P.O. Telecommunications
Educational Pamphlet

Telegraphy 1/1
Draft Series

BASIC TELEGRAPH TRANSMISSION THEORY

CONTENTS

Introduction

The propagation of an electric current over a telegraph line is dependent upon the four primary coefficients of the line, namely, resistance, inductance, leakance and capacitance. These coefficients determine the distance over which effective signals may be sent and govern the speed of telegraph working.

If a direct current signal is passed into a telephone or telegraph line, the amount of current reaching the distant end will be reduced or attenuated. If the transmitted current is switched on and off at intervals, the received signal will also be observed to be distorted. This attenuation and distortion is a result of the effect of the primary coefficients on the signal.

The time taken for the current in any circuit containing resistance and capacitance to rise to a given percentage of its maximum value is directly proportional to the product of the total capacitance and total resistance of the circuit. This product (farads x ohms) is termed the "time constant' (CR) of the circuit and is expressed in seconds.

The time constant therefore determines the rate at which the reversals of current i.e. signals, may be repeated into the line without running into each other and becoming indecipherable at the distant end. It is obvious that the lower the value of CR the greater will be the telegraph speed since the signal current will take a shorter time to reach a given percentage of its maximum value. Telegraph speed, which might be measured in, say, words per minute, should not be confused with transmission speed of current, or velocity of propagation measured in miles per second.

The ideal transmission condition in the case of a direct single-current telegraph system would be where the graph of the received current is square topped like the e.m.f. applied - see Fig. 1.

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The nearest approach to this condition will occur when the line is short and the values of inductance, capacitance, leakance and resistance of the line and associated apparatus are negligible. However in telegraph circuits the effect of capacitance cannot be neglected and the ideal case will not occur in practice. Since the capacitance of underground cable circuits is greater than that of aerial circuits, the time constant of an aerial circuit will be less than that of an underground circuit.

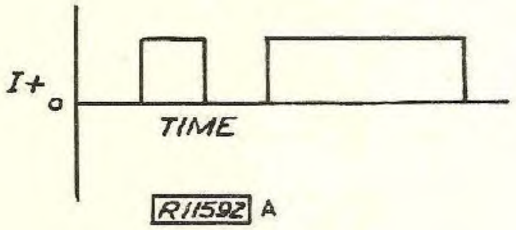

Fig. 1

Telegraph Codes

In telegraph systems, the letters which make up the words to be transmitted are first converted into signals in accordance with a pre-arranged code. There are three main codes in use at present, namely the Morse, Cable and five unit codes.

The Morse Code

The International Morse Code has two elementary signals, generally known as the dot and the dash signals. The difference between these two elementary signals is a matter of duration only, the dash being three times as long as the dot. The letters of the alphabet, together with several special signals and the numerals, are each composed of individual combinations of dots and/or dashes. Certain intervals of time are required for spacing purposes, between elementary signals, letters and words, and these are as follows:-

Between elementary signals - Period equal to the duration of a dot.

Between letters - Period three times the duration of a dot.

Between words - Period seven times the duration of a dot.

The Morse code used in America differs in some respects from the International code; the intervals between the elements of certain letters are of different lengths, and some letters have more than four elements. It will be seen from Fig. 2 that no letter in the International code has more than four elements:-

