EQUALIZATION FOR TAPE RECORDING AND REPRODUCTION

by

P. J. Guy

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This article makes a comparison between the equalization requirements of magnetic tape (audio) recording and reproducing systems to comply with British or American Standards. The various factors which limit both the recording and replay response are detailed and a number of suitable equalizer circuits are described and analysed. Finally, the various methods of measuring the surface induction on a recorded tape are detailed. The article includes circuits of transistorized recording and replay amplifiers which have proved satisfactory in operation.

MANY articles have been written about the equalization required in magnetic recording/replay systems, but until 1960 no complete review of the subject had appeared. In that year an authoritative article was published[1] which, while comprehensive, treated the subject from the American viewpoint and dealt with the N.A.B. (formerly N.A.R.T.B.) response curve.

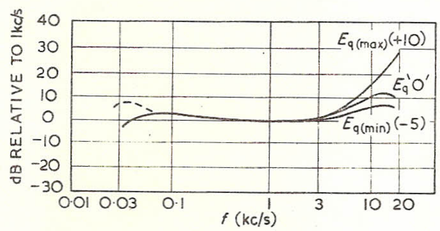


Fig. 1. Response of recording equalizer in typical tape recorder

The dotted bass lift is sometimes provided to offset attenuation of low frequencies during reproduction. The treble boost is to offset (1) changes in μ and D, (2) head losses, (3) treble attenuation due to effect of the leakage field in the vicinity of the recording head

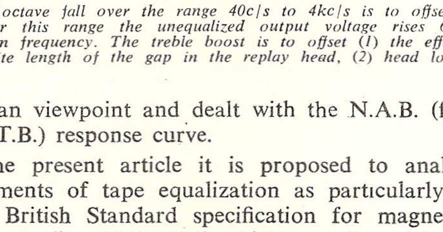


Fig. 2. Response of reproducing equalizer in typical tape reproducer

The 6dB/octave fall over the range 40c/s to 4kc/s is to offset the fact that, over this range the unequalized output voltage rises 6dB/octave increase in frequency. The treble boost is to offset (1) the effect of the finite length of the gap in the replay head, (2) head losses

In the present article it is proposed to analyse the requirements of tape equalization as particularly related to the British Standard specification for magnetic tape sound recording 1568 : 1960 which complies with Publication 94 of the International Electro-Technical Commission, "Recommendations for Magnetic Tape Recording and Reproducing Systems: Dimensions and Characteristics".

* *BBC Engineering Training Department.*

Typical shapes of the response curves of the recording and replay chains of magnetic recorders used for sound recording are shown in Figs. 1 and 2. It will be seen that, unlike those of a disk recording/reproducing chain, the replay response is not a mirror image of the recording equalization.

The recording equalization consists mainly of treble boost, while the replay equalization provides both bass and treble pre-emphasis. It will be realized, nevertheless, that the replay response required is dictated by the recording characteristic employed.

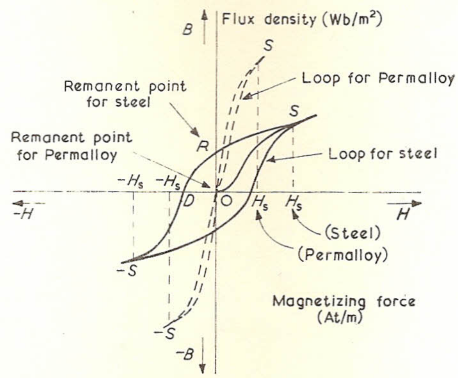


Fig. 3. Comparison between hysteresis loops for steel and Permalloy

Before analysing in detail the equalization required for recording, it is first necessary to consider how the recording is made.

Basically the ability to make a magnetic recording of sound and vision signals depends upon the fact that there are two distinctly different classes of magnetic material, 'hard' and 'soft'. Hard magnetic materials such as cold steel and ferric oxide (Fe_2O_3), while comparatively difficult to magnetize, tend to retain a fairly large proportion of the magnetization induced in them until some demagnetizing force is applied. On the other hand, magnetically soft materials such as soft iron and Permalloy (a soft iron alloy containing approximately 78·5 per cent nickel) are very readily magnetized but generally exhibit little or no remanent magnetization after a magnetizing force has been applied and removed. Fig. 3 shows comparative hysteresis loops for Permalloy and steel.

In order that the recording shall be permanent, a magnetically hard material must be used as the tape coating, while Permalloy or some similar alloy or one of the ferrites must be used for the core of the electromagnet which—energized by the amplified signal it is desired to record—is used as the recording head. The tape is generally made of plastic or paper, coated with magnetic ferric oxide (Fe_2O_3), one of the 'hard' materials.

Because of hysteresis effects, the recording system will be non-linear unless some form of bias (now almost universally high frequency a.c.) of critical value is fed into the coils of the recording head along with the signal. Fig. 4 shows the typical distortion of a sinusoidal signal recorded without bias. The bias reduces the distortion to negligible proportions and raises the recorded level to a marked extent, thus improving the programme/noise ratio.

Axon[2] has made an exhaustive analysis of the effect of recording without bias. Not only is the output waveshape

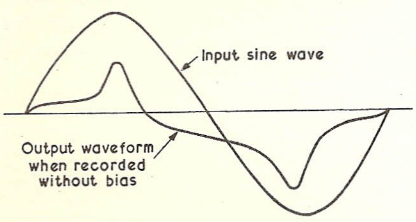


Fig. 4. Typical output waveshape when a sine wave is recorded without bias

distorted, but the output level for a given input is very much smaller than when bias of the correct value is used. An important effect of a.c. bias is to remove the effect of the gap length in the recording head. Without bias a succession of minima occur in the output at frequencies at which the effective gap length in the recording head equals approximately $\frac{3}{4}\lambda$, $1\frac{3}{4}\lambda$, $2\frac{3}{4}\lambda$, etc. (where λ = recorded wavelength = quotient tape speed/frequency). With a.c. bias of critical value, the recorded signal intensity becomes independent of recording head gap length, non-linear distortion for normal peak input level is reduced to about 2 per cent and the recorded level is sufficient to ensure a programme/noise ratio of 55dB when the recording is made with clean heads on an unworn tape.

Though a.c. bias of critical value reduces non-linear distortion and the attenuation distortion due to gap effect (in the recording head) there are still a number of factors in the recording system which tend to result in frequency discrimination.

(1) *Self-demagnetization of the Coating*

The recording is made in the form of a series of magnets, each half a recorded wavelength long. As shown in Appendix 1, self-demagnetization is greater the smaller the ratio of length to cross-sectional area of the magnets induced in the tape, i.e., self-demagnetization is greater the higher the recorded frequency—up to a point. (A limiting factor is that the effective cross-sectional area decreases at high frequencies because high frequencies tend to be recorded in the outermost layers of the coating.

(2) *Decreases in Effective Permeabilities*

This applies to both the head and the tape with increase in frequency. Inspection of a loop tracer of the major and minor hysteresis loops when the sum of two differing frequencies is applied to the magnetizing coil shows that at the higher frequency the effective permeability of the material under test is much less than at the lower, see Fig. 5. Many early papers attributed the major part of the h.f. loss in the magnetic recording response to self-demagnetization. It now appears that these conclusions were inaccurate: self-demagnetization probably contributes only a small part of the total loss and the relevant magnetic property is the permeability[3].

