the output. If the birefringent crystals are of thickness

$$L, 2L, \ldots, (2^{n-1} L)$$

then a linear pattern of possible positions will be obtained in terms of binary input voltages to the deflection bank. The final displacement will depend on the number of polarization changes through the sequence. Figure 4 shows the binary representation of the deflections and the voltages producing them. By the use of switching networks incorporating AND/OR gates the deflections can be made numerically identical with the deflection voltages.[10] By combining two units which produce deflections at right angles 2^{2n} beam output positions can be obtained by addressing them with binary input voltages.

To obtain the maximum resolution and intensity a convergent beam of light would be used (see Fig. 5). This would be brought to a focus on the output side of the last deflector. However, since the two possible optical paths through each of the birefringent crystals are not equal, the position of the focal plane depends on the transverse deplacement of the beam. In imaging paraxial rays this de-focusing effect can be compensated by the equivalent of a linear tilt of the imaging plane. More complex methods of optical path length combination are necessary for beams whose maximum convergence angle exceeds a few degrees. These include using two birefringent crystals whose principal planes are at right angles to each other and which are

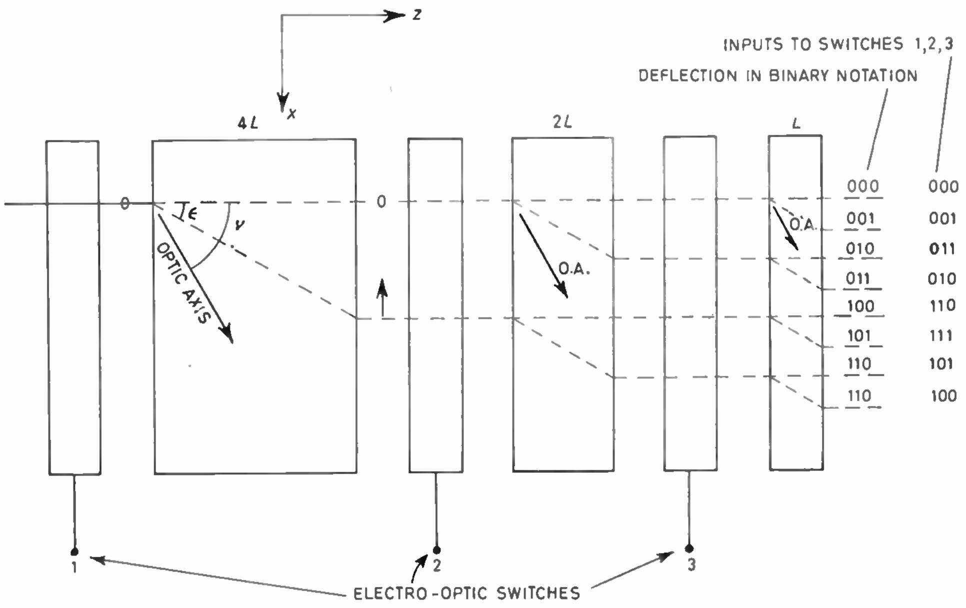


Fig. 4. Schematic of digital light deflector using split angle deflectors.

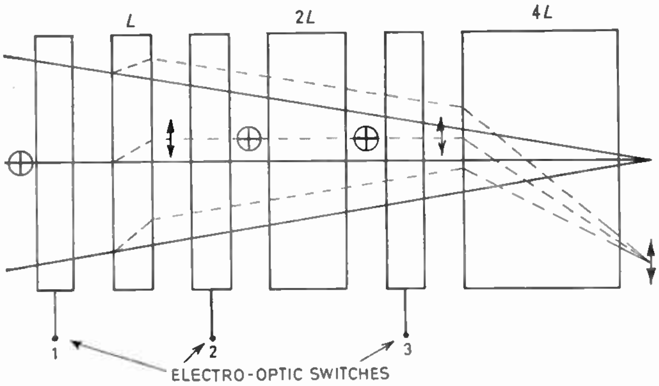


Fig. 5. Digital light deflector using convergent optics.

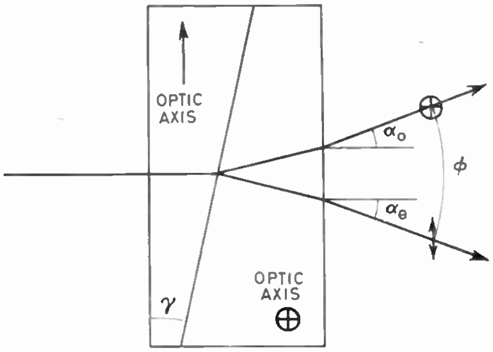


Fig. 6. Wollaston prism beam deflector.

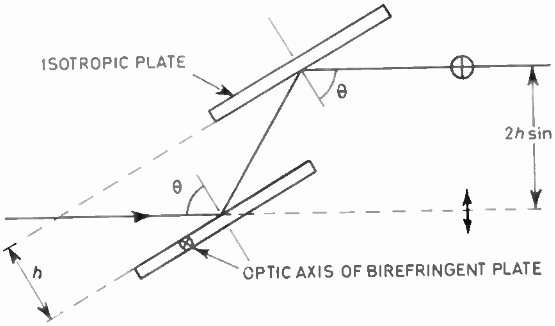


Fig. 7. Total internal reflection (t.i.r.) beam deflector.

cemented together to form a deflection stage. Thus a light beam propagates through the crystal pair first as an ordinary ray and then as an extraordinary ray or vice versa. Hence the two possible optical paths are invariant. The total length of birefringent material must be increased by a factor $\sqrt{2}$ to obtain the same lateral deflection as an uncompensated stage. Alternatively the two principal planes may be rotated by 180°, and a half-wave plate is inserted between the crystals to change ordinary to extraordinary ray and vice versa. In addition it would be possible to combine crystals of different materials with positive birefringence ($n_o < n_e$) and negative birefringence ($n_o' > n_e'$) to achieve the same purpose.

A convergent bundle of rays passing through a birefringent crystal generates background light because the angle of polarization over the bundle incident on the crystal surface varies. Thus the beam splits into major and minor components which propagate through the crystal. The major component propagates according to the principal polarization direction of the incident beam, whereas the minor component propagates in an unwanted direction as background light. The background light increases as the convergence angle increases. In calcite it reaches about 1/20 the intensity of the incident light[11] for a convergence angle of 4·5°. The same effect is produced when convergent light passes through a uniaxial electro-optic crystal. This restricts the angle of beam convergence that can be used. In KDP crystals a practical limit[11] is about 1·5°.

Two other types of birefringent element can also be considered. These are the Wollaston prism deflector[12] and the total internal reflection deflector.[13] These are shown in Figs. 6 and 7. The Wollaston prism deflects the beam to one of two directions when light is incident normally on to its front surface in one or the other polarizations. The total angle of divergence is approximately

$$\phi = \alpha_o + \alpha_e \simeq 2(n_e - n_o) \tan \gamma$$

where γ is the Wollaston prism angle. α_o and α_e are not precisely equal even at normal incidence, and as the beam passes through successive elements the asymmetry of deflection becomes worse. This can reach a value of several degrees in practical situations.[14] By altering the angle of cut, γ, of each Wollaston prism the deflection of a given stage can be made twice that of the preceding stage ($\phi_m = 2^{m-1}\phi_1$) and the binary voltages applied to the deflector stage will produce a linear range of output deflection angles. At the output the beam would be focused to a spot at every deflection position. To resolve two adjacent output positions completely, the minimum permissible angular deflection at the first stage should be greater than the diffraction spread of the light beam. For a collimated Gaussian light beam, the total angular divergence is $4\lambda/\pi d$ where d is the diameter between e^{-2} intensity points.[4] Thus ϕ_1 must be greater than this angle. No detailed calculations of the effects of non-normal incidence of light on Wollaston prisms have been carried out in terms of the production of undesirable background light (I_B). However, it is stated[14] that in a single Wollaston prism

$$I_B/I_O = \beta_0^4/4$$

where β_0 is the maximum convergence angle of a pencil of rays about a normal incidence to the prism.

The principal source of background illumination in this type of deflector is the increasing angle of incidence through successive uniaxial (KDP) electro-optic switches along the deflection bank. To keep within a 1·5° cone of incidence on the last switch of a 10-stage Wollaston deflector the minimum angular deflection produced by the first stage ϕ_1 must be less than 0·36 minutes. Such a small angle is difficult and expensive to achieve in Wollaston prisms. The angular deflector also requires components whose apertures are sufficient to accommodate the angular walk-off of the beam as it is deflected through successive stages. For example a 20-stage deflector bank using collimated light would require crystals of several centimetres aperture at the output stages. However, the deflection elements would be required in relatively thin slices only, which reduces the material requirements.

The total internal reflection (t.i.r.) beam deflector (Fig. 7) uses a plate of birefringent material in which the optic axis is oriented perpendicular to the plane of incidence in a medium of index n_m. A linearly polarized light beam is then totally reflected at the plate if its angle of incidence, θ, is greater than the critical angle for its direction of polarization. Thus for example in the following condition

$$\sin\theta_{ce} = \frac{n_e}{n_m} \leqslant \sin\theta \leqslant \sin\theta_{co} = \frac{n_o}{n_m}$$

$$n_m \geqslant n_o > n_e$$

the extraordinary polarization only is reflected. The ordinary component is transmitted through the plate without loss if $n_m = n_o$. The reflected extraordinary component is again reflected at a parallel mirror of isotropic material at a distance h from the first mirror. Thus a parallel displacement of the two components, $2h \sin\theta$, is produced. The two optical path lengths differ by $n_m b \tan\theta$, and to compensate for this a plate of isotropic material can be used in the path of the undeflected beam. Alternatively, a birefringent plate might be used before the total internal reflector. This would be oriented so that the necessary phase compensation was introduced between the ray components.

The t.i.r. system of beam deflection is only really suitable for producing large linear displacements of a parallel light beam. It would be necessary to use uneconomically large aperture electro-optic switches in conjunction with it.

In all these techniques the principal limitation on the number of possible output positions that can be resolved is governed by the allowable background light generated in the electro-optic switches and birefringent elements. In all deflector systems the maximum resolution will be produced by the use of a focused spot at the output of the deflector. The diameter of the Airy disk at the focus is

$$\delta = 1{\cdot}22/\lambda\beta$$

where 2β is the total convergence angle of the light. This is equal to D/L and D is the limiting aperture of the system. However, there is the constraint that to reduce the background light to less than 1% per deflector stage, the convergence angle must be less than 1·5° in KDP or less than 3° in a calcite splitter. This therefore limits the aperture of the system. Using the 1·5° limit the spot diameter of the deflector is about 30 µm. Thus a deflector bank of 20 stages producing $(2^{10} \times 2^{10})$ different positions must have crystals in it which are about 30 mm square.

4. Analogue Beam Deflection

Analogue beam deflectors have not been studied as extensively as the digital variety. This is due to the present lack of materials in good optical quality with large electro-optic constants. The main approach has been to use prisms of variable refractive index, although electro-optically variable diffraction gratings[16] and interferometers[17] have been proposed.

An electro-optic prism of angle ζ (see Fig. 8) will produce a change in deflection angle $\Delta\psi$ in response to a change in refractive index Δn given by

$$\Delta\psi = \frac{\sin\zeta}{\cos\theta_1' \,\cos\theta_2'}\,\Delta n$$

where θ_1' and θ_2' are the angles of the refracted rays passing through entrance and exit faces of the prism. It can be shown that the maximum change occurs at the angle of minimum deviation,[15] which gives the result

$$\Delta\psi = \frac{B\Delta n}{A}$$

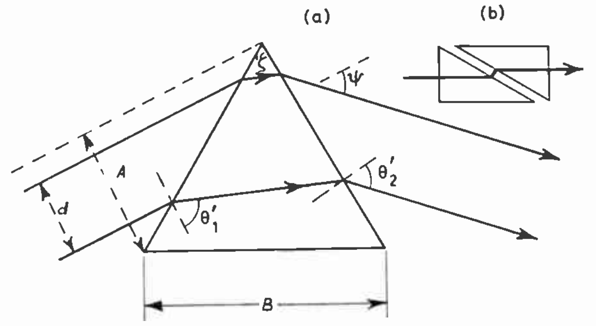
where A is the prism aperture and B is the base of the prism as in Fig. 8. Thus it appears that $\Delta\psi$ can be made arbitrarily large by reducing the aperture of the prism. However, this will also increase the diffraction divergence of the beam passing through the prism aperture. The minimum deflection angle that can be resolved will be of the order of the half angle of the diffraction divergence of the (Gaussian) beam

$$\left(\frac{2\lambda}{\pi d}\right)$$

Thus the number of resolvable beam positions is

$$R = \frac{\Delta\psi\pi d}{2\lambda} = \frac{\pi}{2}\,\frac{B}{A}\,\frac{d}{\lambda}\,\Delta n$$

This is therefore independent of prism angle and depends only on its base length and the ratio of beam width to prism aperture. However, the prism angle must be less than $2\sin^{-1}(1/n)$ to avoid total internal reflection in the prism. Various prism constructions



(a) Electro-optic prism deflector. (b) Prism combination.

Fig. 8.

are possible to adjust the zero-field deviation angle to zero if required (see Fig. 8(b)). This arrangement has the advantage of minimizing reflection losses by normal incidence at prism surfaces. If both prisms in the combination are electro-optic, then the deflection can be doubled for the given base length by the use of 'push-pull' arrangements, although fringing field effects must be considered. An arrangement using multiple passes through an electro-optic prism and mirror combination has also been used to produce enhanced deflections.[18]

Since values of Δn up to 7×10^{-3} have been observed in KTN it should be possible to resolve 110 positions per centimetre of prism base length.[19] However with the present material, which is only sufficiently homogeneous in volumes much less than 1 mm^3, only eight beam positions have been resolved.[19] Similarly, beam deflections of about 1° have been demonstrated in prisms of barium titanate.[20] Using an arrangement of multiple deuterated KDP prisms operated near the Curie temperature (210°K) two hundred resolved positions have been obtained.[21]

5. Electrical Requirements of the Electro-optic Switches

Electro-optic switches are essentially dielectric filled capacitors of a few hundred picofarads capacitance to which several kilovolts are usually applied. If the longitudinal electro-optic effect is used, as in KDP, the electrodes must be semi-transparent, since the light propagation is in the same direction as the applied field. Thus a high transmittance (t) is required in a digital deflection system since an n-stage system has $2n$ electrodes, and thus the total transmission is reduced to t^{2n}. If $t = 0{\cdot}9$ and $n = 16$ the transmitted light is reduced by over 96%. Possible electrode materials include tin oxide, indium oxide, cadmium oxide. Other losses due to reflection at dielectric interfaces can be eliminated by blooming or refractive index matching oils. Unfortunately the requirements for high light transmission and low electrical resistivity in the electrodes seem to be incompatible. Thus power dissipation in the electrodes can present a problem through heating the electro-optic material with subsequent changes in its optical characteristics.

The dissipation is

$$P = \tfrac{1}{2}\omega^2 C^2 V^2 R_s \quad \text{where} \quad \omega \ll \frac{1}{R_s C}$$

where the capacitor C is charged sinusoidally up to a voltage V and R_s is the surface resistance of the electrodes, which is usually of the order of a few hundred ohms. For typical values of C and V we find that in order to restrict the power dissipation to less than 0·5 watt the maximum tolerable switching frequency is less than 100 kHz. This emphasizes the general need for materials in which the electrodes are not in the optical path.

Dielectric losses in the electro-optic material are another source of power dissipation. These also can produce thermal gradients across the modulator crystal which severely affect its optical properties. This is especially true if materials such as KTN are used which are operated close to their Curie point. In the case of KTN the temperature must be maintained[22] uniform to better than 0·01°C. When d.c. biasing fields are used for quadratic effect modulators such as KTN, the finite conductivity of the dielectric can produce space-charge build-up which will effect the steady polarization. In the case of KTN this build-up time is of the order of 10^3 to 10^4 seconds.[22]

To minimize the power dissipation in switching the large reactive energy stored in the many electro-optic elements of a digital deflector schemes have been developed in which the half-wave biasing voltage is provided by a combination of alternating and direct voltages of equal amplitude.[23] Switching between elements can then take place at the frequency of the alternating voltage at instants when both the voltage and current across the switch is zero. Hence the dissipation in the switch is minimized and reactive energy can be stored in the deflector system. The background light effects produced by voltage deviations from the half-wave values are discussed elsewhere.[24]

6. State of the Art and Conclusions

A number of digital light deflectors have been constructed, and the highest published performance has been obtained using 16 stages of KDP switches and calcite split-angle deflectors. This produces a matrix of 256 × 256 resolvable positions.[25] By the use of an additional single stage t.i.r. deflector the number of output positions has been multiplied by two.[11] A deflector using split angle deflectors, Wollaston prisms and t.i.r. deflectors is considered to produce a combination of optimum performance which would resolve 10^6 positions per cm^2 aperture with minimum aberrations.[11] A theoretical and experimental study of a system using Wollaston prisms only has also shown that in a 1 cm^2 aperture 4×10^6 positions could be resolved. This was confirmed by a manually-operated model which produced approximately the predicted resolution.[26]

The present digital light deflectors use deuterated KDP in their electro-optic switches but, in anticipation of improved electro-optic materials, a study has been carried out of deflectors using KTN or zinc telluride.[22] These indicate a potentially high performance which is described in terms of a $(\text{capacitance})^{\frac{1}{2}} \times$ random address-rate product, where the capacity is defined as the total number of output beam positions. The upper limit to this product is set by the allowable power dissipation or by temperature fluctuations if the material operates near its Curie temperature. It is estimated that this product is of the order of 10^9 in deflectors using reactive drive powers of the order of 10 watts. Thus it should be possible to address randomly a matrix of 10^6 output positions at rates of 10^6/s. Digital deflectors of the same capacity using KDP should be about an order of magnitude slower.[27]

There have, so far, been no published reports of high-capacity digital deflectors operating at such speeds. However, the present indications are that high-speed, high-capacity, digital light deflection offers considerable promise as a new technique in such fields as computer memories, displays, and optical printing. The analogue beam deflection techniques must await the development of greatly improved electro-optic materials before they can be used in practical applications.