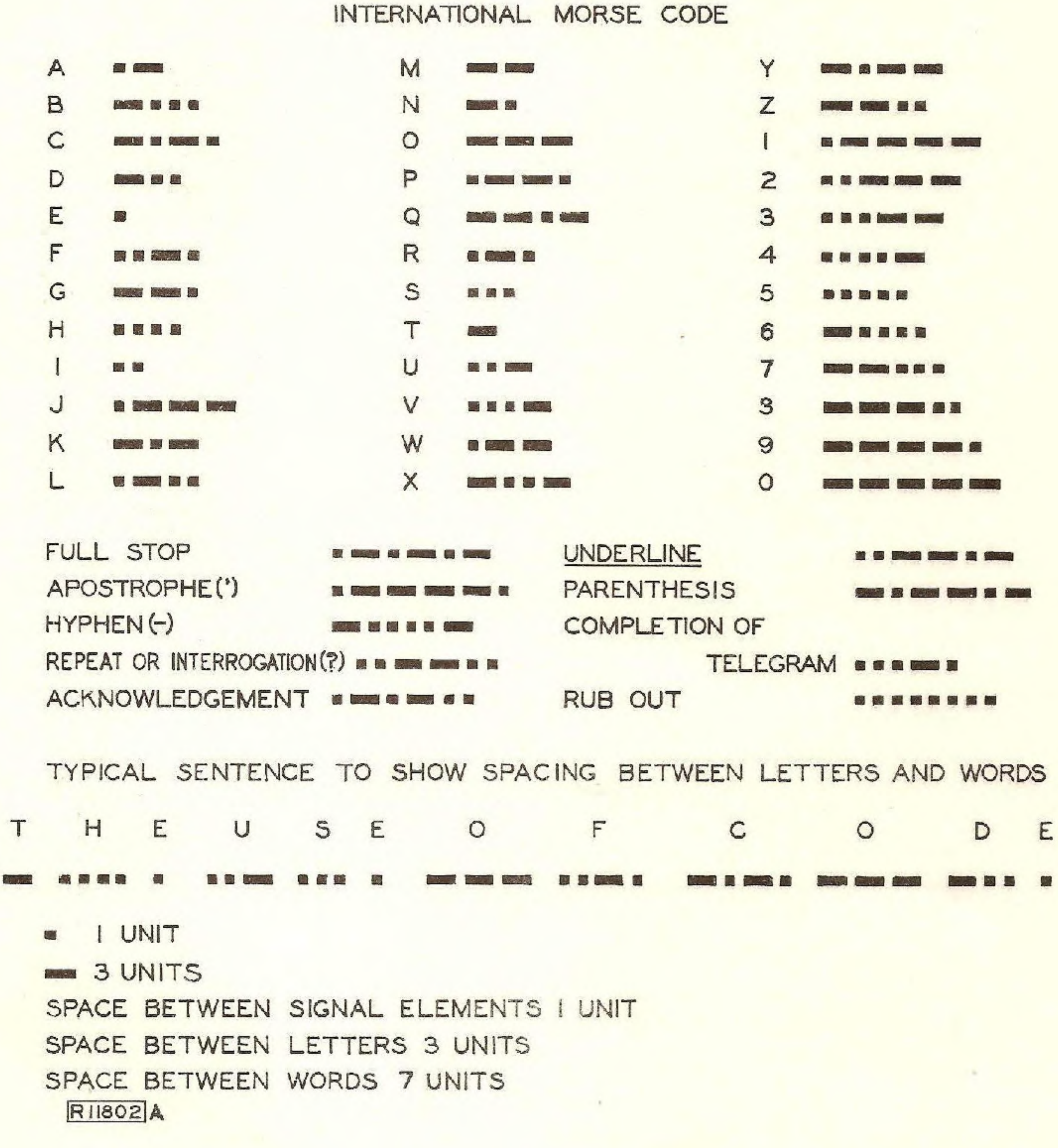

Fig. 2

Comparing the letters "A" (dot, dash) and "B" (dash, dot, dot, dot,) it can be seen that the period of time required to signal "B" is greater than that required to signal "A". The dash and dot signals are sometimes referred to as "mark" signals and the intervals as "space" signals.

Since the shortest signal in the Morse code is one dot and the longest is five dashes, the longest signal is 19 times longer than that of the shortest.

The Cable Code

This code is used extensively by the cable companies on long submarine circuits and is similar to the Morse code except that the dots and dashes are distinguished by their battery potential and not on a basis of time.

In land-line telegraphy the distinction between dots and dashes is in the length of the signal. If the dot is taken as 1 unit in length (or duration) then a dash has a length of 3 units. The space between successive letters is 3 units and between words 5 units.