(3) *Erasing Effect of Bias Flux*

The apparent erasing effect of the bias flux on the right-hand side of the spread of the flux in the tape over the recording head gap. This is greater the higher the recorded frequency.

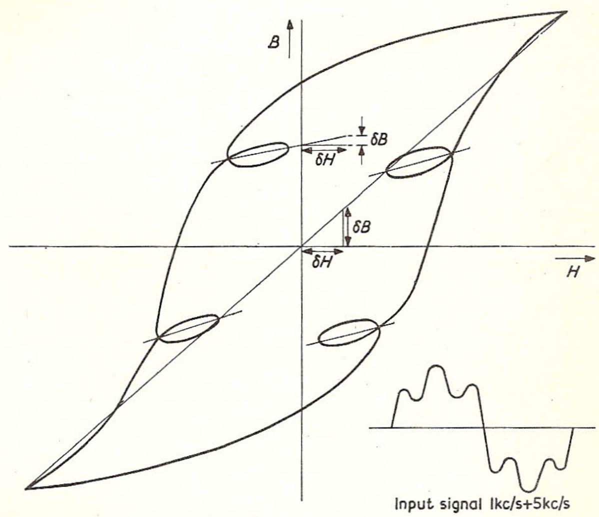


Fig. 5. Minor hysteresis loops formed on major loop when magnetizing signal contains the fifth harmonic of the fundamental

(4) *Losses in the Recording Head*

(a) Each time the magnetizing current in the recording head is reversed a heat loss due to hysteresis is produced. This loss is proportional to the area contained within the hysteresis loop and to frequency (the higher the recorded frequency the more the reversals of the magnetizing current). The attenuation due to this effect is kept to a minimum by using Permalloy for the core.

(b) The recording and bias fluxes tend to induce eddy currents in the core which give rise to lines of force which oppose the flux inducing them and dissipate energy in the form of heat. The loss is kept small by laminating the core.

In modern high-quality heads, the attenuation due to both these effects is very small, $<$1dB at 15kc/s.

(5) *Frequency Discrimination of the Leakage Field in the Tape on the Right-hand Side of the Gap in the Recording Head*

Nearly all the magnetizing flux in the tape coating over the gap in the recording head is concentrated in a small area which spreads only marginally beyond the sides of the physical gap. However there are some leakage lines which, on the right-hand side, have a longitudinal component which aids or opposes the already induced magnetization (see Fig. 6(a) and (b)). As shown, the leakage flux has a longitudinal component which aids low frequencies and tends to attenuate high frequencies. This effect is minimized by making the recording flux as sharply defined as possible, by using a narrow shim in the recording head gap. (*circa* 1 mil or less).

The recording losses detailed above (except the iron losses in the core of the recording head and the changes in the effective permeability which depend upon frequency only) are all dependant both upon the frequency recorded and upon the tape speed, because the length of the induced magnets in the tape is always $\frac{1}{2}\lambda_r$ (where λ_r is

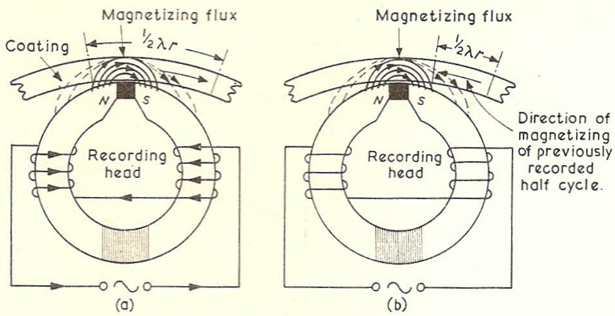


Fig. 6. Flux distribution

(a) When low frequencies are recorded, the leakage flux (shown dotted) has a longitudinal component in phase with the magnetization already induced in the coating. (b) When high frequencies are recorded, the longitudinal component of the leakage flux is in opposition to the internal flux in the tape over the previously recorded half cycle

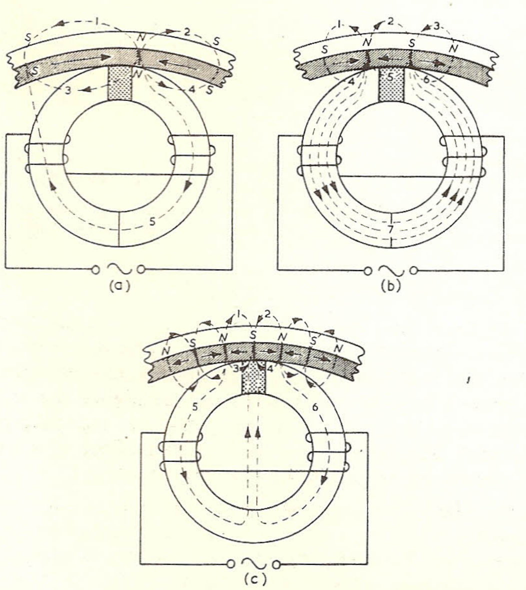


Fig. 7. Flux paths in the vicinity of a replay head when reproducing various frequencies

(a) At very low audio frequencies: E_o *falls off at more than 6dB/octave as frequency is reduced. (b) In mid-audio frequency range (100 to 4 000c/s):* $E_o = N(d\Phi_c/dt)$, *i.e., rises 6dB/octave. (c) At the first extinction frequency:* E_o *is at a minimum. The numbers refer to the various available flux paths. The flux, Φ, is always equal to the m.m.f. of the magnets in the tape divided by the reluctance, S, of the given path*

the recorded wavelength $= u/f$ where u is the tape speed and f is the frequency). Furthermore the amount of equalization required to offset these losses is determined by the type of head used and also the type of tape coating. In professional recorders the recording equalization is always variable and the usual procedure is to replay a test tape upon which a standard frequency run has been recorded, adjusting the replay equalization to give a level response. The replay chain thus calibrated is then used to measure the level reproduced when recording and replaying a frequency run. The recording equalization is then adjusted to give a flat overall response.

Bass and Treble Losses on Playback

Reproduction is effected by passing the recorded tape, at the same constant speed as used in recording, over the gap in a ring-type replay head. The varying magnetization in the tape coating induces changing lines of force in the replay head. The output voltage induced at the terminals of the coil depends upon the rate of change of the flux induced in the core and is therefore (over much of the audio spectrum) proportional to the frequency recorded. Over this frequency range the unequalized output voltage therefore rises at 6dB/octave, and, to produce a linear output, the reproducing equalizer must provide equivalent bass boost. At very low frequencies where the recorded wavelength is long compared with the gap in the replay head, a smaller proportion of the flux threads the core (see Fig. 7(a)). The unequalized output voltage therefore falls off at more than 6dB/octave with decrease in frequency in this region. Additional bass boost in the reproducing chain to compensate for this would tend to bring up hum and rumble components, due to the tape drive, and it is usual to include the necessary extra bass boost in the recording chain.