7. Acknowledgment

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Shadow Mask Picture Tube Convergence Techniques

By

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Summary: The problems of shadow mask display tube convergence are described for both triangular and in-line configuration of the three beams and various solutions to these problems are discussed. The merits of various circuits are compared and the adjustment procedure is outlined.

1. Introduction

The shadow mask tube may, in many respects, be considered reasonably close to the ideal as a colour television receiver display device, there being virtually three independent cathode-ray tubes, one for each primary colour, in a single envelope and with common horizontal and vertical deflection systems. Deviation from this ideal occurs since the three guns cannot all be situated on the tube main axis. This results in positional and geometrical errors between the three rasters unless means of correction are provided.

Shadow mask tubes that are at present in production may be divided into two types, the most important being that with the three electron-gun systems at the vertices of an equilateral triangle. In Europe, the two sizes at present available are 25 in and 19 in, but in the United States a number of additional sizes are being manufactured including 15 in, 21 in and 23 in. Further additional sizes including 14 in and 17 in are in production in Japan.

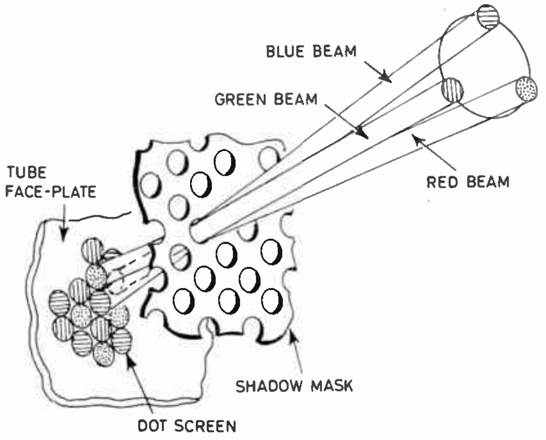
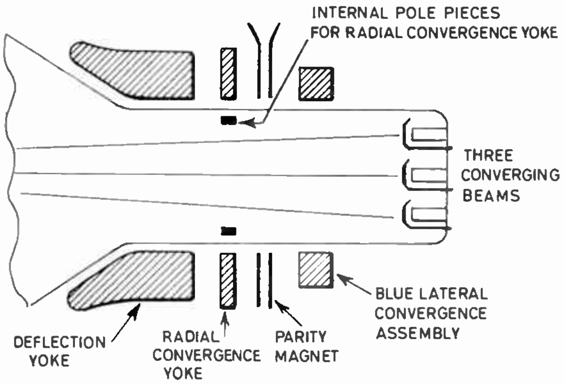
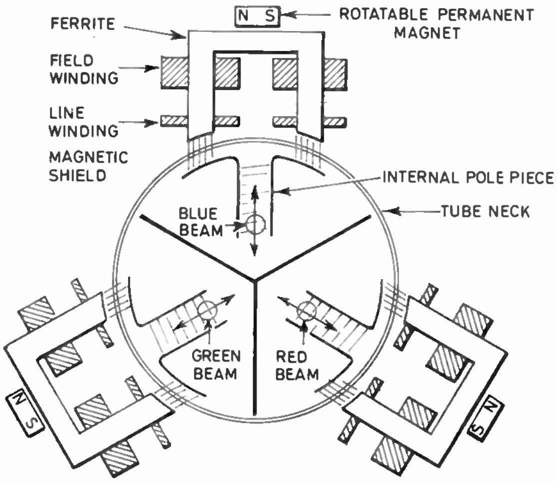


Fig. 1. (a) Action of shadow mask.



(b) Position of units on tube neck.



(c) Convergence yoke and internal pole-pieces.

The second type includes tubes with the guns arranged in either a vertical or horizontal line. There is only one available size of this group at present, an 11 in tube with horizontally-arrayed guns, manufactured in the United States.

The first type, the largest and most important, will be considered. Figures 1 (a, b and c) show the well-known means of colour separation in the shadow mask tube.

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2. Purity and Convergence

The term, purity, infers that electrons from a particular gun will only strike the phosphor dots that generate the appropriate colour. Figure 2 shows the situation for the undeflected beams where it is seen that the beams must approach the mask and screen at the correct angle. This angle is defined by the spacing between the mask and the screen and is provided by the assembly of the guns being tilted towards the main tube axis.

Because of tolerances in assembly the undeflected beam may not coincide with the centre of the screen, and therefore the purity will not be correct. Within these assembly tolerances, adjustment is possible by means of a ring magnet unit, usually called the 'purity magnet', mounted on the neck of the tube (Fig. 1(b)). This unit usually consists of two diametrically magnetized rings, rotatable either independently or together, and produces a field, adjustable in strength (maximum 20 gauss) and direction, but always perpendicular to the main tube axis. The three beams can thus be moved equally before deflection so that when undeflected they coincide with the centre of the screen. This is a condition for purity.

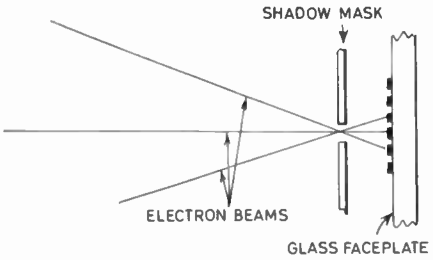


Fig. 2. Paths of undeflected beams.

When the magnet rings are opposing each other the movement of the beams is less than 3 mm and when the fields are in phase the movement is at least 40 mm. An alternative arrangement uses a pair of electromagnetic poles giving horizontal and vertical movement respectively. This technique requires the use of very stable supplies and has limited application where remote control is essential. Figure 3 shows both types of purity magnet assembly.

When the beams suffer deflection, the bending does not form a sharp angle but a curve of decreasing radius as the amount of deflection is increased (Fig. 4). It is thus necessary to refer to the 'virtual centre of deflection' and note that with increasing deflection it moves towards the screen. This effect is allowed for in the optical process whereby the phosphor dots are laid down using the shadow mask as a master, associated with the choice of a suitable length for the deflecting field. It is clear from the above that there is only one position on the tube neck for the deflection yoke that will give purity over the entire screen. There are thus two purity adjustments, firstly to obtain purity in the centre of the screen and secondly for correctly positioning the scanning yoke along the tube neck to obtain a complete pure field.

The discussion of the requirements of colour purity is only concerned with the angle at which the electron beams pass through a hole in the shadow mask. This does not infer that at any given instant or position of

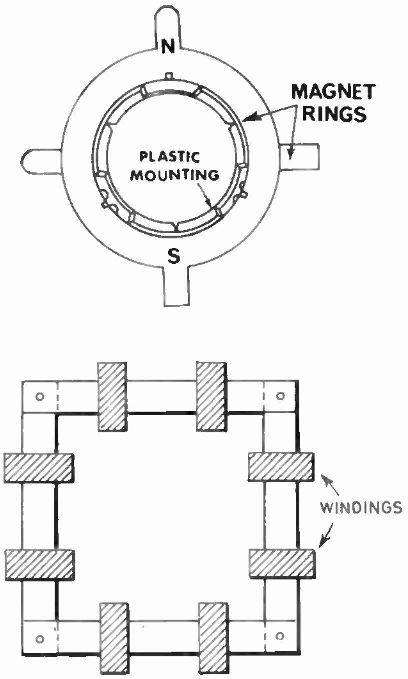


Fig. 3. Two types of purity magnet assemblies.

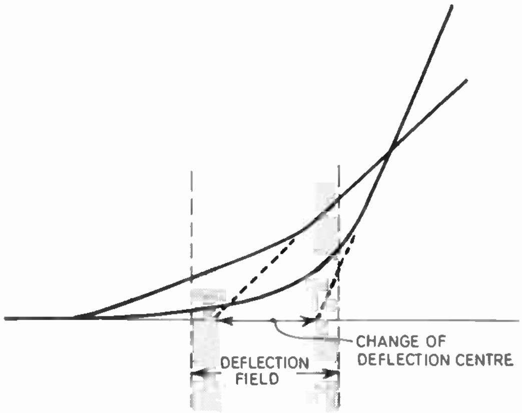


Fig. 4. Change of deflection centre.

deflection all the beams on the raster will pass through the same hole. When this does not occur there will be either a difference in geometry or position of the rasters (Fig. 5). The process of correcting these errors is called convergence, i.e. obtaining the situation where all the three beams 'converge' at all points of the raster to pass as far as possible through a common hole or holes in the mask.

If errors in purity and/or convergence are large the inevitable inter-relation between them will be observed, gross convergence errors giving rise to inaccurate beam landing and very serious impurity giving anomalous misconvergence effects.

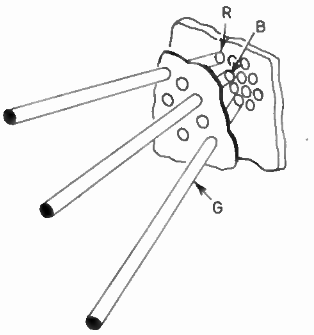


Fig. 5. Purity correct but convergence at fault (compare Fig. 1(a)).

Since none of the electron guns is on the main axis of the tube, means for correction must be provided for all the three beams. All guns are provided with magnetic pole-pieces (Figs. 1(b) and (c)) which permit a radial movement of the beams by means of externally applied magnetic fields. (The first shadow mask tubes used a mixture of magnetic and electrostatic fields.) If the tube is considered to be aligned with the blue gun at the vertex of the triangle defining the gun positions uppermost, the red and green beams may be brought into convergence by applying the necessary fields to their pole-pieces. Although only radial motions are possible, it simplifies the concept if they are considered to be resolved into two sets of orthogonal components, vertical and horizontal. Figure 6 shows how an increase in field strength on both red and green pole-pieces causes them to converge horizontally, whereas varying the field in opposite sign results in a vertical motion. In both cases an apparent, but unimportant 'overall' movement occurs.

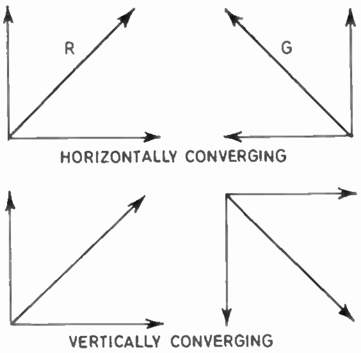


Fig. 6. Effect of increase in field strength on both red and green pole-pieces.

The application of a field to the blue pole-pieces will give rise to a vertical motion enabling convergence with red/green to be obtained in this plane, but convergence with red/green will not necessarily exist horizontally. An additional magnetic assembly is provided (Fig. 1(b)) giving a horizontal motion to blue, normally referred to as the 'blue lateral' unit. Earlier shadow mask tubes were fitted with internal pole-pieces for this unit which were shaped like an 'E' and coupled the external magnet to the beam in such a way that a horizontal movement resulted (Fig. 7(a)). Tubes now being manufactured have a much smaller neck diameter and do not have internal pole-pieces for blue lateral. One approach uses an external unit as in Fig. 7(b), showing how red/green and blue are moved in opposite horizontal directions. An alternative method uses a six-pole magnet as in Fig. 7(c). Since it is offset from the tube axis eccentrically, horizontal motion of blue in relation to red/green is always opposite. The disadvantage of this latter arrangement is that the application of an alternating field to such a magnet assembly is more difficult. A further alternative would be the use of ferrite pole-pieces in which the application of alternating fields is more efficient. The field is more concentrated and less undesired cross-talk occurs.

Summing up, the three beams may be brought into convergence by the application of three radial and one lateral magnetic fields.

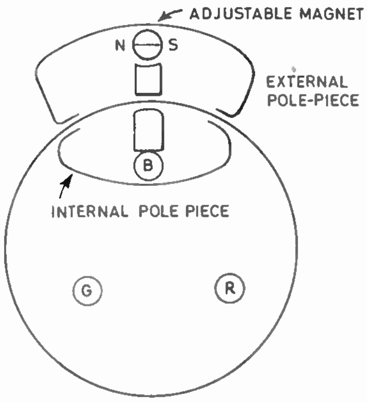
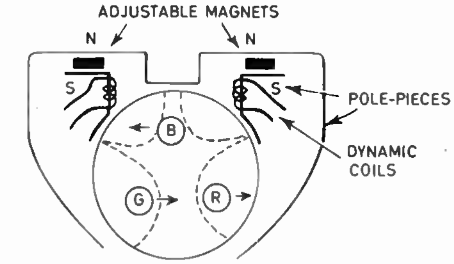
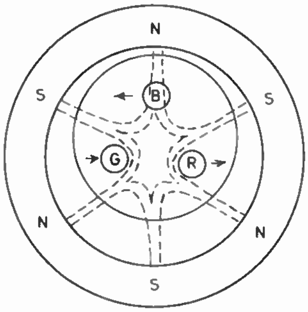


Fig. 7. (a) Blue lateral adjustment for 70° tubes.



(b) Blue lateral adjustment with dynamic correction for 90° tube.



(c) Blue lateral adjustment with 6-pole assembly for 90° tube.

Fig. 7.

3. Convergence Techniques

Assuming that the three rasters can be corrected so that they are similar in geometry, any positional error can be corrected by application of either one of the following three: (i) a d.c. electromagnetic field, (ii) a variable permanent magnetic field, or (iii) a combination of the two methods, usually called static convergence. This latter, with the emphasis on the permanent field, is the most common since high-stability electromagnetic fields are not easily produced economically in a domestic receiver.

The correction of the geometrical errors is usually called ‘dynamic convergence’, because it is a positional correction, the required magnetic fields are normally derived from the scanning circuits, the currents at line and field repetition rates being fed to the coils as in Fig. 1. Figure 8 shows the errors that might be expected in the absence of any dynamic convergence correction.

If a raster with such distortion is corrected with currents derived from the scanning circuits, but without any provision mutually to modulate line with field and field with line currents, convergence can only be correct for points along a centre horizontal line and points along a centre vertical line. The quality of convergence away from these lines will be marred by trapezium errors as shown in Fig. 9. Mutual modulation of line by field and vice versa might be an unacceptable technique in an economic domestic receiver design and could be difficult to adjust and impose serious servicing problems. This problem is overcome to a considerable extent by making the scanning fields deliberately astigmatic. Figure 10

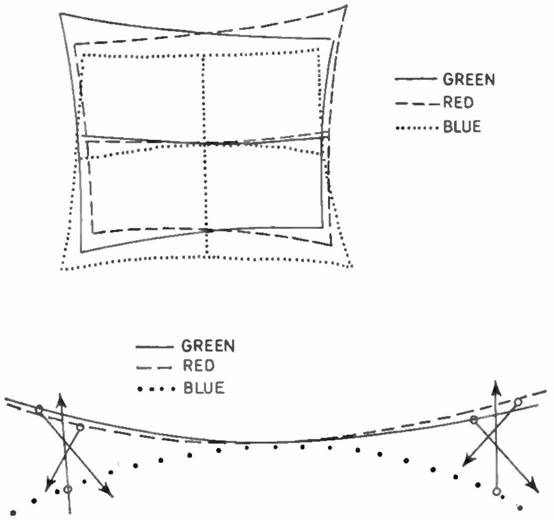


Fig. 8. Errors that might be expected in the absence of any dynamic convergence correction without trapezium correction.

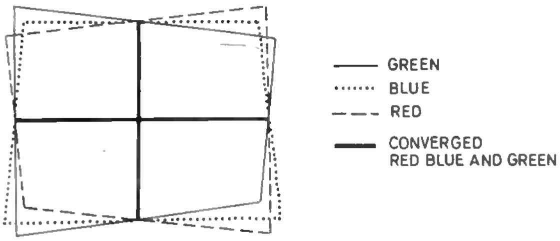


Fig. 9. Errors in converged raster without trapezium correction.

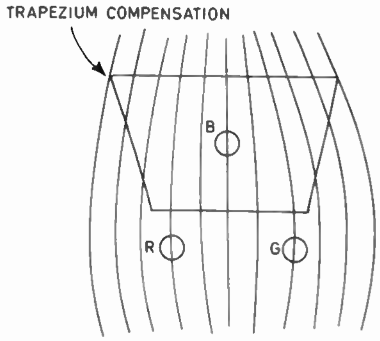


Fig. 10. Horizontal deflection correction for blue raster trapezium errors.

shows the horizontal scanning yoke field employed to correct the trapezium distortion of the blue raster. Figure 11(a) shows a grid pattern statically converged with trapezium correction in the scanning yoke, but without dynamic convergence applied. Ideally on such a grid pattern, viewing any vertical line, blue should be between green and red. On the horizontal lines of the grid, red and green should be approximately in convergence automatically and blue always curving below them.

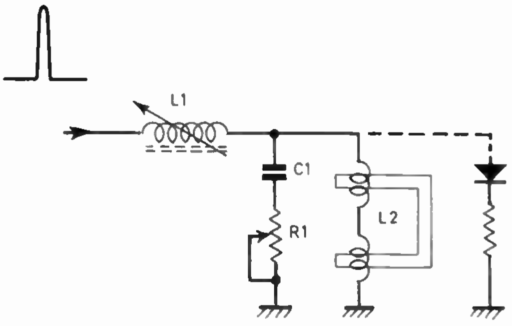


Fig. 12. Horizontal convergence waveform generation.