In submarine telegraphy a dot is represented by a positive current whilst a dash is represented by a negative current. Since the signals are quite different in character, the length of the dash may be shortened to that of the dot and the two signals may still be readily distinguished. The earthing period between signals may be made very short (about $\frac{1}{2}$ or $\frac{1}{3}$ of a unit) the space between letters reduced to 1 unit and the space between words reduced to two units. The result is an increased speed of signalling and from a commercial point of view this is very desirable.

When a short earthing period is given between signals the signals are known as "beat" signals. If this interval is omitted, as it is with some automatic transmitters, the signals are termed "block" signals. Fig. 3 should make clear the differences between land-line morse, beat and block signals. Positive currents (dots) are shown above the centre line and negative currents (dashes) are shown below. The centre line indicates the earthing period.

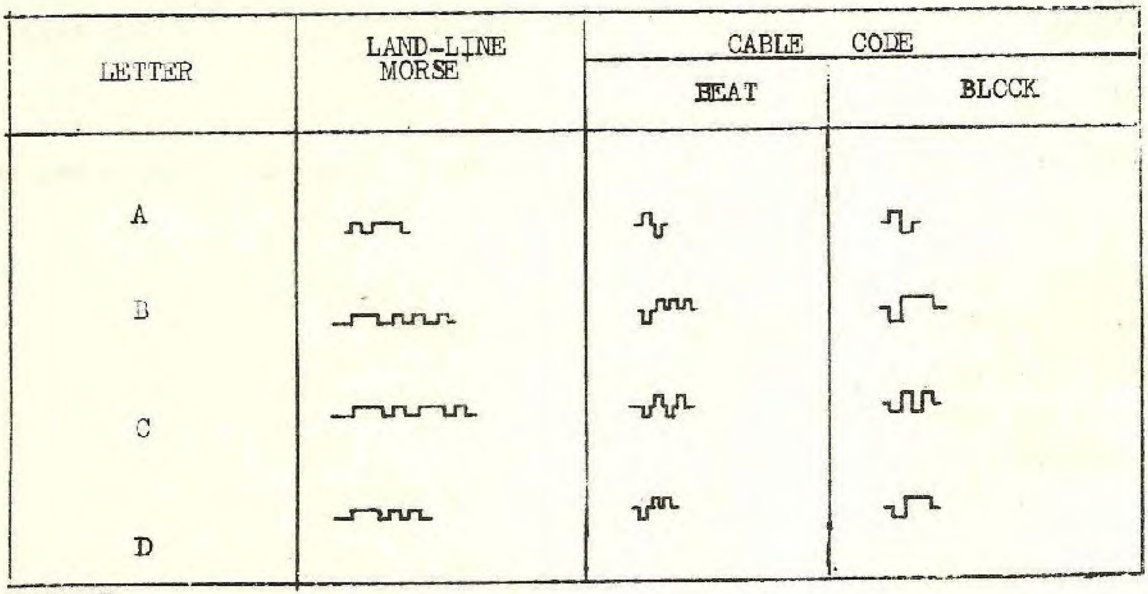

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Fig. 3

The Five Unit Code

In the five unit code, a combination of five current pulses of equal duration is used to form every character.

These pulses are caused by negative or positive potentials (with respect to earth). The negative pulses are termed marking units and the positive are termed spacing units. In the combinations formed there is no interval between the marking and spacing pulses, the space between words being formed by a combination in the same manner as for letters.

It will be apparent then, that in using a five unit code the period of time required for signalling is the same for all characters.

Fig. 4 (a & b) represents graphically two characters formed by the five unit code used for the teleprinter system.

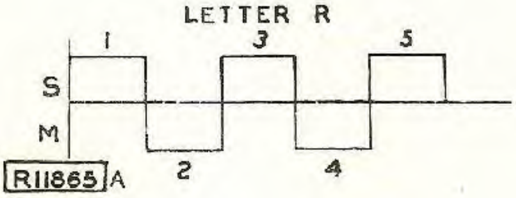


Fig. 4(a)

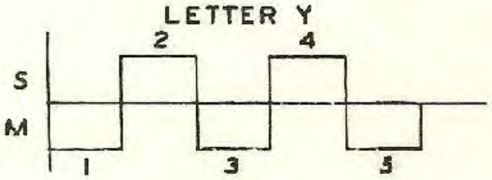


Fig. 4(b)

In this system it is necessary to start the receiving mechanism before the code combination is transmitted and to stop the mechanism again after the combination has been received. In order to do this two additional current pulses are required, one termed the start signal and the other the stop signal. Fig. 5 shows the combinations represented in Fig. 4 with the start and stop pulses added. The start pulse consists of a positive spacing current of one unit in length, and the stop pulse a negative marking current of 1½ units.