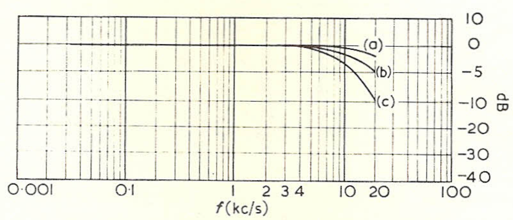


Fig. 8. Curves showing effect of gap losses on replay response

(Note: losses shown presume effective gap length 10 per cent wider than the physical gap)

Curve (a), gap length 0·09 mils, speed 7½in/sec
Curve (b), gap length 0·09 mils, speed 3¾in/sec
Curve (c), gap length 0·25 mils, speed 7½in/sec

At high frequencies where the recorded wavelength approaches the effective gap length in the replay head, the fluxes in the two halves of the core (see Fig. 7(c)) tend to be in anti-phase. This produces a minimum in the response when the recorded wavelength equals the effective gap length (about 15 to 20 per cent longer than the physical gap length). The frequency at which this minimum occurs is called the extinction frequency. With a physical gap in the replay head of 0·25mil—still standard on many professional-type machines in this country—the extinction frequency is about 23kc/s when the tape speed is 7·5in/sec. The loss due to gap effect has been shown to be equal to

$$20 \log \frac{\lambda_r \sin(\pi\delta/\lambda_r)}{\pi\delta}$$

where δ is the effective gap length—in this case approximately 0·30mil. A curve showing the effect of gap loss on unequalized output voltage is shown in Fig. 8.

At half the extinction frequency the loss due to this effect is only about 3dB. With such a gap length some treble boost is necessary to offset gap effect if a linear response up to 15kc/s is required. With a modern head, with a physical gap length of 0·09mil, the effective gap length is only approximately 0·1mil, the extinction frequency is raised to 75kc/s and the loss in the audio spectrum is negligible[1]. However it is found that (at any rate with most of the tapes now available) it is not possible to use as much a.c. bias into the recording head if this additional high frequency response is to be realized—because at 7½in/sec the erasing effect of the bias current is quite pronounced at frequencies above 10kc/s. This does mean, of course, that the proportion of non-linear distortion is raised to a degree that makes it more noticeable than can be tolerated in professional-type recorders. The solution must be with the tape manufacturers—and indeed some tapes are becoming available which require less a.c. bias than hitherto.

Some tape recorder manufacturers prefer not to decrease the bias, but instead increase the treble boost in the recording chain by the requisite amount to offset the partial erase of the bias. This solution increases the risk of overload distortion at high frequencies, i.e., it reduces the maximum level that can be tolerated on recording. This in its turn tends to worsen the programme/noise ratio.

Another factor to be considered is that if the gap length in the reproducing head is made smaller to improve the high frequency response, it is bound to raise the frequency at which the bass fall off with reduction in frequency begins to bring the unequalized output voltage down perilously near to the inherent background noise. The extent to which very low frequencies can be satisfactorily equalized without increasing the hum and rumble content in the output to a noticeable degree is limited. This drawback can be minimized by more careful attention to the tape drive system—but, of course, improvements in this direction can be costly and difficult to arrange.

When a recording is made with constant current into the recording head and correct h.f. bias, there is, in the low frequency range from 40c/s to 500c/s, a divergence from the expected 6dB/octave slope of the unequalized voltage output from the replay head. The amount of the divergence seems to depend upon the type of replay head used. When a non-magnetic conductor is used as the replay head, the divergence, taking 500c/s as a convenient reference point, is of the order of 2dB at 40c/s—the response rising to this extent with decrease in frequency. When a conventional ring-type head is used the divergence increases to 3½dB at 40c/s. The discrepancy therefore seems to be partly a function of the configuration of the ring-type replay head and partly to some property of the ring-type recording head which is still under investigation. Below 40c/s the output voltage falls off rapidly for the reason described in a previous paragraph.

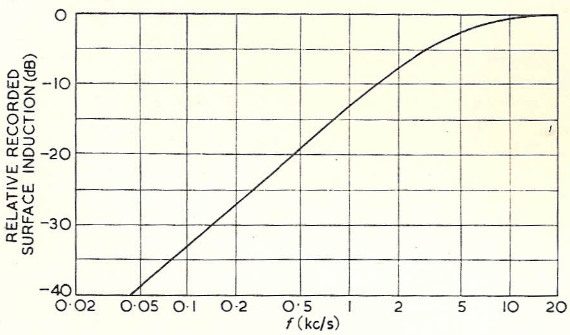
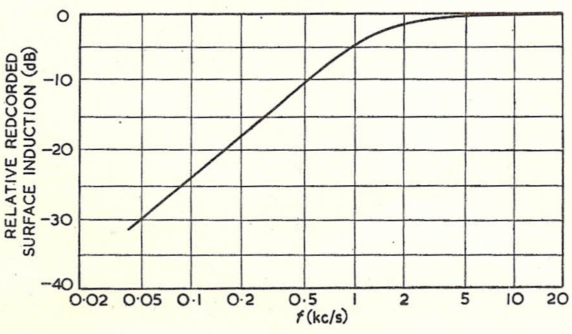


Fig. 9. British Standard 1568:1960 tape recording characteristic for 15in/sec recording (35μsec)

Fig. 10. British Standard 1568:1960 tape recording characteristic for 7½in/sec recording (100μsec)



The British Standard

In the British Standard 1568 : 1960 the recording characteristics for 15in/sec and 7½/sec are as follows:

(a) *Recording at 15in/sec.* With constant voltage applied to the input of the recording chain, the curve of recorded surface induction (in this connexion the term surface induction means the normal surface induction, that is to say the flux directly at right-angles to the surface of the tape) versus frequency shall rise with increasing frequency in conformity with the admittance of a series combination of a capacitance and a resistance having a time-constant of 35μsec. See Fig. 9. The approximate relative values are given in Table 1.

(Note: The corresponding reproducing characteristic is that which gives a flat response when reproducing a sound track recorded with the relative surface inductions stated above.)

(b) *Recording at 7½in/sec.* With constant voltage applied to the input to the recording chain, the curve of recorded surface induction shall rise with increasing frequency with the admittance of a series combination of capacitance and resistance having a time-constant of 100μsec. See Fig. 10. The approximate values are given in Table 2. (Note: The corresponding

TABLE 1
35 microseconds

FREQUENCY (c/s)	LEVEL (dB)
40	−41·11
50	−39·18
60	−37·59
100	−33·16
200	−27·14
300	−23·63
400	−21·15
500	−19·23
700	−16·35
1 000	−13·36
2 000	− 7·90
3 000	− 5·18
4 000	− 3·60
4 547·3	− 3·01
5 000	− 2·62
6 000	− 1·97
7 000	− 1·53
8 000	− 1·22
9 000	− 0·99
10 000	− 0·82
12 000	− 0·58
15 000	− 0·38

TABLE 2

100 microseconds

FREQUENCY (c/s)	LEVEL (dB)
40	−32·0
50	−30·01
60	−28·48
100	−24·05
200	−18·08
300	−14·65
400	−12·26
500	−10·47
700	− 7·90
1 000	− 5·48
1 591·55	− 3·01
2 000	− 2·13
3 000	− 1·08
4 000	− 0·64
5 000	− 0·42
6 000	− 0·29
7 000	− 0·22
8 000	− 0·17
9 000	− 0·13
10 000	− 0·11
12 000	− 0·08
15 000	− 0·05

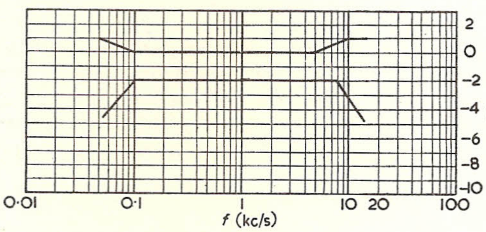


Fig. 11. Tolerances on recorded levels 15in/sec

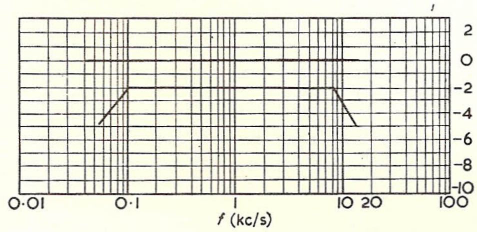


Fig. 12. Tolerances on recorded levels and reproducing equipment response 7½in/sec

reproducing characteristic is that which gives a flat response when reproducing a sound track recorded with the relative surface inductions stated above.)