4. Horizontally-derived Convergence

4.1. *Voltage-driven Circuits*

Although rigorous analysis shows that the distortions and their inverse, namely, the correcting waveforms, are in the form of complex conics, the approximately parabolic waveforms normally used are adequate. Until recently there has been a great similarity between the various circuits used for the horizontally-derived convergence waveforms. The normal voltage-driven approach (see Fig. 12) is to apply a line repetition frequency pulse occurring during the scan fly-back period to an inductance (L1) having the coil of the convergence assembly on the tube neck (L2) in series with it. The current flowing will have a sawtooth waveform. If the inductance L2 is tuned to resonate near to the line scanning frequency by means of C1, a sinusoidal current will flow, but since the circuit is of fairly low *Q*, second harmonic distortion will be present. It is usual to resonate L2 C1 at approximately two-thirds of the line scanning frequency to assist in suppressing the third harmonic component, which would tend to cause asymmetrical errors. The inductance L1 is made variable to permit control of the amplitude of the waveform. Such a waveform approaches a parabola quite closely and has been used with a low value of R1, giving appropriate *Q* to provide the symmetrical parabola required for blue correction in the older 70° deflection tubes. Present day tubes with 90° deflection angle require a waveform which varies more rapidly at the left and right edges of the picture than does the arrangement described above. Two methods are in use to achieve this. One approach uses a saturable reactor to produce a reduction in inductance at the edges of the picture. The second uses an additional tuned circuit resonating at the second harmonic. This gives further emphasis to the second harmonic component in the waveform required by the greater deflection angle (Fig. 14).

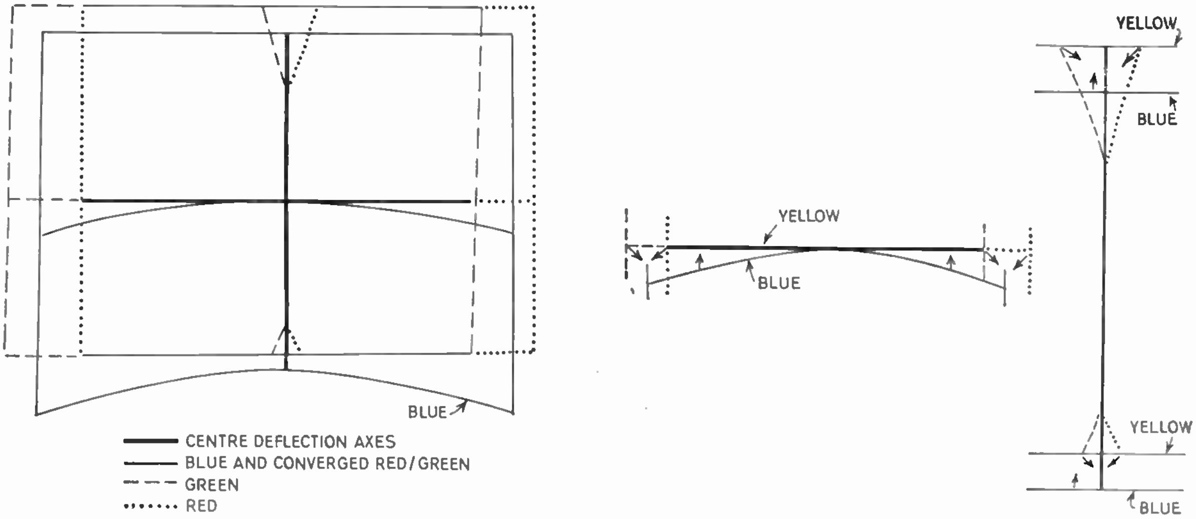


Fig. 11.

(a) Approximate convergence errors without dynamic convergence but with trapezium correction in scanning yoke.

(b) Horizontal convergence errors (arrows indicate direction of correction); vertical convergence errors (arrows indicate direction of correction).

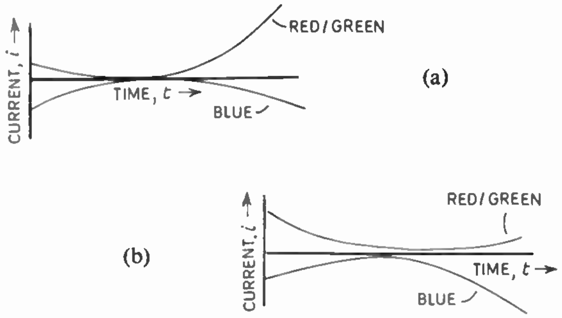


Fig. 13. (a) Horizontal correcting currents.
(b) Vertical correcting currents.

The horizontal convergence for red and green requires that the parabolas be asymmetrical since red requires most correction on the right side and green requires most correction on the left side of the picture. The same circuit will provide such a waveform (Fig. 13(a)) if the resistor R1 is increased in value. As the resistance is increased, the saw-tooth component mentioned above becomes more apparent, giving the required tilt. The sign of the saw-tooth component has to be opposite for red with respect to green, but this occurs automatically since the coils are on the other side of the tube vertical axis. The tilt produced by this circuit may not be sharp enough to give correct convergence at the extreme edges of the picture, so an additional pulse is sometimes applied between the 'cold' end of the convergence yoke inductance and ground.

The resolution of the radial red and green convergence motions into relative vertical and horizontal components has been described (sect. 2, Fig. 5). This technique is normally applied to horizontal red/green dynamic convergence using a circuit such as shown in Fig. 15. Here the amplitude adjustment is divided into two parts, L1 which varies the waveform amplitude through red and green coils with the same sign, and L2 which varies it with opposite sign. Referring to Figs. 5 and 15, L1 (usually called 'master amplitude control') will cause a relative horizontal motion of red and green; L2 (termed the 'differential amplitude control'), effects vertical convergence. Exactly the same concept is applied to the tilt controls, R1 and R2 giving separate horizontal and vertical adjustments.

A further understanding of the mode of operation may be gained by carefully considering the actual adjustment procedure. As a preliminary, it should be noted that the lines being parallel is equivalent to the lines being coincident since only a static error is inferred. During the adjustment procedure, when it is helpful to judge the overall effect, the static convergence magnet may be adjusted to give correct centre convergence. Adjustment is carried out looking along the centre horizontal line of a grid pattern and at the intersections of the vertical lines with it. L1 is first adjusted for equal spacing of red/green verticals, comparing the centre with the right-hand side. Since the tilts of the waveform are not necessarily correct, the left-hand side of the picture may be misconverged vertically and horizontally. After adjustment of the amplitude controlling inductances, the two resistors are set in a similar manner observing the left-hand side of the picture. Unless the tilts are relatively near to the correct value at the start of the adjustment procedure, adjustments made for the right-hand side of the picture will result in changes on the left-hand side and vice versa, so a series of adjustments and readjustments must be made. The reason for this is made clear if the process of adjustment on the right-hand side of the picture is further considered when the tilt is incorrect; in the case where there is too little tilt, the difference in amplitude that is necessary on the right-hand side will be given by differential amplitude rather than by the requisite tilt. On the left-hand side where the opposite tilts are required, the signal that should have the largest amplitude will have been reduced, in fact

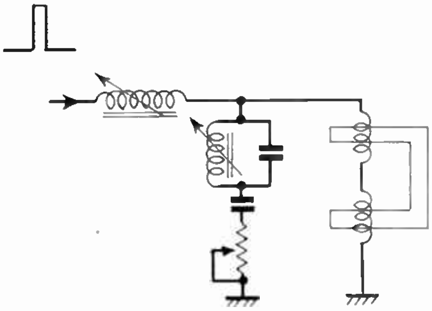


Fig. 14. Blue horizontal convergence waveform generation.

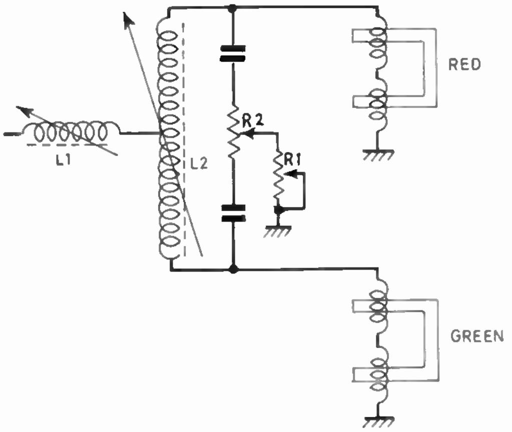


Fig. 15. Matrixed red/green horizontal convergence.

increasing the naturally existing error. The correcting adjustment then made to the tilt for the left-hand side will cause the right-hand side to become over-converged . . . and so on, the errors being reduced by each readjustment. In practice some three adjustments are required for a good standard of convergence. Since horizontal lines are very nearly in convergence automatically for red and green, it might be thought that no vertical adjustment is required. This is not, however, the case since there is a large tolerance on the coupling efficiency of the external to the internal pole-pieces.

The adjustment of the blue horizontal convergence is relatively simple. In its most rudimentary form (Fig. 12) the inductance is adjusted to converge blue with yellow horizontals on the right-hand side and the resistor similarly on the left, repeating as necessary. This circuit, when used with a 90° colour tube will give insufficient correction at the extreme left- and right-hand sides of the picture. Where the circuit of Fig. 14 is used employing the second harmonic tuned circuit, it is adjusted for appropriate phase, i.e. such that the point where it reduces the amount of correction is at the centre of the screen. Care must be taken to see that too much emphasis of the second harmonic component does not take place or the blue horizontal lines will describe a series of waves.

Varying either the amplitude or the shape of any of the convergence waveforms will change the mean position of the beam, since the waveforms are a.c.-coupled and are not symmetrical about zero. This infers that a readjustment of the static convergence could be required for any adjustment of the dynamic controls. This difficulty is to a considerable extent overcome by the circuit shown dotted in Fig. 12. The value of the resistor in series with the diode is such that a compensating unidirectional current flows through the convergence coils offsetting the change in mean position. The limitation of this arrangement is that the diodes extract significant energy from the circuit and that the correction is not perfect.

Certain other matters affect the standard of horizontal convergence that can be achieved between red and green and between the resulting yellow and blue verticals. Although the amount of tilt on red and green be correct, its law may not be suitable; in this case, if convergence is made accurate at extreme left and right, there will be a section between centre and one side where there will be errors. Alternatively, the errors may be allowed to accumulate at the extreme edges of the picture. The main scanning yoke is designed to be astigmatic for correction of trapezoidal errors as already discussed, but other unwanted effects can occur due to unbalance between the pairs of coils that make up the yoke. Should such unbalances be present, then in the unconverged state red and green horizontals will cross over and errors in the corners will be exaggerated. Misconvergence due to this cause cannot be corrected by any of the normal adjustments without introducing other disturbing errors. If the line coils of the scanning yoke are connected in parallel, a differential inductance as in Fig. 16 may be used, adjusting it for the condition where red and green horizontals do not cross over.

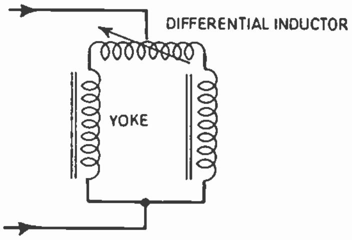


Fig. 16. Horizontal scan yoke balancing.

Operation of the line shift control can also introduce an asymmetrical misconvergence since the centre of the raster will not necessarily coincide with the geometrical centre of the tube. When this happens, the tilt on red and that on green will no longer be respectively symmetrical about the geometrical centre of the tube. The result will be difficulty in obtaining equally satisfactory convergence on both left and right sides of the tube. The effect can readily be seen on the blue unconverged horizontal lines where the bowing will be asymmetrical if the shift is off-set. There can be other reasons for a beam-shift with the same result. An instance of this in the case of the 90° tubes is that over the range of adjustment of the purity magnets that may give acceptable purity, errors of convergence can arise. The change from the older 70° to the modern 90° deflection angle tubes has brought a decrease in the neck diameter with a number of consequential advantages. This has necessitated a marked decrease in the spacing of the guns and their dimensions. There is, as a result, some measure of crosstalk between the convergence fields of the three guns; therefore, when carrying out adjustments it is essential to check the convergence of all the three rasters.

In these circuits, circulating current has to be quite high, so care must be taken with the controls from the point of view of dissipation and stability of value. This is particularly of consequence in the blue circuit where typically 2 watts may have to be dissipated.

In a practical receiver design, considering obtainable waveforms and tolerances of scanning yoke fields, it is not unusual to find that the blue raster exceeds that of the converged red/green in width (see Fig. 8). Since the luminance of blue is low, if such errors are small, they are not disturbing. However, it is usually the practice to apply a line rate saw-tooth current waveform to the blue lateral unit, thus giving independent control of blue width. Usual American practice employs a somewhat different scanning yoke trapezium correction. Blue scan width adjustment is carried out in this case by tilting the scanning yoke, varying differentially the effectiveness of the horizontal scanning field upon the blue and the red/green rasters. If the blue is asymmetrical with respect to the red/green raster, i.e. there is a difference between red/green and blue horizontal linearity, correction may be applied by rotating the convergence yoke while leaving the main deflection yoke in position. This allows a controlled amount of crosstalk to occur between either the red or the green pole-pieces and the blue beam.

4.2. *Current-driven Circuits*

The present necessity in the U.K. for a colour television receiver to operate monochrome on both 405 and 625 line standards increases the number of preset adjustments associated with horizontally derived convergence. If the circuits already described are used, the only method of practical dual standard operation is complete duplication, switching the convergence yoke to two entirely independent control units. This infers up to eighteen adjustments associated with horizontal convergence alone. It would be most advantageous if this number could be considerably reduced and the problems avoided which result in interaction between shifts and convergence and purity and convergence. Further, the circuits described require a considerable number of adjustable inductances. These have the disadvantage of being more expensive and fragile than potentiometers. Recent circuit developments will now be described that have resulted in a new convergence circuit concept that overcomes, to a large measure, these deficiencies.† If the line convergence yoke coils are driven from a line saw-tooth waveform source of constant voltage, the current waveform through the coils will depend upon the L/R ratio of the coils. Figure 17 shows the resulting current waveform for various L/R ratios. It is to be noted that the curve is very close to the required convergence waveform for red/green and that the ratio of inductance to resistance is that of a practical coil. Figure 18 shows a complete convergence circuit for red/green using this concept providing master and differential controls. Since the shape of the current waveform has been defined by the coil design, only a minimum of shaping is required. A suitable source of low impedance saw-tooth voltage is readily available.

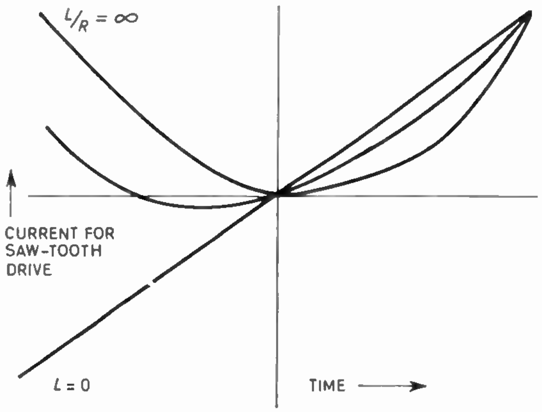


Fig. 17. Convergence current waveform for various L/R ratios.

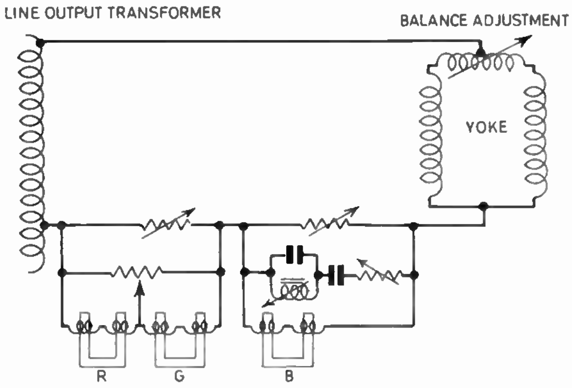


Fig. 18. Constant voltage convergence circuit (single-standard version).

If a low resistance is placed in series with the main scanning yoke line coils, a saw-tooth will be developed; this low resistance in practice consists of the network of controls in Fig. 18, thus making an extremely simple convergence circuit.

The required correcting waveform for blue is, as already shown, approximately a symmetrical parabola. Unlike the tilted waveform for red and green, this cannot be obtained directly since it would require an infinite L/R ratio. A capacitor is added as shown in Fig. 18, the circuit operated in resonance as already described. The added second harmonic tuned circuit increases the slope of the waveform at the extreme left and right borders of the picture. The red/green and blue circuits may then be placed in series and all connected in series with the main scanning yoke.

This circuit can be adapted for dual standard operation with a minimum of complexity and Fig. 19

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† D. J. King, 'Convergence and raster correction circuits', *Mullard Technical Communications*, 9, No. 83, September 1966.