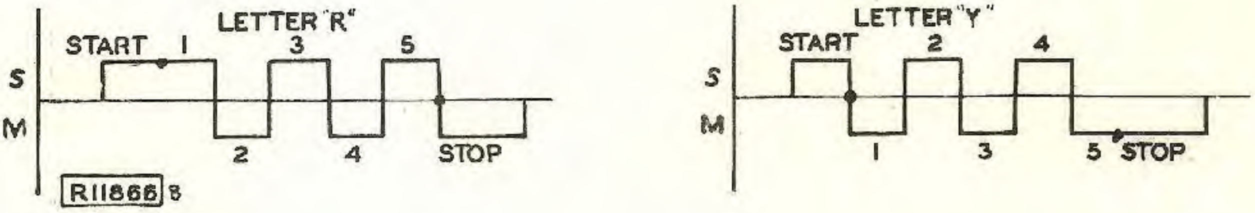
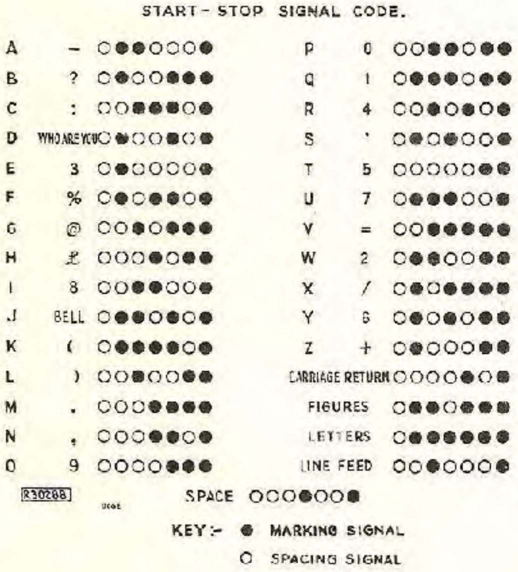


Fig. 5

The five unit code is given in Fig. 6; each character is preceded by a spacing signal, and terminated by the stop element.

It will be seen from Fig. 6 that there are thirty two different character combinations available by the use of the 5-unit signalling code. A much larger number of combinations is, however, required for transmitting special characters known as "secondaries". Most of the teleprinter keys are, therefore, arranged to send two characters. To enable this to be done, two combinations are appropriated, one for operating the letter shift mechanism ("LTRS" key), and the other for operating the figure shift ("FIGS" key) mechanism; the type selecting mechanism is so designed, that all the combinations received between the receipt of the "letter shift" combination and the receipt of the "figure shift" combination cause letters to be printed. After the receipt of the "figure shift" combination the secondary characters are printed until the "letter shift" combination is again received.



START - STOP SIGNAL CODE.

A	–	○●●○○○●	P	0	○○●●○●●
B	?	○●○○●●●	Q	1	○●●●○●●
C	:	○○●●●○●	R	4	○○●○●○●
D	WHO ARE YOU	○●○○●○●	S	'	○●○●○○●
E	3	○●○○○○●	T	5	○○○○○●●
F	%	○●○●●○●	U	7	○●●●○○●
G	@	○○●○●●●	V	=	○○●●●●●
H	£	○○○●○●●	W	2	○●●○○●●
I	8	○○●●○○●	X	/	○●○●●●●
J	BELL	○●●○●○●	Y	6	○●○●○●●
K	(	○●●●●○●	Z	+	○●○○○●●
L	)	○○●○○●●	CARRIAGE RETURN		○○○○●○●
M	.	○○○●●●●	FIGURES		○●●○●●●
N	,	○○○●●○●	LETTERS		○●●●●●●
O	9	○○○○●●●	LINE FEED		○○●○○○●

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SPACE ○○○●○○●

KEY:- ● MARKING SIGNAL

○ SPACING SIGNAL

Fig. 6

Transients

In any telegraph circuit there is a time interval between the application of the signalling voltage to the line and the response of the receiving apparatus. The effects taking place during this interval are known as transients.