(c) *Recording at 3¾in/sec.* No recommendation is made since proposals are under consideration to change the I.E.C. recommendations of 200μsec.

TOLERANCES ON RECORDED LEVELS

Sound tracks on magnetic tape shall be recorded to the characteristics specified within the following tolerances.

(a) For recording at 15in/sec as in Fig. 11.

(b) For recording at 7½in/sec as in Fig. 12.

(NOTE. These tolerances are those specified by the International Radio Consultative Committee for recordings on magnetic tape used for programme interchange between broadcasting organizations.)

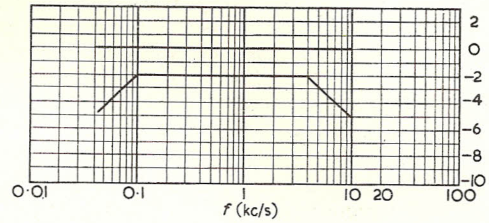


Fig. 13. Tolerances on reproducing equipment 15in/sec

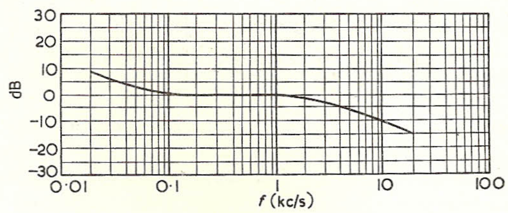


Fig. 14. The N.A.B. recording characteristic (signal to be recorded on the tape at 7½in/sec)

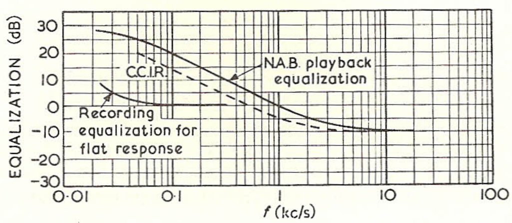


Fig. 15. The N.A.B. tape equalization when reproducing at 7½in/sec (19·05 cm/s)

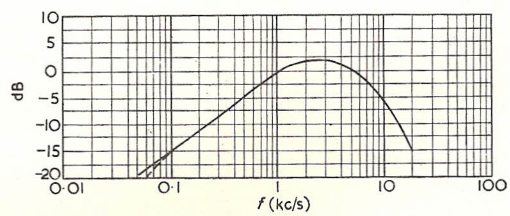


Fig. 16. Unequalized replay response of a tape recorder at 7½in/sec when the replay gap is 0·25 mil.

The rising slope is due to the fact that—over this range—the output is proportional to the rate of change of flux in the core of the head. The fall off is due to the various factors which tend to attenuate the higher audio frequencies: self-demagnetization, changes in effective permeability, gap effect and head losses

TOLERANCES FOR REPRODUCING EQUIPMENT

When professional grade reproducing equipment reproduces a sound track having the relative surface inductions specified, then its output shall be independent of frequency within the following tolerances.

(a) For 15in/sec as in Fig. 13.

(b) For 7½in/sec as in Fig. 12.

The N.A.B. standard for 15in/sec (38·1cm/sec) is 50μsec/3 180μsec and though the differences are, in the main, less than the tolerances mentioned above, there is a difference of 4·3dB at 40c/s and 2·5dB at 10kc/s.

There is a more marked difference between the British

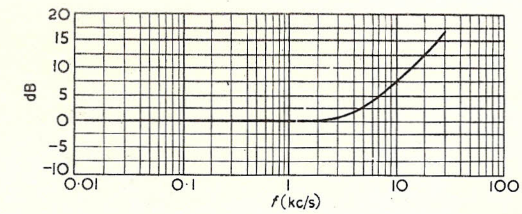


Fig. 17. Typical curve for high frequency attenuation due to changes in effective permeability and self-demagnetization when the tape speed is 15in/sec

Standard and N.A.B. standards for 7½in/sec (19·05cm/sec). The effective N.A.B. recording characteristic for this speed is shown in Fig. 14, though N.A.B. defines only a reproducing characteristic. This is shown in Fig. 15 solid curve. On the same graph the effective replay response, when the recording characteristic is that stipulated in the British Standard, is shown dotted.

How the Surface Induction is Measured

The open-circuit voltage developed in a ferromagnetic reproducing head depends on the surface induction on the tape while it is in contact with the head. It has been found that, provided a coated high coercity tape is used, the surface induction in free space will be altered, when the tape is placed in contact with the head, by an approximately constant factor over the whole range of wavelengths. Under these circumstances the relative surface induction at different frequencies can be measured by at least three methods that are described in Appendix 3. From such measurements the departure of the responses of a reproducing head from the ideal can be defined and consequently a standard replay chain can be established.

In both the N.A.B. Standard and the implied equalization to conform with the new British Standard Recording Characteristic, the replay response falls at 6dB/octave over a certain range of frequencies and then becomes approximately flat. The crossover frequency (the frequency at which the response curve is 3dB away from the flat response) is 3 180c/s in the case of the N.A.B. characteristic for 7½in/sec and 1 590c/s in the case of the British Standard and this is at first sight rather puzzling. In fact various playback characteristics are feasible (at a given tape speed) providing that the recording response is suitably varied.

The reason why, with both standards, most of the bass equalization is in the replay chain is that if it were put into the recording chain the tremendous amount of bass boost (over 30dB at 7·5in/sec and 20dB or more at 15in/sec) required to produce a flat response would greatly overload the tape and produce excessive distortion.

The required treble boost is divided between the recording and replay chains because to put it all into the recording chain would greatly increase the risk of overload distortion at the treble end and to put it all into the replay chain would unduly accentuate tape hiss and noise in the reproducing amplifier. Another reason for putting some of the treble boost in the replay chain and some in the recording chain is that the gap and iron losses in the replay head will vary with the type of head used, as will the bias erase effect and iron losses in the recording head.