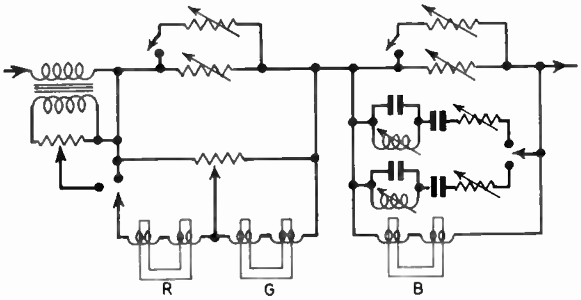

Fig. 19. Dual standard version of the circuit shown in Fig. 18.

shows the complete 405/625 line version. It is not necessary to switch the differential control since the ratio of red/green waveforms is the same on both standards and the controls are non-reactive. It is necessary to switch the master amplitude adjustment and to include the additional tilt circuit. This is required to allow for yoke tolerances and because there is a large percentage difference between the two line scanning frequencies and hence the impedance of the convergence coils is considerably different on the two standards. The tilt transformer in Fig. 19, being inductive, develops a pulse across the secondary winding, and the required amount is tapped off by the control and applied in series with coils. Whereas the saw-tooth developed across the resistor drives a tilted parabola through the coils, the pulse gives rise to a saw-tooth. By selecting the phase of the secondary of the tilt transformer, it will either add to the tilt or tend to cancel it, making the resultant current either more or less symmetrical.

The blue circuit has to be duplicated for dual standard application since its operation depends on resonance.

Most circuits when switched for two-standard operation require some method of readjusting the static convergence between standards. This is because, although the dynamic convergence may be adequate, there is sufficient difference between the wave shapes to cause the mean value to differ. In the majority of circuits this is achieved by switching the appropriate resistors in series with the clamp diodes for the two standards. The circuit described in this paper does not require any attention to static convergence between standards for red and green since the wave shapes can be made virtually identical. Final trimming of static convergence between the two scanning standards is achieved by having separate width adjustments for both standards.

The advantages of this type of circuit can be summarized as follows:

(i) No adjustable inductances are required; this is advantageous from considerations of cost and ruggedness in the field.

(ii) In the case of a single-standard receiver the circuitry is extremely simple and for a dual standard receiver complete duplication of the horizontally-derived convergence circuit is not necessary.

(iii) Convergence quality is more consistent with drifts in supply voltages and ageing of components, since the convergence waveform is derived directly from the scanning current.

(iv) An overall higher standard of convergence is possible as the desired waveforms can be obtained by design rather than adjustment.

5. Vertically-derived Convergence

Figure 11(b) shows the vertical errors and the waveforms of the necessary correcting currents are shown in Fig. 13(b). It is to be noted that the blue raster requires a correcting parabola tilted such, that it has greater effect at the lower part of the picture than at the top. Red and green require similar correction, but with the opposite asymmetry to blue.

The form of the horizontally-derived convergence circuits already described, is controlled to a considerable measure by the nature of the load presented by the convergence yoke inductances, it being, at line repetition frequency predominantly inductive. A different situation exists in respect of the vertically-derived circuit since the resistive component of the load is much more important.

A typical circuit is given in Fig. 20: the cathode current of the field output valve is integrated by the parallel capacitor to give approximately a parabola and the centre tapped winding on the field output transformer develops a saw-tooth wave of either polarity. The potentiometers allow the amplitude of the parabola and the amplitude and sign of the saw-tooth to be adjusted and fed to each end of the con-

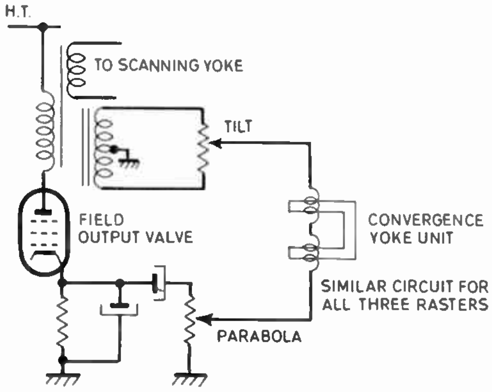

Fig. 20. Basic field convergence circuit.

vergence inductance respectively. The circuit is identical for all three rasters.

Again, it is of interest to consider the actual adjustment process. The best starting situation is with no waveforms applied, i.e. the tilt controls set at the centre of their range and the parabola controls set to zero. The blue vertical lines are automatically straight and hence a reference for the adjustment of green and red. Both green and red require a greater signal at the top of the picture than at the bottom, so a satisfactory procedure is to view, say, red and blue and adjust red parabola and tilt controls alternately to line, up the red and blue centre line, ignoring the horizontal intersections. The same procedure should then be carried out for green and blue. Too little tilt will infer either over-convergence at the bottom of the picture or under-convergence at the top, depending upon the amount of applied parabola. Too great a tilt will give exactly the opposite effect.

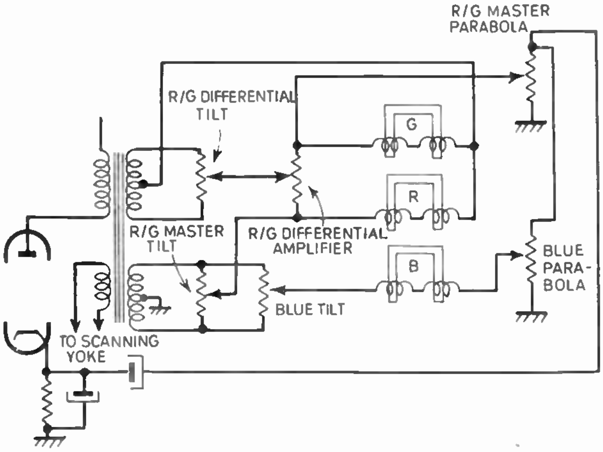

Fig. 21. Differential form of field convergence circuit shown in Fig. 20.

Lining-up red and green verticals with blue infers that in an ideal situation red and green horizontal intersections of the vertical will be converged. It is still necessary to adjust the blue parabola and tilt controls to line-up the blue horizontal intersections with the resulting yellow lines. The blue controls are thus capable of affecting only vertical movements and operate rather like size and linearity controls on the blue raster.

As in the case of the horizontal circuit, the vertical red and green adjustments may also be made differential, conferring similar advantages in separating vertical and horizontal adjustments. A further advantage is that red and green can be converged together rather than on blue. The typical circuit for this purpose is shown in Fig. 21 and it is to be noted that, whereas for the horizontal circuit no extra components are required for differential operation, this vertical circuit is rather more complex.

The adjustment sequence for the differential circuit is as follows:

> Red and green are viewed together, the initial position of the controls being of no importance. The two master amplitude controls are adjusted to converge the vertical lines.
>
> The two differential controls are then adjusted to converge the horizontal intersections.

There is a similar situation in the vertical to that described for the horizontally-derived convergence circuit due to the wave-shapes, adjustment of the amplitude giving rise to a shift of mean position and hence static convergence. This effect may be reduced by two possible means, one is to add a diode and the other is to use some amount of direct coupling.

The circuits described have a disadvantage in that they cause considerable degeneration in the field-scan output valve cathode, tending to cramp the bottom of the picture. There have been a number of recent approaches to vertical convergence to avoid this. One is to use a transistor as a buffer stage between the field output valve cathode and the convergence circuit, the cathode voltage of the field output valve being the supply voltage for the transistor. An alternative approach is to reduce the impedance of the field convergence circuit to a low value, such that it does not cause significant degeneration in the cathode of the field output valve. It is then connected in series with the cathode bypass capacitor.† This is advantageous since, as shown in Fig. 22(a), the voltage required to generate a parabola of current in the coils is very close to that of the field output valve when operating under the usual 'zero initial slope' condition. As a linear field scan is required and is in fact initially set to be so, this parabolic current through the convergence coils is highly accurate, hence more simple and convenient means of adding the appropriate tilt can be adopted than when using the conventional circuit. One immediate advantage is that it is no longer necessary for the tilt to be of either positive or negative sign, one side of the tilt control being now connected to ground. This is because the convergence yoke current derived from the cathode current waveform has slightly too much tilt for blue and the opposite sign of tilt for that required for red/green. The saw-tooth wave from the field output transformer winding opposes the tilt, reducing it suitably for blue and inverting it for red/green. The circuit of Fig. 22(a) shows that no differential tilt control is required. Only one differential control is provided to equalize the relative coupling

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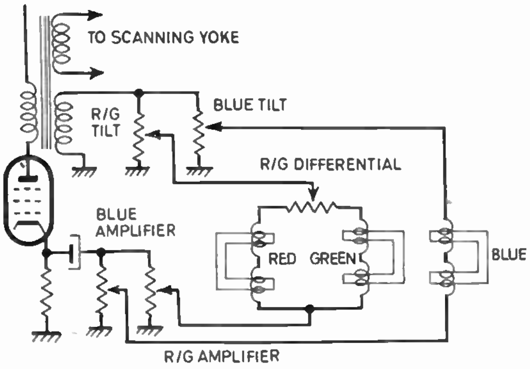
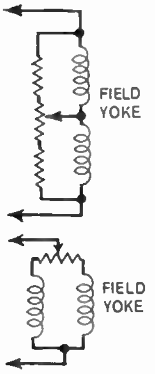
† D. J. King, *loc. cit.*



(a) Alternative field convergence circuit.



(b) Two methods of field yoke balancing.

Fig. 22.

between the convergence yoke and the internal pole pieces. If the balance of the field scanning yoke inductances is not exact, it will be found impossible to adjust the differential control for a satisfactory convergence of horizontals over the entire vertical scan. To allow for this situation a balance adjustment on the vertical scanning yoke is provided as in Fig. 22(b).

A common limitation of vertical convergence accuracy is a small area of insufficient convergence at the very top of the picture area. The reason for this is that the tilt waveform from the vertical output transformer is a combination of pulse and saw-tooth. The effect of the waveform at the top of the picture is greatest since it is due to both pulse and saw-tooth. If this effect is to be completely avoided the current waveform through the vertical scanning yoke rather than the voltage waveform is required. The circuit shown in Fig. 23 enables all convergence waveforms to be obtained from the scanning current itself, in addition to the described advantages it is of use in transformerless circuits. The capacitor C and the coils integrate the saw-tooth voltage across the resistor R1 and a modified saw-tooth is available from the resistor in series with the capacitor.

The following points should be noted:

(a) Before carrying out convergence adjustments, linearity and amplitude setting of both horizontal and vertical scans must be already set, since convergence is a function of scan current.

(b) The interdependence of picture shift, purity and convergence must be remembered and purity re-checked often during convergence procedure.

(c) Although a very high standard of convergence should be obtained along the centre vertical and centre horizontal lines and at intersections with them, the convergence away from these areas, particularly in the corners, is dependent on the tolerances of many components.

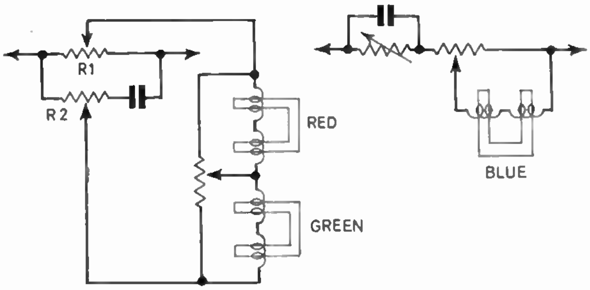


Fig. 23. Field convergence circuit for connection in series with the main scanning yoke.

6. In-line Gun Tubes

Similar problems of convergence and colour purity arise with these tubes as arise in the case of those with the guns in triangular array. The solution will be described in terms of a tube with the guns disposed on the horizontal tube axis since the only member of this family in production is such a tube. Viewed from the screen, the green gun is on the tube main axis and the red and blue guns respectively to the left and right. The diagonal deflection angle is approximately 70° and the nominal neck diameter 1·438 in. Since the green gun is on the main axis it requires no convergence correction, either static or dynamic. Pole-pieces are provided on both the red and blue guns for the application of vertical and horizontal axis correction. Nearest to the cathodes are the E-shaped pole-pieces giving vertical movement and immediately following U-shaped ones for horizontal correction. A purity correcting magnet is also used similar to that used with conventional tubes. The dot structure on the screen forms interlacing rows in the same manner as in tubes with guns in triangular array, but the converged trio of beams will illuminate a row of three dots rather than a triangle. Figure 24 shows the disposition of the components on the tube neck and Figs. 25(a) and (b) indicate the theoretical convergence errors that result.

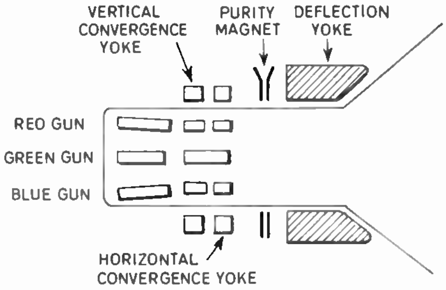
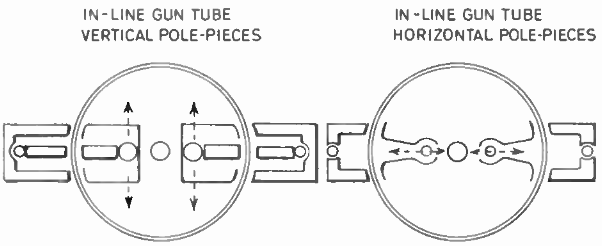


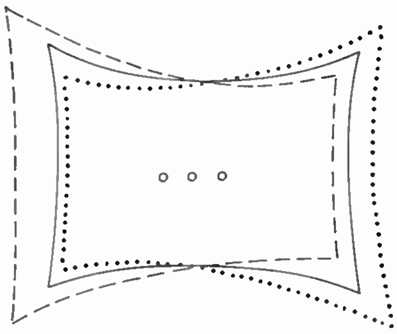
Fig. 24. Horizontal in-line gun tube.

The trapezium errors in Fig. 25(b) may be corrected by suitable yoke design leaving only the errors on the horizontal axis to be corrected with a line repetition frequency parabolic wave. Under ideal circumstances only static convergence correction would need to be applied to the vertical pole-pieces, but owing to limitations in the accuracy with which the trapezium correction can be carried out there must be provision for some dynamic vertical waveform.

In practice the amplitude of the dynamic convergence waveforms is not variable: adjustment is by changing the spacing between the external pole-pieces and the tube neck and allowing the flux of the static convergence field to be variable.



(a) Errors on horizontal axis.



(b) Trapezium errors.

Fig. 25. Theoretical convergence errors in horizontal in-line gun tube.

7. Acknowledgments

The author wishes to acknowledge the co-operation of the Mullard Central Application Laboratory, Mitcham, and to thank the directors of Rank Bush Murphy Ltd. for permission to publish this paper.

8. Appendix

8.1. *The Basic Geometry of Multi-beam Convergence*

For the purposes of analysis, two types of displacement from convergence will be treated. The first is concerned with deflection at right angles to the direction of displacement of the beam from the tube axis. An example is horizontal deflection of the blue beam. The second is where the deflection is in the direction of displacement of the beam from the tube axis. Here an example is provided by vertical deflection of the blue beam. Red and green beams combine both effects since they are displaced from both deflection axes.

8.2. *Deflection at Right Angles to the Beam Displacement Direction*

The situation is shown in Fig. 26. Two relationships will be demonstrated, first the variation of the quantity h as a function of deflection angle, and second as a function of deflection distance on the screen.

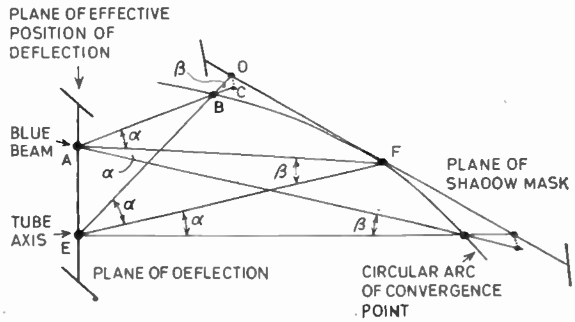


Fig. 26. Displacement from convergence: deflection at right angles to beam displacement.

In Fig. 26:

α = angle of deflection off the tube axis,

β = angle of convergence of the beam towards the tube axis,

DC = h = convergence error on screen,

EF = EB = q = radius of arc of convergence point,

AE = s = spacing of beams at the point of deflection,

FD = x = distance of deflected beam from undeflected position on screen.

Since the convergence point follows a circular arc,

$$\cos\alpha = \frac{\text{EF}}{\text{ED}}$$

Therefore

$$\text{ED} = \text{EF}\sec\alpha$$

Now,

$$\text{BD} = \text{ED} - \text{EF}$$

$$\text{BD} = q(\sec\alpha - 1) \qquad \text{......(1)}$$

ABC and EBD are straight lines

$\angle$AEB and $\angle$BDC are right angles

$\angle$ABE = $\angle$CBD = β

hence, triangles ABE and CBD are similar.

$$\tan\beta = \frac{\text{AE}}{\text{EB}} = \frac{\text{DC}}{\text{BD}} = \frac{h}{\text{BD}} = \frac{s}{q}$$

Therefore

$$h = \frac{s}{q}\,\text{BD} \qquad \text{......(2)}$$

Combining eqns. (1) and (2), one gets

$$h = \frac{s}{q}\,q(\sec\alpha - 1)$$

$$= s(\sec\alpha - 1) \qquad \text{......(3)}$$

showing that the droop of the blue beam on the horizontal axis of the tube is proportional to the secant of the deflection angle. To express eqn. (3) as a function of deflection distance on the screen:

$$\tan\alpha = \frac{\text{DF}}{\text{EF}} = \frac{x}{q}$$

$$x = q\tan\alpha$$

and

$$x^2 = q^2\tan^2\alpha$$

$$= q^2(\sec^2\alpha - 1)$$

From eqn. (3),

$$\frac{h}{s} + 1 = \sec\alpha$$

Thus

$$x^2 = q^2\left\{\left(\frac{h}{s} + 1\right)^2 - 1\right\}$$

$$= q^2\left(\frac{h^2}{s^2} + \frac{2h}{s}\right)$$

and

$$\frac{2h}{s} = \frac{x^2}{q^2} - \frac{h^2}{s^2} \qquad \text{......(4)}$$

Since s and q are constants depending on tube dimensions

$h = F(x)$ is a complex conic.