The time interval originates from three main causes.

(i) The rise of current in the receiving instrument winding is delayed owing to its inductance.

(ii) The current will not rise immediately to its final value at the receiving end because of the resistance and capacity of the line.

(iii) The actuation of the moving parts of the receiver takes time.

(i) Instrument inductance and its effects

In the case of short overhead and unloaded cable circuits the inductance of the receiver is the main factor in determining this time lag.

The growth of current in a circuit having inductance and resistance may be studied by considering the circuit of Fig. 7. If t = the time in secs. after connecting the battery, then when $t = o$ the instantaneous current $i = o$, also at any instant t seconds after switching on the p.d. across the resistance is iR and the back e.m.f. of self inductance is $-L\frac{di}{dt}$

The following treatment, involving the use of the integral calculus, is given at this stage for the sake of completeness. Readers who have not yet reached this standard are advised to memorize the result obtained.

Applying Kirchhoff's law, the sum of the e.m.f.s round the circuit is

$$iR = E - L\frac{di}{dt}$$

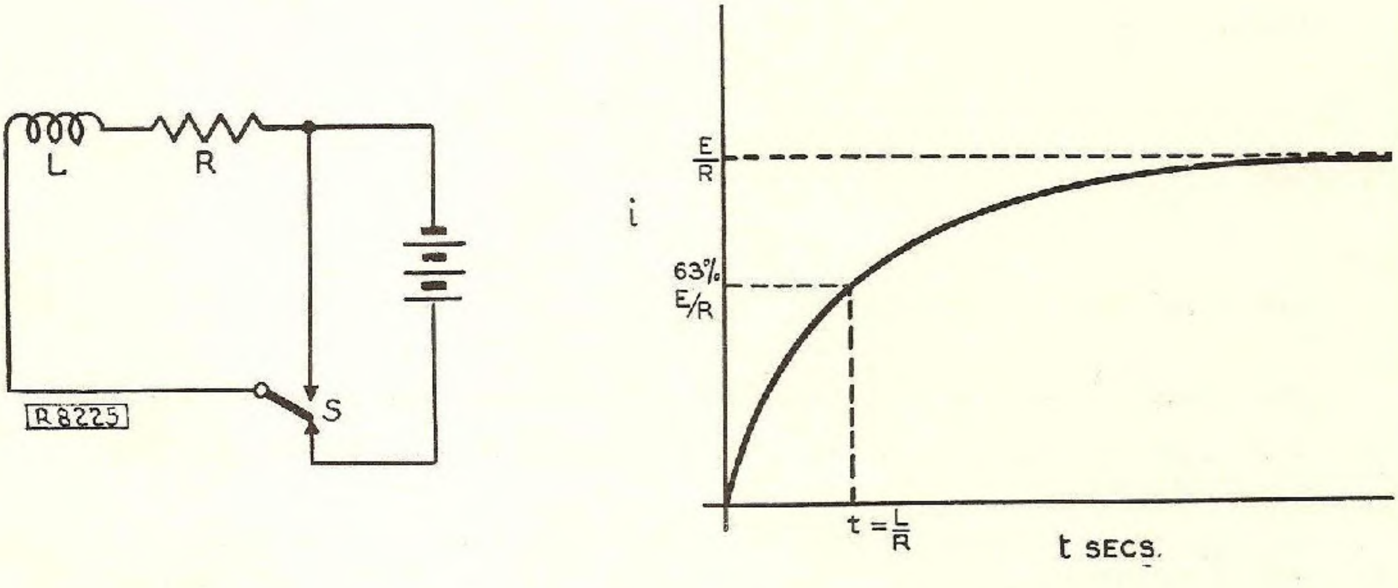


Fig. 7

Rearranging

$$E - iR = L\frac{di}{dt}$$

$$\therefore \qquad \frac{1}{E-iR}\,di = \frac{1}{L}\,dt$$

Integrating both sides,