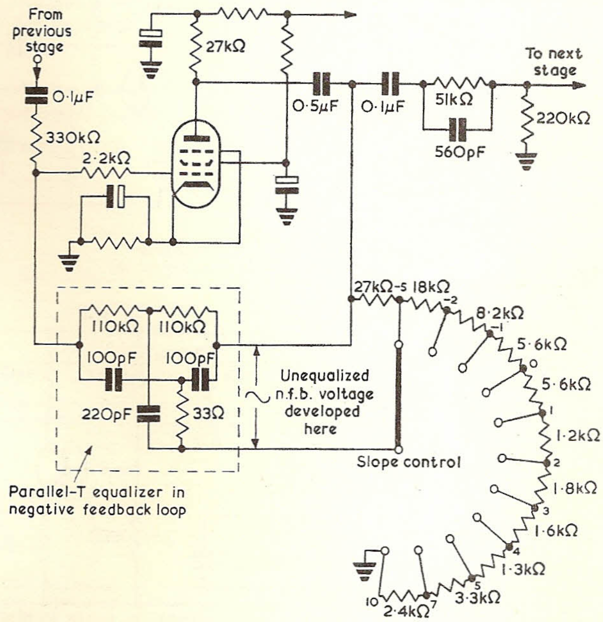


Fig. 19. Simplified circuit of the parallel-T equalizer in the BTR/2 tape recording amplifier (7½in/sec)

(Reproduced by courtesy of E.M.I. Ltd)

Fig. 18. Stage incorporating variable current negative feedback

The negative feedback resistance in the cathode ($R_B + R_1$) is shunted by the series tuned circuit LCR_S. The negative feedback will be least at the resonant frequency of the tuned circuit

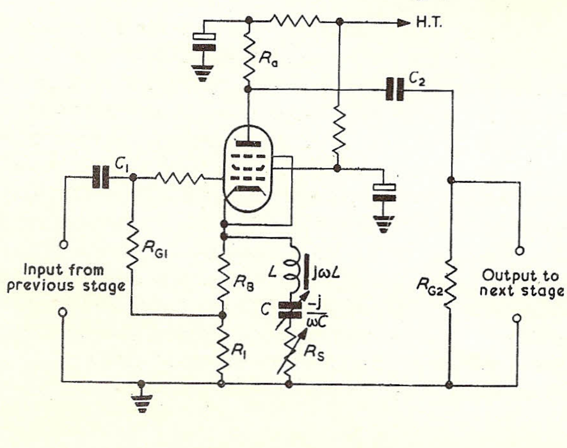
The feedback factor, $\beta = (Z_C/R_a') \cdot (+\mu)/\mu$

$$\text{where } Z_C = \frac{(R_1 + R_B)[R_S + j(\omega L - 1/\omega C)]}{R_1 + R_B + R_S + j(\omega L - 1/\omega C)}$$

$$\text{and } R_a' = \frac{R_a(R_{g2} - jX_{C_2})}{R_a + R_{g2} - jX_{C_2}}$$

and μ *= amplification factor of valve*

The normal gain ($g_m R_a'$) *will be reduced to* $\dfrac{g_m R_a}{1 + \beta g_m R_a}$



Methods of Obtaining Equalization

All equalizers are, of course, networks containing both reactance and resistance, so designed that they are frequency discriminating, i.e., they provide more attenuation to some frequencies than to others. Equalizers may be inserted directly in the programme chain or incorporated between stages in the amplifiers. They may also be included in feedback loops, where it is claimed they achieve less distortion.

As simple two element networks containing reactance and resistance can give maximum frequency discrimination of only less than 6dB/octave, several in series would be necessary. (Over 20dB of treble boost for instance is required to achieve a flat response at 7½in/sec). This increases the insertion loss at frequencies beyond the

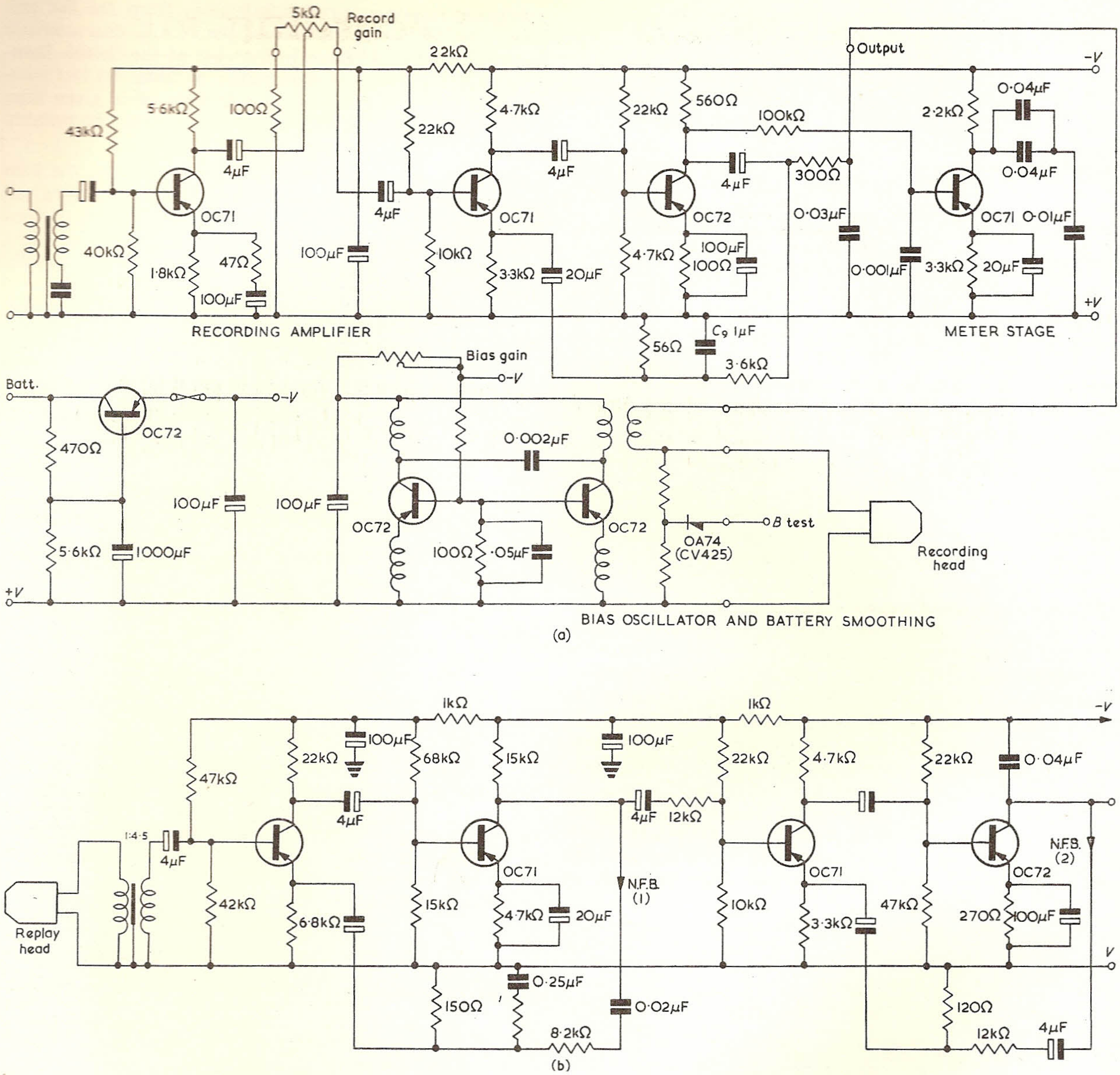


Fig. 20(a). Tape recording amplifier using transistors (BBC recorder RD4/1)
(b). Tape replay amplifier (BBC RD4/1)

The necessary frequency correction is obtained by the reactive elements in the negative feedback loops

turnover point and may necessitate another stage or two in the amplifier. The alternatives are to use (a) a tuned circuit (which involves careful design and screening of the coil to prevent hum pick-up or (b) a parallel−*T* circuit in the feedback loop. Typical circuits are shown in Figs. 18 and 19.