If the term h^2/s^2 is omitted, eqn. (4) becomes

$$\frac{2h}{s} = \frac{x^2}{q^2} \qquad \text{......(5)}$$

by making the constants $2/s = K$ and $1/q^2 = L$, eqn. (5) can be written as

$$h = \frac{L}{K}x^2 \qquad \text{......(6)}$$

This is an equation for a parabola.

8.3. *Deflection in the Plane of Beam Displacement*

The situation is shown in Fig. 27. The variation of the quantity h as a function of deflection p is treated. The dependent variable h is the separation of two convergent beams at the tube screen, these beams being symmetrically displaced about the tube axis.

A, B and O are the positions in the plane of deflection of the two beams and the tube axis respectively.

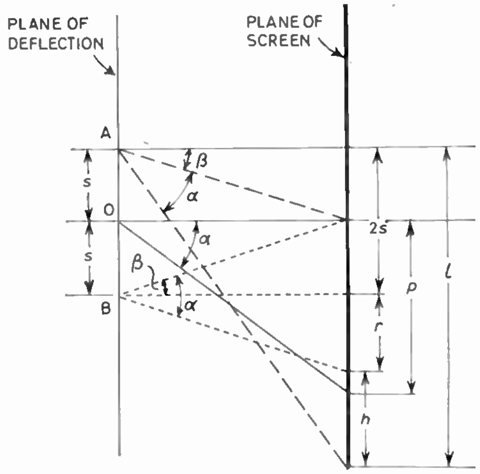


Fig. 27. Displacement from convergence: deflection in the plane of beam displacement.

In Fig. 27:

p = distance of deflection,

q = distance from plane of deflection to tube screen,

s = spacing of beams from the tube axis at the plane of deflection,

α = angle of deflection,

β = angle of convergence of beams.

$$h = 1 - 2s - r \qquad \text{......(7)}$$

$$1 = q\tan(\alpha + \beta)$$

$$r = q\tan(\alpha + \beta)$$

$$p = q\tan\alpha$$

$$\tan\alpha = \frac{p}{q}\tan\beta\frac{s}{q}$$

Therefore

$$1 = (p+s)/(1-ps/q^2) \qquad \text{......(8)}$$

and

$$r = (p-s)/(1+ps/q^2) \qquad \text{......(9)}$$

Substituting eqns. (8) and (9) into eqn. (7):

$$h = \frac{2p^2\left(\dfrac{q^2}{s} - s\right)}{\dfrac{q^4}{s} - p^2} \qquad \text{......(10)}$$

Putting

$$A = 2\left(\frac{q^2}{s} - s\right)$$

and

$$B = \frac{q^4}{s}$$

where both A and B are constants, then eqn. (10) becomes

$$h = \frac{Ap^2}{B-p^2} \qquad \text{......(11)}$$

Since q^4/s is very large compared with p^2

$$h \simeq \frac{A}{B}p^2$$

which is again an equation for a parabola.

8.4. *The Relationship between the Deflected Tube Axis and a Deflected Beam Displaced in the Plane of Deflection*

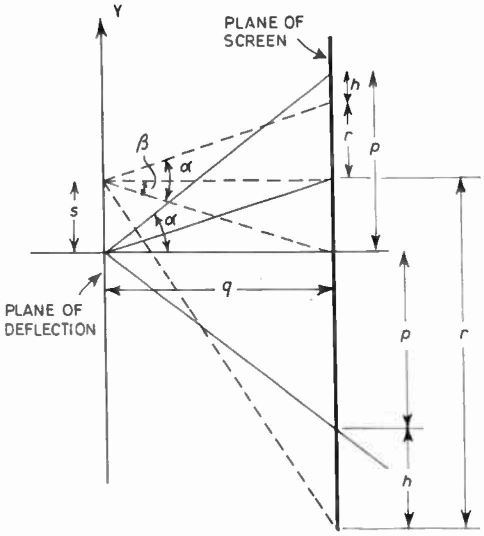


Fig. 28. Diagram showing the relationship between deflected tube axis and deflected beam.

Referring to Fig. 28 where the symbols have the same meaning as above,

$$h = p-r-s \qquad \text{......(12)}$$

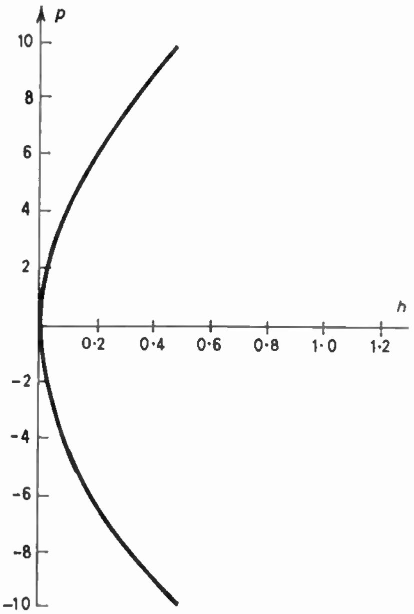


Fig. 29. Convergence error (vertical) away from horizontal axis of blue.

$$r = q\tan(\alpha-\beta) \qquad \text{......(13)}$$

$$\tan\alpha = \frac{p}{q} \quad \text{and} \quad \tan\beta = \frac{s}{q}$$

Therefore

$$r = (p-s)/(1+ps/q^2)$$

Substituting the value of r in eqn. (12) we have

$$h = p - \frac{p-s}{1+\dfrac{ps}{q^2}} - s$$

$$h = \frac{p^2-ps}{\dfrac{q^2}{s}+p} \qquad \text{......(14)}$$

An approximation may be made since $s \ll q$ and $p_{\max}$ is approximately equal to q. Thus $q^2/s \gg p$ and if $A = s/q^2$, eqn. (14) becomes

$$h = A(p^2-ps)$$

Calculated values of the convergence errors are tabulated in Figs. 29, 30 and 31. It must be noted that these values include approximations in respect of shift in deflection centre and the slightly spherical tube face.

Figure 29 shows the vertical error away from the horizontal axis of blue, Fig. 30 is the horizontal separation of red and green and Fig. 31 is the shift of red horizontally with respect to the deflected tube axis. All are for a deflection of up to ±45°.

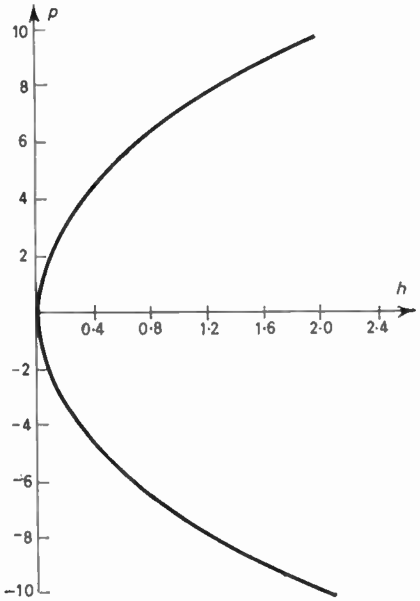


Fig. 30. Horizontal separation of red and green.

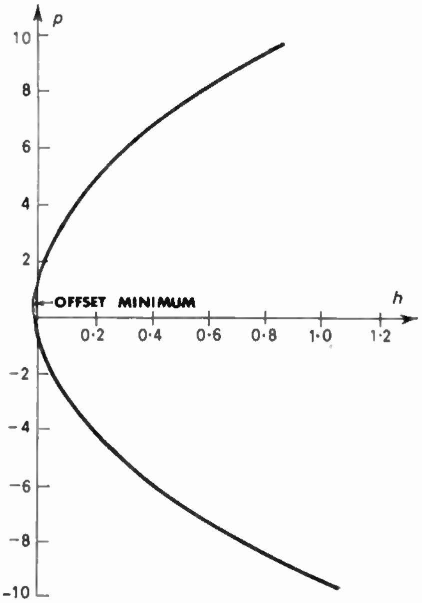


Fig. 31. Shift of red (horizontal) w.r.t. deflected tube axis.

Manuscript first received by the Institution on 22nd February 1967 and in final form on 30th October 1967. (Paper No. 1160/T41.)

STANDARD FREQUENCY TRANSMISSIONS

(Communication from the National Physical Laboratory)

Deviations, in parts in 10^{10}, from nominal frequency for **November 1967**

November 1967	24-hour mean centred on 0300 U.T.			November 1967	24-hour mean centred on 0300 U.T.		
	GBR 16 kHz	MSF 60 kHz	Droitwich 200 kHz		GBR 16 kHz	MSF 60 kHz	Droitwich 200 kHz
1	− 300·3	− 0·3	− 0·2	**17**	− 300·0	0	0
2	− 300·3	− 0·3	− 0·2	**18**	− 300·2	− 0·1	0
3	—	− 0·3	− 0·2	**19**	− 300·1	0	0
4	− 300·2	− 0·3	− 0·2	**20**	− 300·1	− 0·2	0
5	− 300·3	− 0·3	− 0·2	**21**	− 300·1	− 0·1	0
6	—	− 0·1	− 0·2	**22**	− 300·0	− 0·1	0
7	− 300·1	− 0·3	− 0·2	**23**	− 300·0	0	+ 0·1
8	− 300·0	—	− 0·1	**24**	− 300·1	− 0·1	0
9	− 300·2	—	0	**25**	− 300·1	− 0·1	0
10	− 300·3	− 0·3	− 0·1	**26**	− 300·2	− 0·1	0
11	− 300·1	− 0·2	− 0·1	**27**	− 300·1	− 0·2	0
12	− 300·2	0	0	**28**	− 300·1	− 0·1	− 0·1
13	− 300·1	− 0·2	− 0·1	**29**	− 300·1	− 0·1	0
14	− 300·2	− 0·1	− 0·1	**30**	− 300·2	− 0·2	0
15	− 300·1	− 0·1	− 0·1				
16	− 300·2	− 0·1	− 0·1				

Nominal frequency corresponds to a value of 9 192 631 770·0 Hz for the caesium F,m (4,0)–F,m (3,0) transition at zero field.

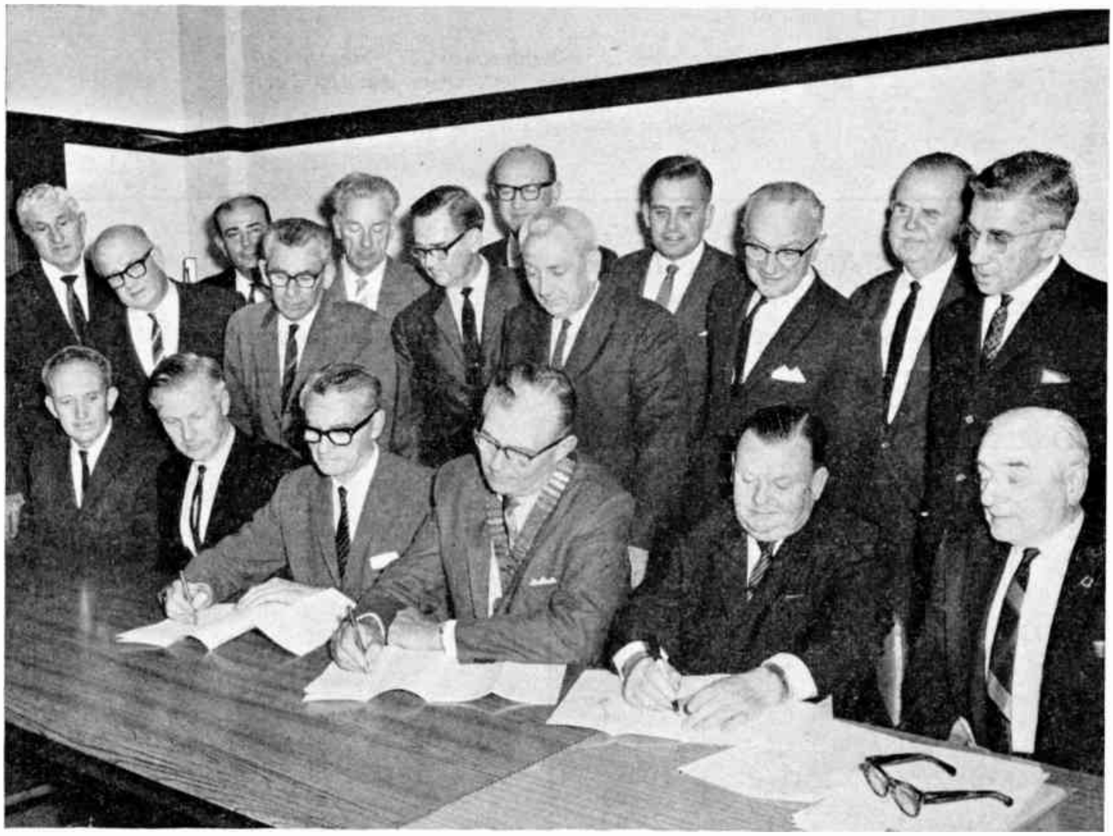
Note: All measurements were made in terms of H.P. Caesium Standard No. 134 which agrees with the NPL Caesium Standard to 1 part in 10^{11}.

Royal Charter for the I.R.E.E. Australia

Members of this Institution and many engineers overseas will learn with pleasure that a Royal Charter of Incorporation was granted to the Institution of Radio and Electronics Engineers Australia on 22nd November 1967. The Australian Institution was founded in 1924 and at the end of 1966 it had 2144 members. Its standing has for many years been officially recognized by the fact that successive Governors-General have granted it their patronage.

Relations between the I.E.R.E. and the Australian Institution have always been extremely close and cordial. On numerous occasions officers and senior members of the I.R.E.E. Australia have visited 9 Bedford Square when in London and have attended conferences and meetings. In the course of his overseas tour in 1966, the Secretary of the I.E.R.E., Mr. G. D. Clifford, visited Science House in Sydney and was able to have useful discussions on matters of mutual interest. Because of the facilities that exist for I.E.R.E. members to attend I.R.E.E. meetings, it has not been considered necessary to establish a Division or Section within Australia. There are in fact well over 100 members of all grades throughout the country and it is known that many of these also belong to the I.R.E.E.

One particularly pleasant way in which the I.E.R.E. has for many years co-operated with the Australian Institution is in the award of its Norman W. V. Hayes Memorial Medal. This Medal, which commemorates a Past President of the I.R.E.E., is awarded annually for the most outstanding paper published in their *Proceedings*, and the I.E.R.E. and the American I.E.E.E. adjudicate the award in alternate years. Reprinting of outstanding papers from each other's publications—an arrangement negotiated by Mr. Leslie McMichael, a Past President of the I.E.R.E. who had a great interest in co-operation with engineers overseas—has been another feature of the cordial relations between the two Institutions. The paper which is recommended for the Hayes Medal is always given special consideration in this respect for reproduction in *The Radio and Electronic Engineer*.



Members of the Council of the Institution of Radio and Electronics Engineers Australia signing the Royal Charter Petition 1966.

Standing: *Left to right:* R. V. Southey, R. K. Crow, R. W. Tremlett, L. N. Schultz, G. G. Hall, F. R. Lackey, S. J. Rubenstein, H. M. Tyler, D. J. Hutchinson, M. H. Stevenson, E. F. Coate, R. D. Boadle.

Seated: *Left to right:* Professor R. M. Huey, H. R. Wilshire, A. W. de Courcy Browne, R. J. Boyle (President), N. T. W. Wedgner and D. G. Wyles.

U.D.C.621.37/9.002

Design for Production

By

H. J. H. WASSELL,
O.B.E., B.Sc.†

Reprinted from the Proceedings of the Joint I.E.R.E.–I. Prod.E.–I.E.E. Conference on 'The Integration of Design and Production in the Electronics Industry,' held at the University of Nottingham on 10th to 13th July 1967.

Summary: This paper underlines the designer's personal responsibility for his design, and the need for him to establish a good working relationship with many experts.

It suggests that modern electronic design is dominated by complex production processes and integrated assemblies, and reviews the implications of this on the design task. It urges the designer to become familiar with the engineering implications of elemental assembly operations, and tailor his design to suit the particular degree of automation existing in his factory. The integrated nature of equipment assembly and testing is considered and a distinction specifically made between design proving and production testing.

Some factors affecting the length of time taken for design are discussed, and the specification of Quality is considered. Production training policy for designers is outlined and the need to integrate design and production engineering is emphasized.

The various aspects of a designer's Code of Practice for the part of his task that is concerned with production are brought out in the course of the paper and summarized in Appendix 2.

1. Introduction

1.1. *The Human Elements in Electronic Design*

To design a product implies acceptance of responsibility for that product. Designers increasingly realize that they cannot be masters of all technologies, and the use of the team analogy is gaining favour to express this dependence on others. On being congratulated on a good design the designer excuses himself—'It was', he says, 'a team effort'. Like many analogies, however, this is misleading. For 'team' the dictionary gives the choice of a 'set of draught horses' or 'a side of players in a game', while Roget places it among the nouns of assemblage.

Now, the electronic designer in charge of a project may truly have a team of men working for him on the project, with such varying experiences as can continuously be applied to the task. These men he leads as does the captain of a side in a game, or drives as does a drayman, but this has always been so. A key-man in this team will be the mechanical designer, since everything has to be expressed in mechanical terms before it can be made. However, the electronic designer needs the skills of many technological experts who are not necessarily members of his team—the industrial designer, the production engineer, the materials engineer, the handbook writer, the marketing manager, the environmental expert, men whose salaries may not be on his list or even on the payroll of his Company. His task is to *integrate*—the title of this Conference is well chosen—these skills into a complete product design and for this he has a personal responsibility. In this process of integration he may consult or he may delegate, but there will be some aspects of the task that he will have to reserve for himself. Among these are the decisions on quality and cost within the terms of reference—the very heart of the design.