$$-\frac{1}{R}\log_e(E-IR) = \frac{t}{L} + \text{constant}$$

$$\text{or} \quad \log_e(E-iR) = -\frac{Rt}{L} + k$$

Now when $$t = o, i = o,$$

whence $$k = \log_e E$$

$$\therefore \quad \log_e (E - iR) - \log_e E = -\frac{Rt}{L}$$

$$\log_e \left(1 - \frac{iR}{E}\right) = -\frac{Rt}{L}$$

$$\therefore \quad 1 - \frac{iR}{E} = e^{-\frac{Rt}{L}}$$

thus $$i = \frac{E}{R}\left(1 - e^{-\frac{Rt}{L}}\right)$$

$\frac{E}{R}$ is the final steady value of current according to Ohm's law and theoretically is only reached when the back e.m.f. is zero; then $t = \infty$. The graph of Fig. 7 shows a curve of instantaneous current i plotted against time t.

When $t = \frac{L}{R}$, $$e^{-\frac{Rt}{L}} = e^{-\frac{R}{L}\frac{L}{R}} = e^{-1} = 0.368$$

$$i = \frac{E}{R}(1 - 0.368)$$

$$= \frac{E}{R}(0.632)$$

i.e. 63.2% of its final value $\frac{E}{R}$.

The interval of time $t = \frac{L}{R}$ is known as the time constant of the circuit, and is the time taken for the current to rise to 63.2% of its final value. This is shown on the graph of Fig. 7.

Provided there is a circuit for the induced current upon disconnexion of the applied voltage, the current will die away in a similar fashion, as shown by the decay curve of Fig. 8, the equation of which is:-

$$i = \frac{E}{R}e^{-\frac{Rt}{L}}$$

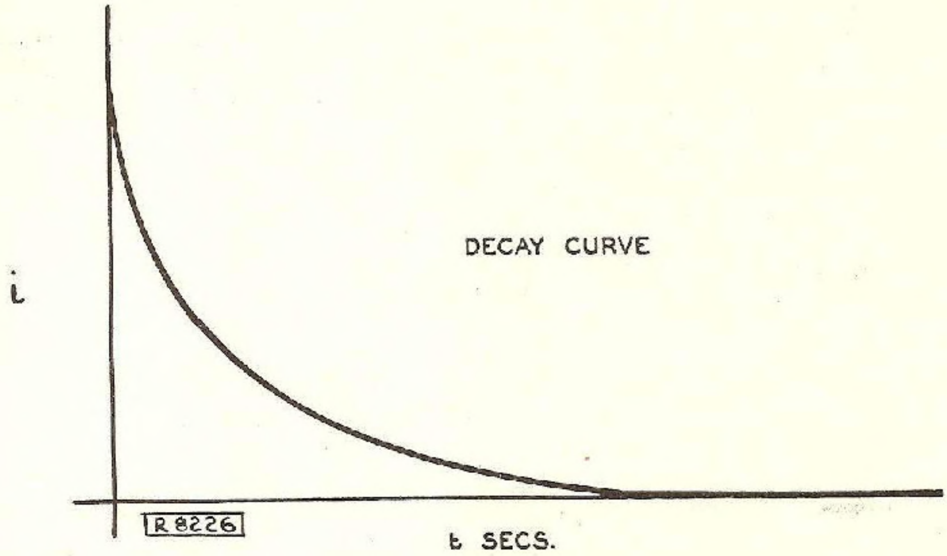


Fig. 8

The rise and fall of double current signals in an inductive receiver are shown in Fig. 9.