The theory of the parallel—*T* is discussed in Appendix 2. The advantages of the latter are that the insertion loss beyond the turnover point is comparatively small, while the components are small and cheap, occupy little space and can easily be made uniform. Moreover there are no discontinuities of slope as the slope control is varied and there is no coil to cause risk of hum pick-up.

As transistor recorders are becoming increasingly in use, typical transistorized recording and replay amplifiers are shown in Fig. 20.

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Equalization for Tape Recording and Reproduction

By P. J. Guy*

(Part 2)

Appendix

(1) Self-demagnetization

When a magnetizing force is applied to a specimen of ferrous material, the magnetizing field gives rise to an internal field in the specimen. In general, the internal field is in opposition to the magnetizing field creating it and causes a reduction in the intensity of the effective magnetizing field and a corresponding reduction in surface induction. This effect is called 'self-demagnetization'. It can be shown that the size of the demagnetizing forces is governed by the ratio of length to cross-sectional area of the magnetized part of the specimen.

In a recorded tape, the magnetizing and demagnetizing fields may have very different distributions through the depth of the tape and a precise calculation of the self-demagnetization loss is not possible. The losses due to this effect are, however, linked with recorded wavelength ($\lambda_r = u/f$ where u is the tape speed and f is the frequency), because the lengths of uni-directional magnetization (always equal to $\frac{1}{2}\lambda_r$ at any given frequency) are shorter the higher the frequency recorded.

Comparative hysteresis loops for long and short specimens of the same material and of the same cross-sectional area are drawn in Fig. 21. It will be observed that the effect of self-demagnetization is two-fold:

(a) To produce the same degree of magnetization while the magnetizing force is still applied, the required magnetizing force is greater the shorter the specimen (of given cross-sectional area).

(b) After any given magnetizing force has been applied and removed, the remanent magnetization is lower the shorter the specimen.

Some idea of the machinery of self-demagnetization may be gathered from considering a magnetic circuit in the form of a ring with a small gap in it[5]. In such a case, the flux in the gap (assuming no leakage) must be equal to the flux in the magnet, i.e.,

$$\Phi_G = \Phi_M \qquad (1)$$

where Φ_G = flux in the gap
and Φ_G = flux in the magnet
and since, by definition, $\Phi = BA$

$$B_G A_G = B_M A_M \qquad (2)$$

where B_G = flux density in the gap, B_M = flux density in the magnet and A_G and A_M are the cross-sectional area of the gap and the magnet respectively. If leakage be taken into account equation (2) becomes

$$F B_G A_G = B_M A_M \qquad (3)$$

where F is leakage constant, greater than one, which can be calculated. Nomographs are available from which the value of F (which varies between 2 and 10), can be determined, if the form of the magnetic circuit is known.

* *BBC Engineering Training Department*

Solving for B_G,

$$B_G = \frac{B_M A_M}{F A_G} \qquad (4)$$

Again assuming no leakage, the magnetomotive force measured across the gap must be equal to the magnetomotive force measured round the magnet, i.e.,

$$M_G = M_H \qquad (5)$$

where M = magnetomotive force, and since $M = HL$, where H is the magnetic field strength and L is the length

$$H_G L_G = H_M L_M \qquad (6)$$

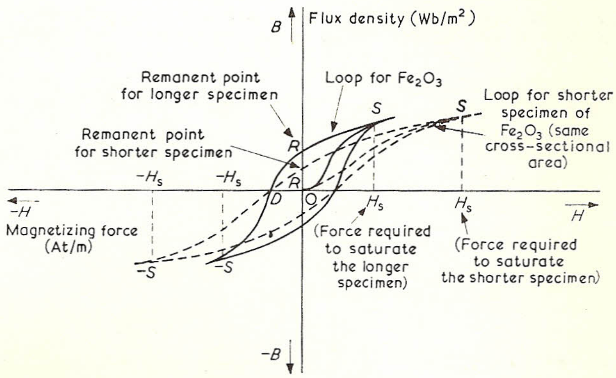


Fig. 21. Comparative loops

Two specimens of same material and equal cross-sectional area—one long, the other short. The shorter specimen requires a large magnetizing force for a given degree of remanent magnetization. Moreover the remanent point is lower the shorter the specimen of given material and constant cross-sectional area

If leakage be taken into account equation (6) becomes

$$f H_G L_G = H_M L_M \qquad (7)$$

where f is a leakage constant greater than one, which can also be calculated. The value of f varies between 1·2 and 1·5 and therefore 1·35 is a good engineering 'guess' for this constant for almost any permanent magnet circuit.

But in air $H = (B/\mu_o)$ so equation (7) may be re-written as

$$(f B_G L_G/\mu_o) = H_M L_M \qquad (8)$$

Equation (8) may be re-written as

$$B_G = (\mu_o H_M L_M / f L_G) \qquad (9)$$

Combining equations (4) and (9)

$$\frac{B_M A_M}{F A_G} = \frac{\mu_o H_M L_M}{f L_G} \qquad (10)$$

and from equation (10)

$$B_M = \mu_o H_M \cdot \frac{F L_M A_G}{f L_G A_M} \qquad (11)$$

If the curve of equation (11) be plotted against co-ordinates B_M/μ_0 and H_M it will be found to be a straight line through the origin, of slope $= FL_MA_G/fL_GA_M$.

This curve is called the *shearing line* and its slope determines the intensity of magnetization which will remain in the specimen after the magnetizing force is removed.

It is obvious, that, the shorter the magnet, the less steep will be the slope, i.e., the greater the self-demagnetization. In the practical case of recorded magnetic tape the slope of the shearing line can only be determined empirically but the results obtained confirm the theory that the losses depend upon the dimensional and magnetic constants of the tape. They also emphasize the important fact that the losses do not increase indefinitely with decrease of recorded wavelength but approach a limiting value[4] as the wavelength becomes small compared with the effective depth of magnetization within the tape.

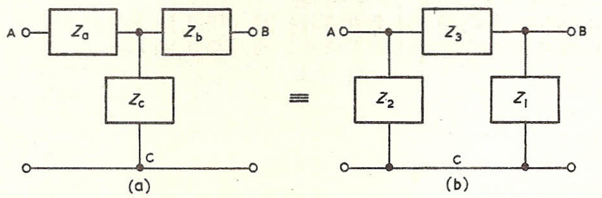
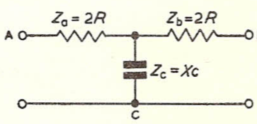


Fig. 22. The delta network (b) is the exact equivalent of the star network (a) if Z_1, Z_2 and Z_3 are given the values calculated from the formula



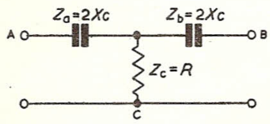
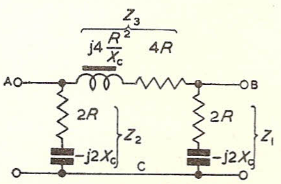


Fig. 23. Star Network, T_1

Fig. 24. Star Network, T_2



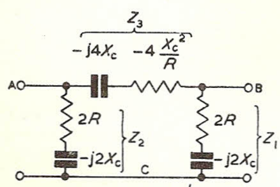


Fig. 25. The delta network equivalent to Star Network T_1 (Fig. 23)

Fig. 26. The delta network equivalent to Star Network T_2 (Fig. 24)

An important point is that when the tape reaches the reproducing head it is once more in contact with a high-permeability core and the losses introduced after it left the recording head are to some extent decreased.