He will need all available techniques to help him, such as P.E.R.T., Value Engineering, Quality Assurance. Indeed, the whole 'methodology' of systematic design is rapidly gaining ground. Nor will it suffice for him to delegate these roles to others. They must become an essential part of his thinking and of his technical equipment. While he will need to use the best available tools, such as computers, he must, above all, be able to use the skills of others, to involve and stimulate others in the creation of the design.

There is a tendency to use the word 'interface' to describe the meeting point between a designer and his expert helpers. Although literally seeming appropriate, it has in fact acquired a technical connotation which is

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† The Marconi Company Ltd., Chelmsford, Essex.

too rigid and formal. If co-operation is to be effective, the designer and the expert must both explore each other's territory to ensure that they are defining their requirements in terms that are fully comprehended by the other. The Peter Bells of this world must be able to sit in the cockpit of aeroplane mock-ups,† as well as over the drawing board, and the electronic designer must meet his production engineer colleague round the numerically-controlled machine as well as over the taped program that controls it.

Since the whole design is the personal responsibility of the designer, and since effective communication takes time, he must be prepared to find the time properly to brief his experts. The manner of this briefing is all important. Too frequently the briefing takes the form of a precise statement of what the designer thinks he wants rather than a description of the problem. Over-precision and over-standardization of expression can put the expert consultant into a straight-jacket from whose depths he can hardly be expected to propose an optimum solution to the problem. Over-precision in the definition of method is paradoxically often accompanied by fluffiness in the definition of purpose. There would seem, therefore, to be at least four rules in the first section of the Code of Practice for designers to govern the designer's relations with specialists:

I. Collaborating with Production and Other Experts

(1) Try and understand some of their background and skills.

(2) Devote time to ensuring that they understand the equipment background.

(3) State the overall purposes of the design clearly and take the specialists into all of them.

(4) Delay defining the 'how' until the specialists have contributed their ideas.

1.2. *The Physical Elements in Electronic Design*

This paper covers a limited part of the designer's task, but it is perhaps as well first to list the main facets of the whole. These are to achieve, in an integrated way—

Performance, Cost, Delivery, Producibility, Transportability, Usability, Saleability, Reliability and Maintainability.

This paper is about *producibility* and how to design towards its achievement. Asking a designer to talk about producibility is rather like asking a chef to talk about oven techniques. 'Not', he might say, 'the most interesting part of producing a culinary masterpiece.' Yet many good recipes are ruined in the oven.

Now, 'to produce' is not just 'to make'. A skilled craftsman can make almost anything, given time. Rather is it to ensure that the designer's concept is turned into a succession of delivered equipments each having a high probability of success and a minimum cost.

The modern electronic designer is haunted by probabilities and improbabilities. Not for him the certainty of the designer-craftsman of old, who personally created his work from raw materials, whose every flaw was known to him. Rather is he concerned with buying much of his material already fabricated into mysteriously encapsulated parcels or with the manipulation of raw material by complex process over which he has little control.

When the founder of the author's firm was designing, 70 years ago, his production problems were almost entirely those of the fabrication of raw materials by traditional techniques.‡ Today, designing for production is dominated by the use of components and complex processes.

Before continuing, it will be as well to define some terms that are of importance to the argument and which are not always used with the same meaning. These are listed in Appendix 1.

Direct, straightforward fabrication has largely given way to the use of complex processes, whether in the construction of such component parts as printed boards, or in the ever-increasing use of integrated assemblies. When the designer invokes a complex process he must follow its disciplines, accept its limitations, and delineate his requirements in the terms it dictates. When he uses an integrated assembly he must equally understand its limitations and be prepared to accept the parameters it provides as its terminals.

Designing for production in these days is largely concerned with coming to terms with complex processes. It is not proposed to cover fabrication in any detail in this paper, since the factors here should be well known, even if they appear from time to time in modern dress: styled explosively; patterned by chemical etching; and trimmed with punched tape.

2. Complex Processes

It is logical to consider complex processes before integrated assemblies, since the latter are usually more or less dependent upon the former. There are several characteristics occurring to a greater or lesser degree in most complex processes, which are important to the designer who wishes to use their results.

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† 'Designers get the team spirit', *Design*, February 1967, p. 33.

‡ See, e.g., 'Radio engineering sixty years ago', *The Radio and Electronic Engineer*, **34**, No. 4, p. 224, October 1967.

2.1. *The Nature of Complex Processes*

(1) Complex processes involve a series of operations which are inter-connected—

by a logical sequence of events (e.g. one stage is a preparation for the next), and/or

by a common environment (e.g. a constant temperature, or a dust-free atmosphere), and/or

by mechanical inter-relationships (e.g. designed to facilitate inter-stage transfer, or as a location for succeeding operations).

(2) They have specific limitations in the range of choice of variations in the product.

(3) They need instructions in accordance with a pre-determined language.

(4) They will normally have been subjected to a considerable amount of quality testing during the development and commissioning period. If the end product has any pretensions to really good reliability, however, full quality experience will only be obtained after many items have been manufactured, incorporated into equipment, and put into service under real live environments. It is to be expected, therefore, that initial deliveries will have some quality failures.

(5) Any change to the pre-determined pattern (whether to correct a quality failure or to introduce a modification) needs trials on a parallel plant until the general quality is proven to be satisfactory. Changes are, therefore, relatively expensive and slow to introduce.

(6) They will have had a considerable financial investment in study, engineering and commissioning. To be commercially viable they must continue in use until at least the break-even point.

2.2. *Desirable Design Actions in Using the Products of Complex Processes*

From the above characteristics of complex processes can be determined the second section of the Code of Practice for designers.

II. The Use of Products from Complex Processes

(1) In fabrications the physical form of the product is, more or less, determined by the design. In complex processes it is, more or less, determined by the process. The designer has, therefore, to understand the physical limitations imposed by the process, so that he may design accordingly. This understanding should go beyond the rules to the reasons behind them, otherwise he may be ambiguous in his requirement and chancy in his use of the product.

(2) He must define his needs precisely in the language demanded by the process. (Incidentally, the cost of training designers to use such languages must not be forgotten.)

(3) If he wishes to influence the range and performance of the products of complex processes, the time to do it is while they are being developed. It is really too late once they are commissioned.

(4) He must not take for granted the reliability of the product, but check its suitability for his own purposes and his equipment's environments, particularly during the first year or so after any process has been commissioned.

3. Integrated Assemblies

3.1. *The Nature of Integrated Assemblies*

The vast majority of passive components and active devices used in electronics fall into this category. There is a great temptation to think of them entirely as black boxes, whose contents can only be approached through their terminals. This is a great mistake because it closes the door on much information that can be of use to the electronic designer. Let us open the lid of the black box and see what we find. First of all, take a simple passive component—a resistor. This is represented on a circuit diagram as a single wavy line. If, however, we draw a constructional circuit diagram for a typical miniature resistor, using the symbols of I for Insulator, C for Conductor, R for Resistance, we obtain Fig. 1.

Each of the connections between the constructional items represents an interface. The component may fail through the gradual deterioration of the bulk material items themselves due, for example, to chemical action, mechanical stress, or diffusion of one into the other. The interfaces may fail for similar reasons plus the effects of differential thermal expansions or mechanical abrasion.

When we look at this constructional diagram we find that what seems a single circuit element with two terminals has, in fact, 11 constructional elements and 22 interfaces.

If we continue this process for all the components in the circuit diagram we produce a diagram with a much finer 'grain' that the first, in which the actual circuit elements—the parts that do the work—are imbedded (see Fig. 2).

3.2. *The Size of Integrated Assemblies*

An important question that the equipment designer should ask himself is 'where exactly shall I cut a piece out of this grainy structure and make it an integrated assembly?' He will take into account such factors as:

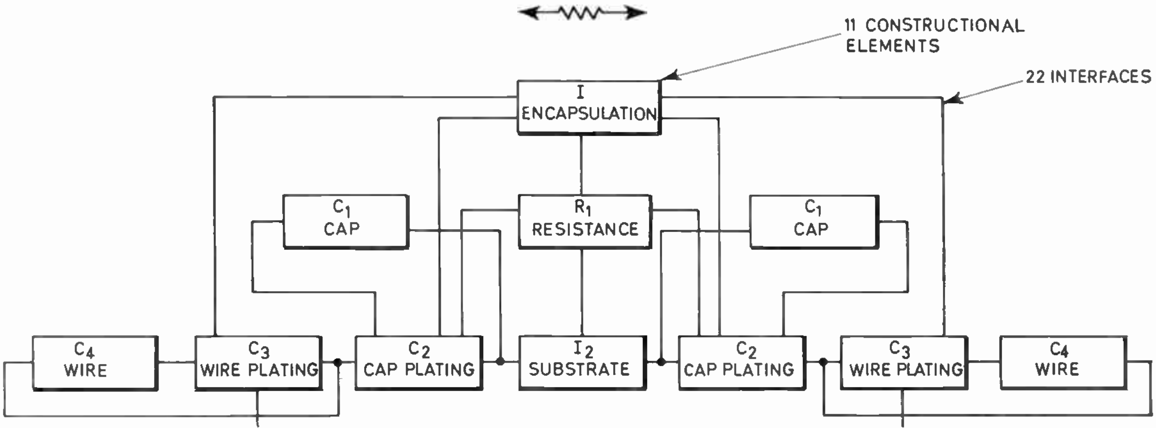

Fig. 1. Constructional diagram for metal oxide resistor.

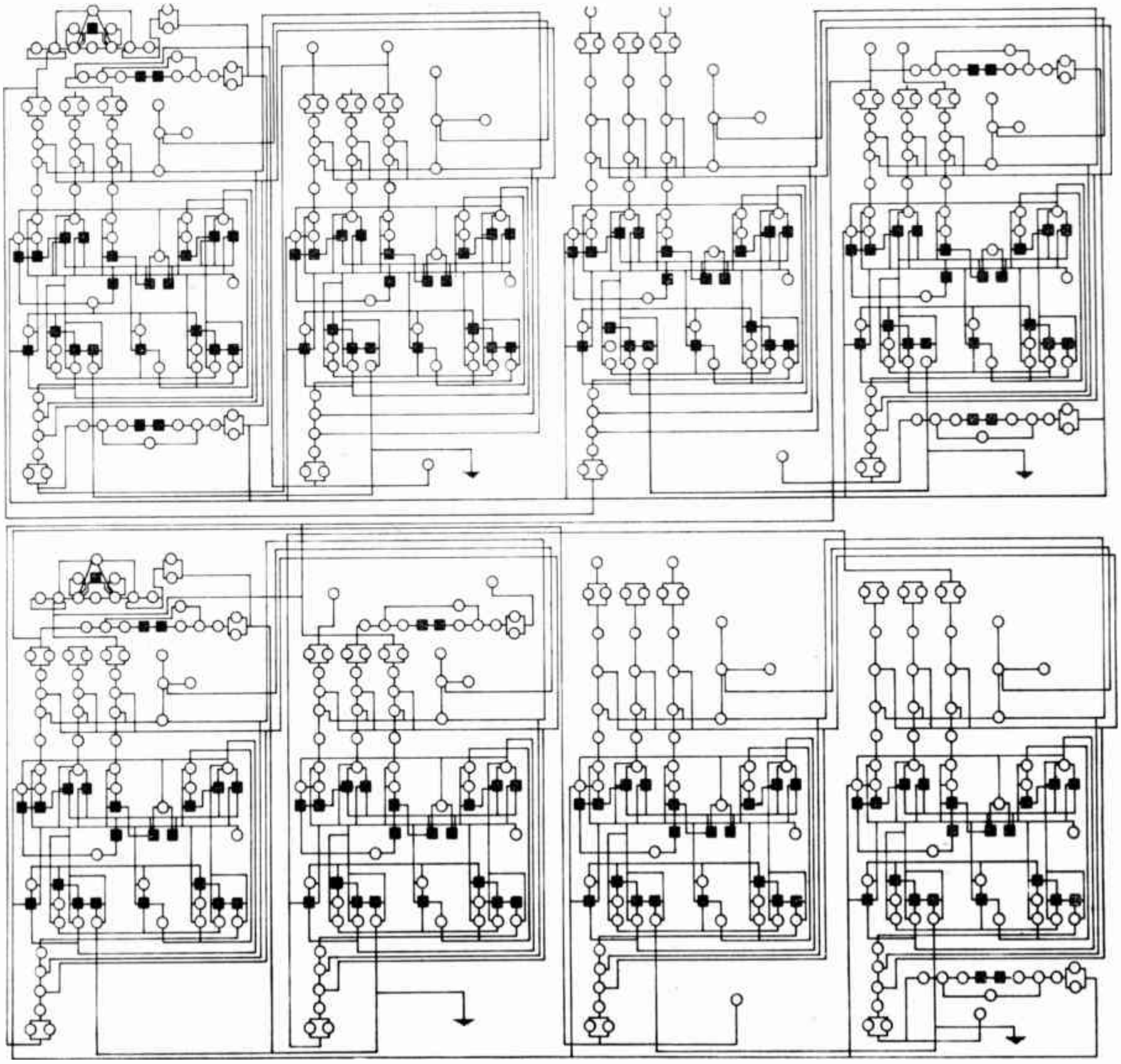

Fig. 2. Constructional diagram for a digital counter having 16 complex assemblies, 168 actual circuit elements, about 600 constructional elements and more than 1000 interfaces.

(1) The fact that many of the constructional items are there only to make the transition between a circuit element within an integrated assembly and its terminals. The connection to the next element can usually be much more direct if it is also contained within the integrated assembly (e.g. as in micro-circuits). This will reduce the probability of faults, all other things being equal.

(2) Assuming that the complex processes by which most integrated assemblies are made will have some imperfections, the probability of any integrated assembly being faulty will tend to increase as the number of included circuit elements increases, all other things being equal. The combination of factors (1) and (2) will tend to result in an optimum size of integrated assembly where the probability of a fault is a minimum.

(3) As each new circuit is enclosed within the integrated assembly, either the degree of design freedom is reduced or the number of integrated assembly types to meet an overall circuit requirement is increased.

(4) As the number of circuit elements increases, the cost of the integrated assembly will tend to increase, all other things being equal. In practice they are rarely equal, so some quite apparently random changes in cost can occur due to market considerations among other things.

(5) As the number of circuit elements increases, the total number of integrated assemblies needed to fulfil a given equipment specification will decrease, and hence the overall equipment assembly problems can become easier.

(6) The more complex the integrated assembly becomes, the wider the variations in the performance of individual units are liable to become, or alternatively the more stringent do its internal design requirements become to avoid such variations.

Looked at through the production man's eyes, there will be an optimum size for any particular type of integrated assembly. If it is too large there will be a tendency for wide variations between units; the defect level may rise; the cost of scrap is higher; there is less likelihood of unit standardization, and hence more stocking problems. If it is too small, the assembly problems will be greater.

System performance criteria will also probably indicate an optimum size for integrated assemblies, and so will maintainability criteria, and unit production cost criteria, but it is highly improbable that the optimum size will coincide for all these various criteria.

The moral to this particular aspect of design is that the equipment designer has a responsibility to influence the size of integrated circuits if he wishes to optimize the overall equipment design, and not merely to take whatever happens to be on the market at any particular time.

3.3. *Hazards in the Choice and Definition of Integrated Assemblies*

However he selects the size of an integrated assembly, the designer will still be faced with a black box to define and use. Having a personal responsibility for the quality of his design he will feel a natural distrust of black boxes. To achieve any feeling of confidence he will want to:

(i) know the general form of the contents so that he may get an idea of their probable reliability and technical suitability for his purpose,

(ii) obtain confirmation that the technical performance of the assembly matches his circuit requirements, and

(iii) be satisfied that *all* deliveries of integrated assemblies can be assembled into his equipment design with a high confidence factor for long, reliable life.

Unfortunately the hazards in these seemingly straightforward requirements are many—some would say vast.

3.3.1. The hazards of the seller/buyer relationship

Perhaps the greatest hazard stems from the buyer-seller relationships that exist in the majority of cases.

Integrated assemblies are increasingly made by specialist firms who sell their wares to the best of their ability and, faced by hard-selling tactics, some young engineers seem more willing to believe a supplier's rosy promises than the words of warning that may come from their more experienced colleagues.

The buyer-seller relationship has other complications. The seller likes to identify his product by a type number rather than by an exact definition of what it will do. This is partially because he reserves the right to make changes without altering the type number, and partially because he hopes that if he can get his type number on to the equipment parts list he will ensure recurrent sales for a long time.

Again, while a reputable supplier will, without question, replace any faulty assemblies, he will not be interested in consequential costs which in these days of cheap components and complicated equipment, delivered all over the world, may be many thousand times the cost of the assemblies themselves.

None of this should be taken, of course, to imply that integrated assembly manufacturers are not thoroughly competent firms, honestly trying to meet the market as they see it, and to supply what our designer wants, or *thinks he wants.* This latter uncertainty itself brings some more hazards.

3.3.2. The hazards of lack of knowledge of construction or performance

Because the box is 'black' and these days frequently very small, the designer often does not really have a clear idea of either the scale of the construction or the functions of the parts. Because of this he may make assumptions which lead to mistaken specifications, or to the omission of vital or desirable clauses.

Not all the relevant device characteristics are contained within the published data. This may be because the makers are deliberately restricting the specification to conform to a common standard, or because the designer may wish to use the device under conditions not visualized by the maker.

The rate of change of technology and the competition between manufactures brings a vast range of new devices on to the market every year, whose long-term reliabilities are unknown and cannot be known until they have been used in real equipment environments.

3.3.3. The hazards of supply, storage, and assembly

Even assuming that by one means or another the designer satisfies himself that a particular integrated assembly is right for his circuit—what are the hazards which will prevent his factory getting a steady supply of devices that will enable his equipment to be economically manufactured, and to have a satisfactory life in service?

The following are examples:

(i) The maker's processes and their Quality Assurance may unknowingly be imperfect in a random way and produce a small percentage of faulty items.

(ii) An undiscovered change may occur somewhere in the process, causing imperfections.

(iii) A deliberate change may be introduced to cheapen the process or to correct a known fault, which itself introduces a number of defects until it is perfected.

(iv) The basic design of the integrated assembly may be faulty from a reliability point of view.

(v) The firm may have a strike, or a fire, or go out of business, or be taken over, or just decide that a particular line is uneconomic, and supplies may cease temporarily or permanently.

To reiterate the initial philosophy, the designer has a personal responsibility to guard against these hazards because *he* chooses the integrated assembly. These kind of things should not just be something 'up with which the factory has to put'.

Even when the integrated assembly is satisfactorily received by the equipment factory, its storing and assembly may introduce faults. It will be subjected to part of a complex process of tests, equipment assembly and test. The choice of the assembly should be based on an appreciation of what will happen to it in the factory and in transport as well as in its service life. Moreover, while common assemblies will usually be ordered against a specific specification regardless of where they are used in the equipment circuit, each in practice will be subjected to the peculiar considerations and environment of its own circuit location. Some locations may swing the specification parameters to the limit, others might very lightly load them. Some may call for 100% utilization, others may only get called into action when peripheral or standby services are used.

Any selection of a common assembly to perform a variety of functions is a process of standardization by choice or by availability, and as such is a compromise. While a progressive policy of standardization can lead to an increasing degree of confidence in an assembly, it can also lead to the dangers of a too easy acceptance of a standard without full consideration of its match to a new circuit need.

3.4. *Designer's Actions in Using Integrated Assemblies*

We may summarize a designer's Code of Practice in relation to integrated assemblies as follows.

III. The Use of Integrated Assemblies

A. Choosing types and influencing policy

(1) Discover all you can about the constructional facts of the assemblies in collaboration with the makers.

(2) Explore reliability experience from all possible sources.

(3) Constantly re-appraise the optimum size of assemblies as part of equipment circuits from performance, cost and reliability points of view.

(4) Think creatively on these matters and do not just accept the trends that emerge from the market.

B. The specific assembly

(1) Define your circuit need as clearly as you can *before* looking for devices. Then choose the assembly to match it as closely as possible.

(2) In choosing the device, look far beyond the specification to the unspecified characteristics. Get formal limit statements from the makers.

(3) Explore the reliability *record* (not sales generalities).

(4) Do any tests necessary to establish the suitability of the device.

(5) Write the specification in terms of your need. Question the Quality Assurance procedures at the maker's factory.

(6) Negotiate with more than one maker and explore variations.

C. Delivered goods.

Agree Quality Control tests at goods-in and sub-assembly stages. Discuss the way assemblies are handled in the factory with the production engineer.

4. Equipment Assemblies and Sub-assemblies

4.1. *Types of Equipment Assembly*

The assembly of electronic equipment is itself becoming increasingly a complex process. Even where human actions are still required, they tend to become more defined, controlled, and in many cases, partially automated.

It is very necessary for the designer to recognize whether the assembly of his equipment will be carried out by a skilled craftsman with general custom-and-practice type control; by the use of semi-skilled personnel with aids, or by a fully automatic process. The skilled craftsman will, under reasonably steady state conditions, require a minimum of detailed instruction, and can take quite a degree of undocumented variation in his stride. In many ways the automatic process is the easiest for the designer to use once he has come to terms with its full disciplines.

The middle method, using an unskilled assembler with varying degrees of assistance, is probably the most commonly employed at this time, and is the most uncertain from a designer's point of view. This uncertainty arises because:

(i) There is usually a largish turnover in personnel so that a continual training process and an uneven level of experience can be obtained.

(ii) Assembly instructions have to be complete and yet expressed in a way that allows for human misinterpretation.

(iii) There will be a number of assembly elemental operations, some purely manual, some assisted, the effect on performance of which has to be understood.

(iv) The factory will be constantly experimenting with a view to improving efficiency. There is, therefore, a possibility that changes may occur during a production run.

(v) The designer has still a fair chance of influencing the assembly methods if he so wishes.

4.2. *The Equipment Assembly Design Process*

Assembly is essentially a sequential process. The sequence adopted, and its consistency, can influence both cost and performance. The extent to which accessibility for assembly is provided by the assembly design, and the sequence chosen, can affect the cost of both assembling and its quality verification.

Designing an assembly is essentially the manipulation of a multi-dimensional jigsaw in which circuit flow, circuit susceptibilities, space utilization, and heat removal have to be juggled. Traditionally, this exercise resulted in a relatively free design, in which the various components jostled together rather like the houses in an old town. More and more the rigidity of complex processes, in particular the printed board, have taken charge and from being truly three-dimensional, designs are now more often than not 'multiple two-dimensional' in character, and an equipment's 'grain' has become as regimented as a modern housing estate. If the designer does not heed the code of practice mentioned above in relation to complex assemblies, and if he is over-awed by the rigidity of the modularity imposed by printed boards, he may well find that he, like the assembler, needs to be only a semi-skilled person.

In fact, the whole of the electronic technology is changing as rapidly as it has ever done, and the apparent rigidities of one type of construction will be no more permanent than were the phases of the past. To design, however, into a rigid environment, be it only of the moment, can easily create a rigid outlook on the part of the designer, in which he blindly accepts the conventions and does not look through them for trends and beyond them to another generation.

The computer can be of great help to the designer in assembly design generally, and in particular for the computation of optimum wiring runs and their automatic scheduling. The very facility with which the computer can accept the disciplines of a process, can take the designer's rules into account, and can produce data ready for the shop floor or the automated machine, itself conceals pitfalls for the designer who uses it too automatically. The computer does not design, it computes, which is only part of the design process. Just as intuition is beginning to be admitted to be behind much of what used to be called the scientific method, so it must play its part in designing. Too slavish a dependence on the computer may be very costly, and may only result in the optimizing of a cumbersome design (The main claim to savings is frequently in time rather than cost, and time savings can be selective according to the position of the activity in the design programme network.)

4.3. *Designer's Actions in Equipment Assembly Design*

The designer's Code of Practice for equipment assembly should include the following recommendations.

IV. Designing the Equipment to be Assembled

(1) Get out on the assembly floor as much as possible to see what happens there. The industrial designer insists on seeing the equipment's environment; the assembly designer should do likewise.

(2) Study the elemental assembly operations, establish their reliability characteristics, and agree precise sub-routines with the production engineers.

(3) Establish a three-dimensional plan for component location; wiring run location; heat removal; assembly access; ergonomic and aesthetic considerations; circuit flow; unit distribution; assembly accessibility, and test and inspection accessibility. It is not a bad idea to have a mock-up in wood or card for even simple equipments.

Involve the production engineer, the industrial designer, the test engineer (see Section 1 above).

Do not be mesmerized by modularization.

Do not make assumptions about the physical form until the sub-assembly philosophy has been worked out on value engineering lines.

(4) Maintain a good liaison with the shop floor, even when the production is running.

5. Equipment Testing

Testing is a subject deserving of at least one paper in its own right. The following notes are, therefore, only intended to draw attention to the fact that testing and assembly should be considered as an integrated operation, and to distinguish between design proving and production proving.

5.1. *The Integration of Testing with Equipment Assembly*

To leave all testing until the end of assembly can increase the cost and reduce the probability of fault detection. The testing operation is normally aimed at confirming that the specified performance has been achieved, and at providing the instrumentation for alignment. Faults are not only present in complex assemblies and fabrications on delivery to the assembly point, but are added progressively as the assembly operation proceeds. It is probably true to say that the 'best' (i.e. the cheapest and most searching) fault-finding time is as soon as possible after the fault has been inserted.

In practice there are three main stages at which testing can most fruitfully be done. These are:

(a) At the integrated assembly or fabrication delivery point.

(b) At the sub-assembly stage, when the integrated assemblies have taken their particular usage position and when the immediate assembly faults have been built in.

(c) At the complete assembly stage where the whole equipment can be checked to its performance defining specification.

5.2. *The Impact of Equipment Design on Testing Efficiency*

If we take the above three stages (remembering that there may in practice be others) we will find that the ability to test fully at each stage is dependent upon:

(a) The completeness of the performance exploration that can be carried out by access to the available terminals.

(b) The extent to which the working environment can be simulated.

(c) The adequacy with which the design has explored the interchangeability of integrated assemblies, equipment sub-assemblies, or complete equipments.

The desirability of organizing sub-assemblies on a 'completeness of performance' basis and of providing adequate, rapid access for testing purposes will be clear. At the same time it must not be forgotten that, all other things being equal, the most sub-units there are, the more plugs and sockets there will be and the greater the cost.

Now, the access points for test do not have to be via plugs and sockets, nor do they have to be only at the periphery of a sub-assembly, but if access is going to be rapid, then it must be engineered into the assembly right from the start.

5.3. *The Need to Distinguish between Design Proving and Production Proving Tests*

The equipment designer should distinguish between testing to verify the adequacy of his design and testing to verify the adequacy of production. The differences may be summarized as follows:

(i) Production testing is only concerned with establishing that each particular model meets its specification, either as a total equipment or within any contracted interchangeability limits. Design testing will seek to explore margins and test the reaction to system fault conditions.

(ii) Production testing is generally concerned with the economics of testing many models, design testing with a few.

(iii) Production testing will be done by testers, preferably as unskilled as possible. Design testing will be done, for the most part, by design engineers or senior test engineers.

(iv) Unit production testing will be done over a relatively short period; design testing may be extended over many months or even years.

The two operations will clearly be different in specification and equipment needs, so that even if the design testing phase extends into the early production stages, as it may well do for small quantity production runs, it should still be kept as a separate operation, to a separate specification.

5.4. *Designer's Actions in Designing for Equipment Testing.*

The Code of Practice for the designer relative to test, within the limitations of this paper, should, therefore, include the following requirements:

V. Designing the Equipment to be Easier to Test

(1) Evolve an overall assembling/testing plan which increases the probability of faulty detection and minimizes overall cost.

(2) Consider the extent to which the integrated assemblies, equipment sub-assemblies and complete equipment should be subjected to environment exploration, as well as to nominal parameter checks.

(3) Visualize the optimum circuit access for testing and build in any necessary connection (or disconnection) points.

(4) Do not assume that production testing is the same kind of thing as design testing. Study the problem with test engineers and collaborate with them to produce test specifications that are aimed at the production environment.

(5) Where design proving is likely to be continued into the production phase, prepare separate specifications, and provide separate test equipment as necessary.

6. When Should Designing Stop?

Designing costs money. The cost of designing (divided by the number of equipments to be sold) has, in effect, to be added to the cost of producing, in order to arrive at the product cost.

The effective designer optimizes the *total* cost. He uses the techniques of value engineering to eliminate the item of doubtful function, and he should equally use the same techniques to eliminate the design activity of dubious value. Nevertheless, to achieve a true simplicity in design sometimes takes longer than just to follow his nose. To consider the details of production processes takes longer than to ignore them. To investigate the likely reliability of an equipment is more time consuming than just keeping his fingers crossed.

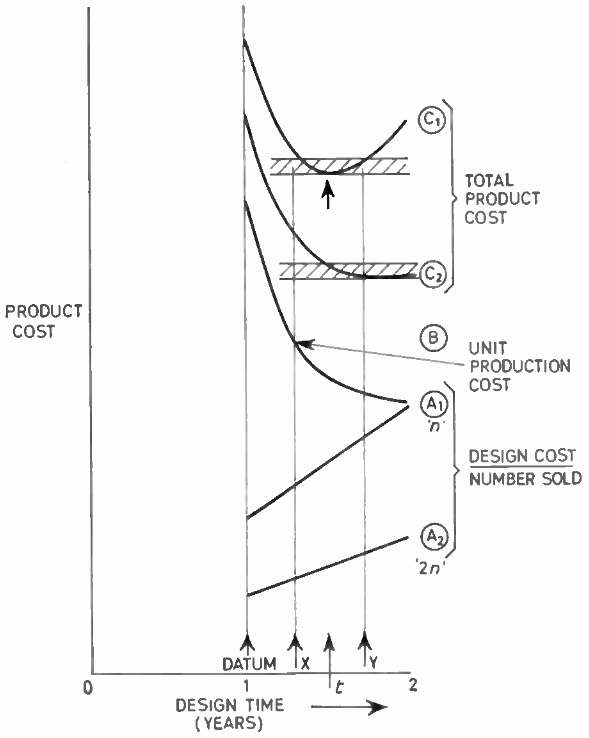

Fig. 3. The variation of product cost with design time.

Suppose we take as a datum a design where just sufficient effort has been put in during one year to produce the required equipment performance without any particular consideration for its producibility or value. A design, in other words, that is more elaborate than it need be and which the factory will produce only with some difficulty.

The factor

$$\frac{\text{number sold}}{\text{design cost}} = n, \text{ the unit production cost,}$$

and the total product cost figures for such a design, might be those shown at the starting points of curves A_1, B and C_1 respectively in Fig. 3.

If we now carry on designing, the design cost will increase along curve A_1.

If the effort is directed at the high cost areas, the corresponding drop in the unit production cost should be rapid initially (curve B), and then fall more slowly as the law of diminishing returns sets in.

The total product cost will be as in C_1, having a minimum at design time *t*. Allowing for the practical tolerances in the estimation of cost and progress, the actual minimum will lie within some band (shown in Fig. 3 shaded). The designer will have the option of stopping the extra design activities at either X or Y, the overall product cost being the same. If he carried on to Y, the unit production cost will be lower. Suppose that, with the possibility of such a reduction, the number of equipments sold could be doubled to $2n$. The

$$\frac{\text{design cost}}{2n}$$

curve would now be A_2, and the new total product cost would be C_2, i.e. not only is the product cost lower, but its minimum is at a longer design time. In other words, to carry on beyond X can encourage the reduction of cost which will make further sales possible.

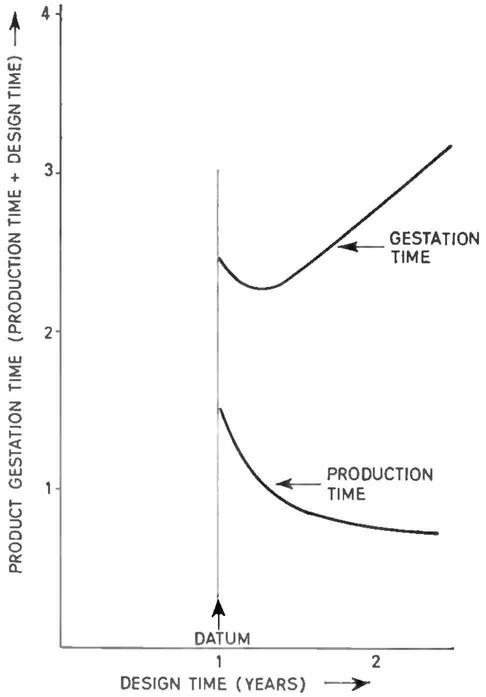

Fig. 4. The variation of product gestation time with design time.

Instead of looking at the effect on cost of extra design time, the effect on product gestation time can be considered as in Fig. 4. Here the design time is added to the production time to produce the total gestation time, again a curve which may have a minimum. In the case shown, the minimum occurs earlier in the extra design time period than does the cost minimum. On the other hand, once the design is launched, the reduced production time will be an advantage to minimizing the stock levels needed to meet any given market.

The designer clearly has a responsibility to keep his finger on the pulse of *overall* unit production cost as his design progresses, and to assess, as far as he can, how much his continued actions will affect the overall gestation time. In making this assessment he will remember, no doubt, that if a single component is found unsatisfactory in production, the delay inserted will be made up of time for failure investigation; solution engineering; new production; re-assembling, and re-testing. He will think about complex processes and the time needed to introduce effective changes. He will ponder on the fact that, whereas he ought to be able to estimate the cost consequences of his extended design actions quite closely, hold-ups in production will almost certainly arise due to unforeseen factors.

Having thus communed with himself he will almost certainly push the design stop point as far forward as his eloquence can convince his commercial management to be necessary.

6.1. *Designer's Actions to Control Design Time*

The designer's Code of Practice in these matters, therefore, could well be stated as follows:

VI. Optimizing the Design Time

(1) Monitor constantly the *overall* unit production cost as the design progresses.

(2) Continually assess the 'production risk factor' of all components and assemblies, and concentrate on depth of proof and control where the risk factors are highest.

(3) In collaboration with production and sales personnel, continually attempt to assess the best design stop point for minimum overall cost and minimum gestation period.

7. Quality

Quality, which really includes reliability within its all embracing terms, is the sum of those product attributes that a customer has ordered, or that are offered to him, or which he might reasonably expect to get from a reputable firm.

For its achievement, Quality needs adequate engineering definitions of that which has been contractually committed (or might be expected to be committed), and adequate verification processes and procedures all the way down the pyramid of proof that must exist in any firm dealing in complex electronic equipment. The necessity for separating the verification of Design Quality from Production Quality has already been indicated in Section 5.3. The design actions appropriate to optimizing the verification of Quality by testing have been summarized in Section 5.4.