Daniel[4] has calculated that if the recorded magnetization is uniformly distributed over the cross-section of tape, the mean coefficient of self-demagnetization is given by

$$z = -(H_x/j_x) = 4\pi \left\{1 - \frac{\lambda_r}{2\pi C}\left[1 - \exp\frac{-2\pi C}{\lambda_r}\right]\right\}$$

Where H_x = mean value of the longitudinal component of field strength created by the tape coating.

j_x = longitudinal component of the intensity of magnetization recorded in the tape.

λ_r = recorded wavelength.

and C = thickness of the coating.

From this equation it can be seen that when the wavelength is much longer than the tape thickness, the demagnetizing coefficient is very small, but as the recorded wavelength decreases the demagnetization coefficient increases until it approaches a limiting value of 4π (the coefficient corresponding to an infinite sheet of magnetic material magnetized perpendicularly to its plane).

(2) The Parallel-*T*

The parallel-*T* or twin-*T* resistance capacitance network has been used for many years and there is a comprehensive literature on its uses and properties[7–12]. There are many ways of analysing this network and one of these is to use the well known star-delta transform. It can be shown that to find the delta network equivalent to a given star network the following hold true:—

$$Z_1 = \frac{Z_aZ_b + Z_aZ_c + Z_bZ_c}{Z_a}$$

$$Z_2 = \frac{Z_aZ_b + Z_aZ_c + Z_bZ_c}{Z_b}$$

$$Z_3 = \frac{Z_aZ_b + Z_aZ_c + Z_bZ_c}{Z_c}$$

Where Z_a, Z_b and Z_c are the impedances of the three star arms and Z_1, Z_2 and Z_3 are the impedances of the three equivalent delta arms—see Fig. 22.

In the case of the parallel-*T*, in the delta network equivalent to T_1 (Fig. 23).

$$Z_1 = Z_2 = \frac{4R^2 - j4RX_c}{2R} = 2R - j2X_c$$

$$\text{and } Z_3 = \frac{4R^2 - j4RX_c}{-jX_c} = j(4R^2/X_c) + 4R$$

i.e., the delta equivalent of T_1 is as shown in Fig. 25.

In the delta network equivalent to T_2 (Fig. 24)

$$Z_1 = Z_2 = \frac{-4X_c^2 - j4RX_c}{-j2X_c} = -j2X_c + 2R$$

$$\text{and } Z_3 = \frac{-4X_c^2 - j4RX_c}{R} = (-4X_c^2/R) - j4X_c$$

The delta equivalent of T_2 is as shown in Fig. 26.

The complete parallel delta network equivalent to the parallel-*T* is shown in Fig. 27(c).

At resonance $|X_L| = |X_c|$ (approximately)

i.e. $|(4R^2/X_c)| = |4X_c|$

$\therefore\ |R| = |X_c|$

and as $R = (1/2\pi f_r)\,C$, the resonant frequency, $f_r = (1/2\pi RC)$.

At this frequency the circuit is very rejective.

In a particular case where R = 50kΩ and C = 300pF

$$f_r = \frac{10^{12}}{6{\cdot}28 \times 5 \times 10^4 \times 3 \times 10^2} = \frac{10^6}{6{\cdot}28 \times 5 \times 3} = 10\,620\text{c/s.}$$

Ways of Modifying the Slope

There are many ways of modifying the slope. One way is to connect *A* to *B* with a high variable resistance (about 2MΩ). Another way is shown in Fig. 19, where the parallel-*T* equalizer is in a negative feedback loop and the unequalized feedback voltage is taken from a potential divider across the output of a stage. It is also possible to modify the slope by changing the values of *C* and *R*.

G. V. Buckley[7] in a simplified analysis makes use of Bartlett's Bisection Theorem to find an equivalent network in the shape of the familiar Wheatstone type of bridge. The process step by step is shown in Fig. 28.

Step 1 shows the basic parallel-*T* circuit.

Step 2 shows Fig. 1 bisected.

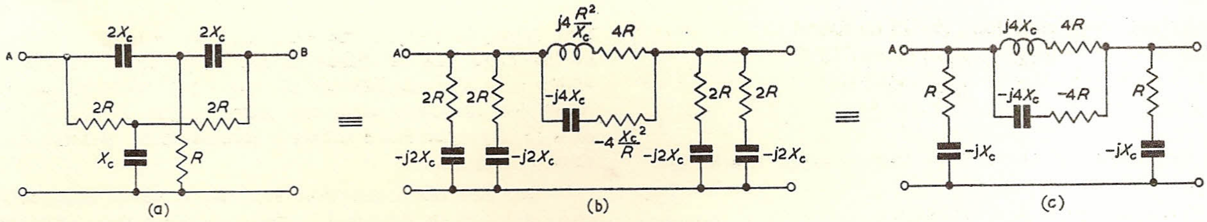


Fig. 27. The complete equivalent of a parallel-T

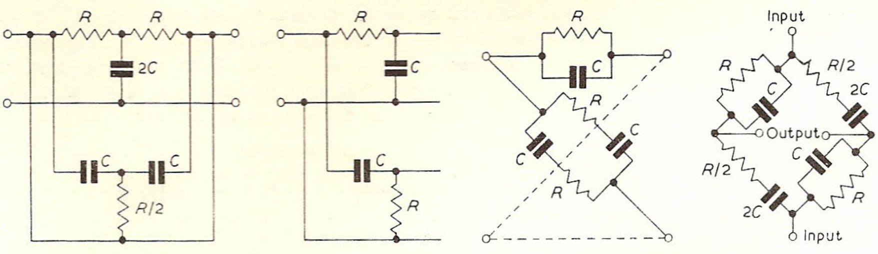


Fig. 28. These diagrams illustrate the transformation of a parallel-T circuit through a lattice to a true bridge

Equation (8) completely defines the network, from which the attenuation and phase characteristics for any set of parameters can be plotted.

Fig. 30 shows normalized attenuation (a) and phase (b) characteristics of the parallel-*T* network.

It is also very desirable to know the input impedance of the network.

Let Z_{in} = input impedance

From Fig. 29

$$Z_{in} = (E/i_1) - R_1 \quad \dots\dots\dots\dots\dots \quad (9)$$

where from equations (1), (2) and (3)

$$i_1 = \frac{E\,(Z_1 + Z_2)\,(Z_1 + Z_2 + 2R_0)}{\Delta} \quad \dots\dots\dots\dots\dots \quad (10)$$

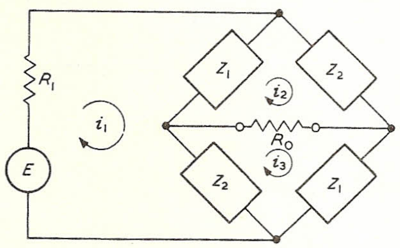


Fig. 29. General bridge circuit

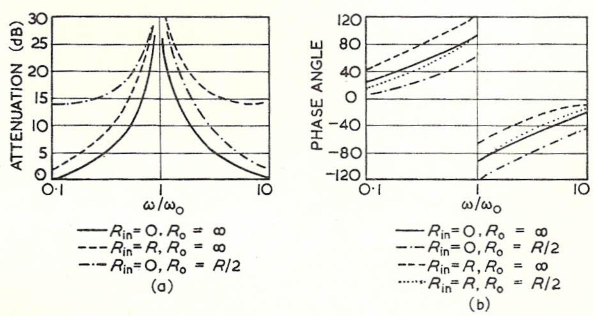


Fig. 30. Normalized attenuation (a) and phase (b) characteristics of parallel-T networks

The Step 3 lattice network is obtained as follows:—

The series arms of the lattice network consist of the input impedance to the network of Step 2 with all the bisected ends short-circuited; while the cross arms of the lattice consist of the input impedance of Step 2 with all the bisected ends open-circuited.

The process could readily stop at this point, as the lattice is a familiar network, but Step 4 is more familiar and more easily understood. Thus Step 4 is the final equivalent network which satisfies the conditions of simplified mathematical analysis and ease of understanding of its mode of operation.

Examination of Fig. 28, Step 4 shows that if the network works from a zero-impedance source into one of infinite impedance, only two equations are necessary for its analysis. If the source and load impedance have finite values then three equations are necessary. This is seen from Fig. 29 where the impedances have been generalized. Although the source and load impedances have been shown as resistors they could also be of the form $R \pm jX$.

From Fig. 29 the mesh equations are:—

$$E = i_1(R_1 + Z_1 + Z_2) - i_2 Z_1 - i_3 Z_2 \quad \dots\dots\dots\dots \quad (1)$$

$$0 = i_1 Z_1 + i_2(R_0 + Z_1 + Z_2) - i_3 R_0 \quad \dots\dots\dots\dots \quad (2)$$

$$0 = -i_1 Z_2 - i_2 R_0 + i_3(R_0 + Z_1 + Z_2) \quad \dots\dots\dots \quad (3)$$

From these equations the determinant is found which is:

$$\Delta = (Z_1 + Z_2)\,[2R_1R_0 + (R_1 + R_0)(Z_1 + Z_2) + 2Z_1Z_2] \quad \dots\dots\dots\dots \quad (4)$$

The output voltage is

$$e_0 = (i_2 - i_3)R_0 \quad \dots\dots\dots\dots\dots \quad (5)$$

where

$$i_2 = \frac{E\,[R_0Z_2 + Z_1(R_0 + Z_1 + Z_2)]}{\Delta} \quad \dots\dots\dots\dots\dots \quad (6)$$

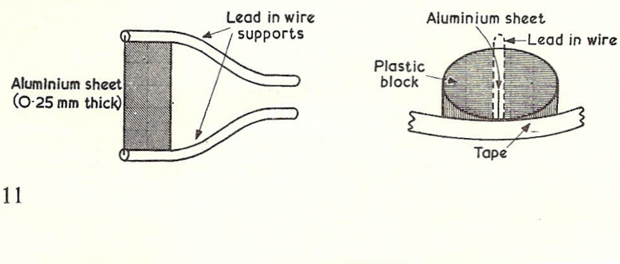
and

$$i_3 = \frac{E\,[R_0Z_1 + Z_2(R_0 + Z_1 + Z_2)]}{\Delta} \quad \dots\dots\dots\dots\dots \quad (7)$$

Substituting equations (6) and (7) into equation (5) gives

$$e_0 = ER_0 \frac{Z_1 - Z_2}{2R_1R_0 + (R_1 + R_0)(Z_1 + Z_2) + 2Z_1Z_2} \quad \dots\dots\dots\dots\dots \quad (8)$$

Fig. 31. Typical construction of non-magnetic reproducing head consisting of a single turn one part of which is made of thin aluminium in a plastic support



Therefore from equations (9) and (10)

$$Z_{in} = \frac{R_0(Z_1 + Z_2) + 2Z_1Z_2}{Z_1 + Z_2 + 2R_0} \quad \text{.............. (11)}$$

(3) Methods of Measuring the Surface Induction on a Tape

There are two ways in which the surface induction/frequency characteristic of a magnetic tape may be measured.

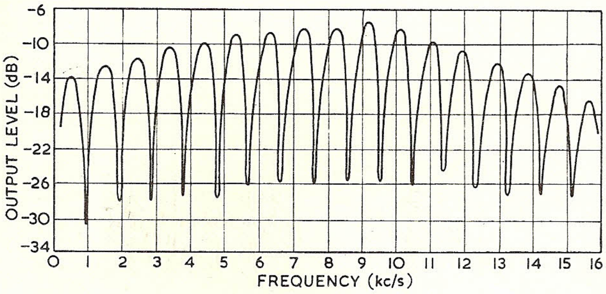


Fig. 32. Typical response curve of a "Long Gap" reproducing head

(1) By the use of a non-magnetic reproducing device such as a single conductor across which the tape is passed. This, of course, is only practicable as a laboratory method. See Fig. 31.

(2) By means of ring-type reproducing head. This necessarily affects the surface induction on the tape in a way that is dependent on the recorded wavelength. The gap in the head can be either of the usual short length (in which case a correction for the gap effect must be made), or of ten or more times the usual length. The response of a long-gapped head shows a succession of maxima and minima (Fig. 32).

When suitable correction has been made for eddy current losses in the head, a curve through the successive maxima bears a direct relation to the relative surface induction on the tape. This curve falls 4dB/octave compared with the curve of surface induction/frequency in air determined by either the non-magnetic reproducing device or by a head with a short gap (i.e., a linear surface induction would be indicated by the fact that the curve joining the respective maxima rose 2dB/octave.)

REFERENCES

1. Burstein, Herman. Equalisation. *Audio 44*, 28 (1960).
2. Axon, P. E. An Investigation into the Mechanism of Magnetic Tape Recording. *Proc. Instn. Elect. Engrs. 99*, 109 (1952).
3. Daniel, E. D., Axon, P. E., Frost, W. T. A Survey of Factors Limiting the Performance of Magnetic Recording Systems. *Proc. Instn. Elect. Engrs. 104B*, 158 (1957).
4. Daniel, E. D. The Influence of Some Head and Tape Constants on the Signal Recorded on a Magnetic Tape. *Proc. Instn. Elect. Engrs. 100*, Pt. 3, 168 (1953).
5. Underhill. Permanent Magnet Design. *Electronics, 16* (Dec. 1943, Jan. and Feb. 1944).
6. Guy, P. J. How to Get the Best out of Your Tape Recorder. (Norman Price (Publishers).)
7. Buckley, G. V. Parallel-T RC Network, Simplified Analysis. *Wireless Engr. 33*, 168 (1956).
8. Stanton, L. Theory and Applications Parallel-T Resistance Capacitive Selective Networks. *Proc. Inst. Radio Engrs. 34*, 447 (1946).
9. Wolf, A. Note on a Parallel-T Resistance-Capacitance Network. *Proc. Inst. Radio Engrs. 34*, 659 (1946).
10. Hillan, A. B. The Parallel-T Bridge Amplifier. *J. Instn. Elect. Engrs. 94*, Pt. 3, 42 (1947).
11. Cowles, L. G. The Parallel-T Resistance-Capacitance Network. *Proc. Inst. Radio Engrs. 40*, 1712 (1952).
12. Brown, D. A. H. The Equivalent Q of Resistance-Capacitance Networks. *Electronic Engng. 25*, 294 (1953).