It only remains, therefore, to look at the specification of Quality for Production purposes, assuming that the designer has himself been given an *adequate* Design Quality specification, to obtain which he will frequently have had to be extremely persistent. The points made here are concerned with completeness and method of specification.

7.1. *Completeness of Specification*

Completeness in this context means the inclusion of such matters as the following:

(i) All aspects of the contractual specification. The designer may think that aspects of the customer Quality specification are exclusively covered and proved during the design phase, and omit to mention them to the factory. In practice the factory may unwittingly take some steps that will reduce this aspect of Quality.

(ii) All *interpretations* of the customer specifications which are necessary to express the requirements in factory engineering terms.

(iii) All necessary definitions of workmanship standards, whether by codes of practice or approval models.

(iv) Details of any special facilities or environment that have been assumed in the design.

(v) Definition of the spares policy in regard to sub-assemblies or units. (Knowledge of the extent of interchangeability is an important matter to the factory.)

(vi) Particulars of any essential *order* of assembly and alignment that has been assumed in the design.

(vii) Just as comprehensive information for special customer requirements or for design changes as for the basic design itself.

7.2. *Method of Specification*

The traditional method of specifying a design has been by drawings and their associated schedules, plus material, process and performance specifications.

A drawing is an essential design tool through which the designer can explore the evolution of his design. In some cases he places over-reliance on his ability to visualize a three-dimensional device from a two-dimensional projection, and would be better advised to use models or to train himself to sketch in perspective.

Once the design is completed, the designer traditionally also expresses his wishes to the factory in drawing form.

Now, in many cases a drawing and its associated schedules form a kind of artificial interface language, different from the day-to-day language of both the designer and the factory. The former is concerned, for example, with a three-dimensional object having a specific size and finish. The latter is concerned with a piece of raw material and a machine and its controls and the settings that they must progressively follow in order to turn the raw material into the desired object. A designer who is perfectly aware of what he wants cannot communicate these wishes to the operator until both of them have mastered the vocabulary and grammar of the drawing language. It is rather as though communication between an Englishman and a Frenchman always had to take place in Esperanto. The use of this interface language involves the cost and time of training engineers and craftsmen in its own use, and the dangers of misinterpretation of the requirements of both operator and factory, with the usual repercussions on Quality. The language may even be elevated to a virtue in its own right, with its own loved literature.

The introduction of numerically-controlled machines has done a great deal to put the designer and the machine in direct contact, with the production engineer making the introductions, and this will, it is hoped, increasingly encourage the designer to specify his needs in terms that are of direct use to the machine, or craftsmen whose job it is. Certainly the designer will have to know more about how the machines or men work, but surely his education will be well spent in this direction. The accurate definition of Quality cannot but benefit from such a direct contact.

The above philosophy must not be thought to imply that drawings will have no place in the future of specifications, but rather that they will probably perform a less artificial role.

The designer must in future delineate his design by whatever is the most effective and direct method, whether it be punched tape, photographs, operation schedules, drawings, specifications, or by filling in a questionnaire prepared by a complex process manager, and it would be salutary to all of us if we stopped referring to the 'date of release of the drawings' as though that was the end of design.

The philosophy for the designer in regard to Quality Specifications can be summarized as follows:

VII. The Specification of Quality

(1) Give the contractual Quality Specifications to the factory as well as the Production Specifications.

(2) Interpret the Quality Specifications into precise factory language.

(3) Define workshop codes of practice.

(4) Detail special facilities or environments needed by the design.

(5) Define interchangeability.

(6) Indicate any assumed order of assembly or adjustment.

(7) Specify variations or changes thoroughly.

(8) Delineate the design requirement in terms directly to be used by man or machine as far as possible.

8. Design Engineer's Training

When an engineer has learnt all about electrons, holes, communication theory, noise, logic, power supplies, waveguides, modulation, and how to program a computer, what does he need to learn in order to be able to design effectively for production? What background does he need to stand him in good stead when the techniques of today merge into those of tomorrow? The following points are relevant:

VIII. The Background Needed by an Engineer to to be Able to Design for Production

(1) He needs to feel the pulse of Quality in its making and its verifications. He must watch men and machines making mistakes and producing variable Quality. He must appreciate that he too would produce variable Quality in their place. He must learn the pitfalls of inspection and testing, and realize the interdependence of many people in the achievement of Quality.

(2) He needs to practice buying and to understand the half-truths of the market place.

(3) He needs to see how his design is dissected and then rebuilt in accordance with a control pattern that will influence the manufacturing cycle.

(4) He will need to see the instructions that he gives through the eyes of the people or machines that have to use them.

(5) He must learn that there are many ways of 'killing a cat' production-wise, and that the best must be sought.

(6) He must become master of costing and estimating factors.

The writer's personal opinion as to how any particular training period should be proportioned is shown in Fig. 5.

How then should an engineer get this background training, how long should it take, and when should it happen? The points that follow are again essentially the writer's opinion.

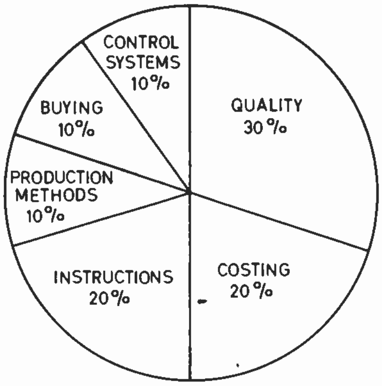

Fig. 5. Allocation of time for engineer's training.

8.1. *The Form of Training*

(a) It should take the form of specific instruction and/or training tasks rather than a general tour of duty in a variety of departments. The time for familiarization with each new department subtracts from the learning time, the standard of tuition will be variable, and the opportunities random for the study of particular cases.

(b) Quite a proportion of the training could be given in a workshop specially set up for the purpose and doing real work. The trainee does not need himself to learn how to operate machines, or to assemble, or to wire, but he does need the opportunity critically to examine what happens.

(c) Another appreciable section of the training would be suitable for formal lecturing, case studies, or other 'class room' types of training method.

(d) The remainder of the training could be given on location or tour in real factories, but again in relation to specific tasks or observing a range of facilities or practices and under the tutorship of a trained teacher.

8.2. *Training Duration*

If the training can be concentrated on learning the matters that have to be learnt and avoiding any appreciable amount of marking time, one year should suffice.

8.3. *Timing of Training*

The ideal time for an embryonic designer to be trained on production matters is after he has been in engineering laboratories long enough to have begun to appreciate some of the problems of designing circuits, but before he is involved in designing equipment. This would probably be about 1 to 2 years after a graduate first joins a company.

It is appreciated that considerable resolve will be needed on the part of engineering managers to release men for further training once they are just beginning to be useful, but the benefits will be reaped a hundred-fold when the designers come back into the laboratories.

9. Conclusion

In the past the designer could get by with a rudimentary training in general workshop practice, and by expressing his wishes in the interface language of drawings. In the future a deep and continuing knowledge of the factory's complex processes will be necessary before a designer can begin to design effectively, and the factory will not be able to produce efficiently unless he expresses his wishes in the direct terms needed for men and machine instruction. The integration of design and production is no high sounding phrase coined to grace the order paper for this Conference. It is a vital necessity if the electronic industry is to face world wide competition.

10. Acknowledgments

The author wishes to thank all his colleagues in his Company's factories and design laboratories from whom has come any of the wisdom that may appear in this paper. The mistakes and foolishness are, of course, his own.

11. Appendix 1: Definition of Terms Used

Fabrication. An individual part made from raw or processed material, not itself contributing directly to a circuit function.

Integrated Assembly. One or more circuit elements and their associated fabrications, inter-connected and enclosed in such a way as to need complete definition by an overall specification at its terminals. Not capable of maintenance by part replacement within its boundary.

Examples are:

Components (involve one-circuit element).

Integrated circuits (a general term used in a restricted way, i.e. for microminiature or thin-film circuits involving solid-state active devices).

Encapsulated assemblies.

Thermionic valves.

Sealed relays.

Sub-assembly. A collection of components and/or fabrications brought together for the convenience of production. Generally capable of partial or complete dissembly. Not necessarily having a complete functioning specification in its own right.

Complex Process. The production of a fabrication, or an assembly by a series of inter-dependent processes, each of which has to be controlled to specific limits, and where the end-product performance is markedly determined by the precision of control of each elemental operation in the process.

It is characteristic of a satisfactory complex process that its product will consistently meet its quality specification. It does not follow that all its functionings are fully understood.

12. Appendix 2: A Design-for-Production Code of Practice

This Code of Practice consists of extracts from the paper collected together in the hope that a more useful mnemonic list will thus be available, to which engineers can add their own contributions.

12.1. *Collaborating with Production and Other Experts*

(1) Try and understand some of their background and skills.

(2) Devote time to ensuring that they understand the equipment background.

(3) State the overall purposes of the design clearly and take the specialists into all of them.

(4) Delay defining the 'how' until the specialists have contributed their ideas.

12.2. *The Use of Products from Complex Processes*

(1) In fabrications the physical form of the product is, more or less, determined by the design. In complex processes it is, more or less, determined by the process. The designer has, therefore, to understand the physical limitations imposed by the process, so that he may design accordingly. This understanding should go beyond the rules to the reasons behind them, otherwise he may be ambiguous in his requirement and chancy in his use of the product.

(2) He must define his needs precisely in the language demanded by the process. (Incidentally, the cost of training designers to use such languages must not be forgotten.)

(3) If he wishes to influence the range and performance of the products of complex processes, the time to do it is while they are being developed. It is really too late once they are commissioned.

(4) He must not take for granted the reliability of the product, but check its suitability for his own purposes and his equipment's environments, particularly during the first year or so after any process has been commissioned.

12.3. *The Use of Integrated Assemblies*

12.3.1. Choosing types and influencing policy

(1) Discover all you can about the constructional facts of the assemblies in collaboration with the makers.

(2) Explore reliability experience from all possible sources.

(3) Constantly re-appraise the optimum size of assemblies as part of equipment circuits from performance, cost and reliability points of view.

(4) Think creatively on these matters and do not just accept the trends that emerge from the market.

12.3.2. The specific assembly

(1) Define your circuit need as clearly as you can *before* looking for devices. Then choose the assembly to match it as closely as possible.

(2) In choosing the device, look far beyond the specification to the unspecified characteristics. Get formal limit statements from the makers.

(3) Explore the reliability *record* (not sales generalities).

(4) Do any tests necessary to establish the suitability of the device.

(5) Write the specification in terms of your need. Question the Quality Assurance procedures at the maker's factory.

(6) Negotiate with more than one maker and explore variations.

12.3.3. Delivered goods

(1) Agree Quality Control tests at goods-in and sub-assembly stages. Discuss the way assemblies are handled in the factory, with the production engineer.

12.4. *Designing the Equipment to be Assembled*

(1) Get out on the assembly floor as much as possible to see what happens there. The industrial designer insists on seeing the equipment's environment; the assembly designer should do likewise.

(2) Study the elemental assembly operations, establish their reliability characteristics, and agree precise sub-routines with the production engineers.

(3) Establish a three-dimensional plan for component location; wiring run location; heat removal; assembly access; ergonomic and aesthetic considerations; circuit flow; unit distribution; assembly accessibility, and test and inspection accessibility. It is not a bad idea to have a mock-up in wood or card for even simple equipments.

Involve the production engineer, the industrial designer, the test engineer (see Section 1).

Do not be mesmerized by modularization.

Do not make assumptions about the physical form until the sub-assembly philosophy has worked out on value engineering lines.

(4) Maintain a good liaison with the shop floor, even when the production is running.

12.5. *Designing the Equipment to be Easier to Test*

(1) Evolve an overall assembling/testing plan which increases the probability of fault detection and minimizes overall cost.

(2) Consider the extent to which the integrated assemblies, equipment sub-assemblies and complete equipment should be subjected to environment exploration, as well as to nominal parameter checks.

(3) Visualize the optimum circuit access for testing and build in any necessary connection (or disconnection) points.

(4) Do not assume that production testing is the same kind of thing as design testing. Study the problem with test engineers and collaborate with them to produce test specifications that are aimed at the production environment.

(5) Where design proving is likely to be continued into the production phase do separate specifications, and provide separate test equipment as necessary.

12.6. *Optimizing the Design Time*

(1) Monitor constantly the *overall* unit production cost as the design progresses.

(2) Continually assess the 'production risk factor' of all components and assemblies, and concentrate on depth of proof and control where the risk factors are highest.

(3) In collaboration with production and sales personnel, continually attempt to assess the best design stop point for minimum overall cost and minimum gestation period.

12.7. *The Specification of Quality*

(1) Give the contractual Quality Specifications to the factory as well as the Production Specifications.

(2) Interpret the Quality Specifications into precise factory language.

(3) Define workshop codes of practice.

(4) Detail special facilities or environments needed by the design.

(5) Define interchangeability.

(6) Indicate any assumed order of assembly or adjustment.

(7) Specify variations or changes thoroughly.

(8) Delineate the design requirement in terms directly to be used by man or machine as far as possible.

12.8. *The Background Needed by an Engineer to be Able to Design for Production*

(1) He needs to feel the pulse of Quality in its making and its verifications. He must watch men and machines making mistakes and producing variable Quality. He must appreciate that he too would produce variable Quality in their place. He must learn the pitfalls of inspection and testing, and realize the interdependence of many people in the achievement of Quality.

(2) He needs to practice buying and to understand the half-truths of the market place.

(3) He needs to see how his design is dissected and then re-built in accordance with a control pattern that will influence the manufacturing cycle.

(4) He will need to see the instructions that he gives through the eyes of the people or machines that have to use them.

(5) He must learn that there are many ways of 'killing a cat' production-wise, and that the best must be sought.

(6) He must become master of costing and estimating factors.

Manuscript received by the Institution on 29th March 1967 (Paper No. 1161).

Letters to the Editor

The Acoustic Target Strength of Fish

SIR,

I should like to comment on the paper by B. R. Carpenter which you recently published[1] and on an earlier paper by D. H. Cushing *et al.*[3] from the same laboratory.

The reader might easily draw the conclusion that Fig. 1 of the first paper is based on my observations which had been published previously,[2] whereas it is drawn from the second paper by Cushing *et al.*[3] (This figure gives the dependence of the acoustic target strength of a fish on its length.)

I hope that this note will help to clarify the situation for other workers in this field.

In this figure there are three regions: (a) the Rayleigh scattering zone, (b) the geometrical region, with (c) an intermediate region between these two. Since the graph is drawn on a log/log scale, the slopes of these three parts represent the powers (n) of the corresponding laws relating fish target strength with fish length, of the form:

$$\text{target strength} \propto (\text{fish length})^n.$$

The values of n in Fig. 1 are as follows:

(a) 2; (b) 1; (c) ½

which differ from the theoretical values of n given by me (Ref. 1, page 354), namely:

(a) 6; (b) 3; (c) 2

for dorsal aspect of the fish. This value for (a) gives the lowest possible target strengths in the Rayleigh scattering region, treating the swim-bladder in the simplest case as a rigid body. Further details are given in Ref. 2 as well as in a more recent paper[4] which takes account of a possible resonance of the swim-bladder in region (a), when n has a value of about 2 (which is in agreement with the experimental results due to Cushing *et al.*).

There are also discrepancies in Fig. 2 of Mr. Carpenter's paper (which was reproduced from Cushing *et al.*).[3] For example, in the Rayleigh scattering region, the vertical separation for a 10/1 change in frequency should be 40dB in view of the λ^{-4} law and the 'knee' occurs at increasingly higher values of the target strength for longer fish. (These values may be calculated from Fig. 3 of Ref. 4.)

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3rd July 1967

SIR,

To determine the dependence of target strength on the logarithm of the length of fish, we have always used the relation of Midttun and Hoff.[5] They suggest that the swim-bladder might be contributing a component of directivity to this relationship. But their fit to data was very much better than ours,[3] and it made it possible to use the reliable dependence of target strength on the length. In our 1963 paper Dr. Haslett's theoretical curve was indeed used but used only to locate the middle zone; the diagrams of target strength vs. log length were in fact based on the data from Midttun and Hoff which were published at that time.

There has been considerable discussion on the possible trend of target strength with frequency. Hashimoto and Maniwa[6] showed an increase of target strength with frequency. Weston[7] has suggested that, with increased frequency, the relative importance of the swim-bladder decreases. Hence we were not sure that the observations of Hashimoto and Maniwa were really representative. Dr. Haslett has recently examined the trend of target strength at a wide range of frequencies and we look forward to seeing his results in a published form.

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10th October 1967

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SUBJECT INDEX

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This index classifies under subject headings the abstracts published throughout the volume in 'Radio Engineering Overseas', summaries of papers presented at the Conference on 'R.F. Measurements and Standards' held at Teddington in November 1967, and abstracts of some of the papers published in the *Proceedings* of the Indian Division of the Institution of Electronic and Radio Engineers during 1967.

OTHER JOURNALS FROM WHICH ABSTRACTS HAVE BEEN TAKEN DURING THE SECOND HALF OF 1967

E.B.U. Review (Switzerland)

Electronics and Communications in Japan (English language edition of *Denki Tsushin Gakkai Zasshi*)

Nachrichtentechnische Zeitschrift (Germany)

L'Onde Electrique (France)

Philips Technical Review (Holland)

Proceedings of the Indian Division of the Institution of Electronic and Radio Engineers

Proceedings of the Institution of Radio and Electronics Engineers, Australia

Radio Engineering and Electronic Physics (English language edition of *Radiotekhnika i Elektronika*) (U.S.S.R.)

Review of the Electrical Communication Laboratory NTT (Japan)