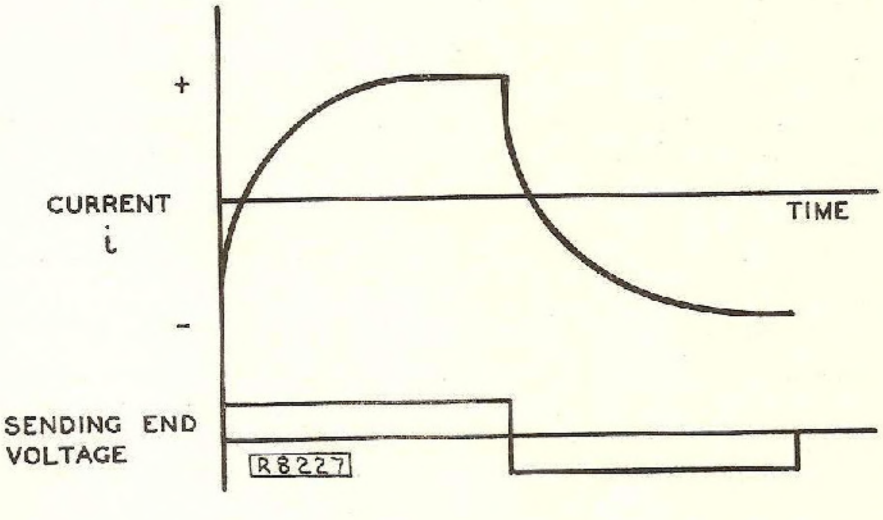


Fig. 9

Effect on Signals

It will now be appreciated that if a series of signals follow each other very quickly, the current in the receiver coils may not reach the maximum value (as found from Ohm's Law) and also may not fall to zero between signal elements. For instance the three dots for the letter S of the Morse Code, sent at high speed, would result in a current curve in the receiver of the form shown in Fig. 10.

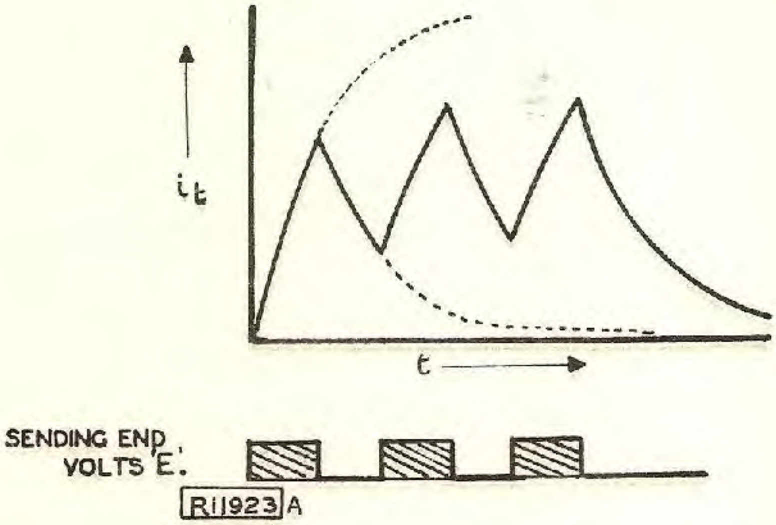


Fig. 10

Under such conditions the receiver would probably fail to respond and the three signals would be reproduced as one continuous signal equal in length to that of the sum of the three dots.

The dotted curves show the rise and fall of current which would occur if the signalling condition (i.e. mark or space) persisted for a sufficient length of time.

The current in the receiver can be made to rise more rapidly by increasing the ratio $\frac{R}{L}$. The equation $i = \frac{E}{R}\left(1 - e^{-\frac{Rt}{L}}\right)$ shows that an increase of $\frac{R}{L}$ will result in reduction of the time t required to reach the nominal operate current of the receiver or relay. Fig. 11 shows the relative rise in current in a certain inductance with three values of series resistance 5000Ω, 1000Ω and 500Ω. The 5000Ω resistor will obviously give improved definition of signals and more rapid response of the relay to changes in current; it will, however, be evident that the steady value of current when the transmitter stands on mark or space will be reduced by the increase in the total resistance of the circuit. The extent to which series resistance may be added is therefore limited by the voltage of the available signalling battery. It should be noted that the curves of Fig. 11 are not obtained with the same voltage, the voltage for the higher resistances being increased in order that the final value of current shall be the same in each case.

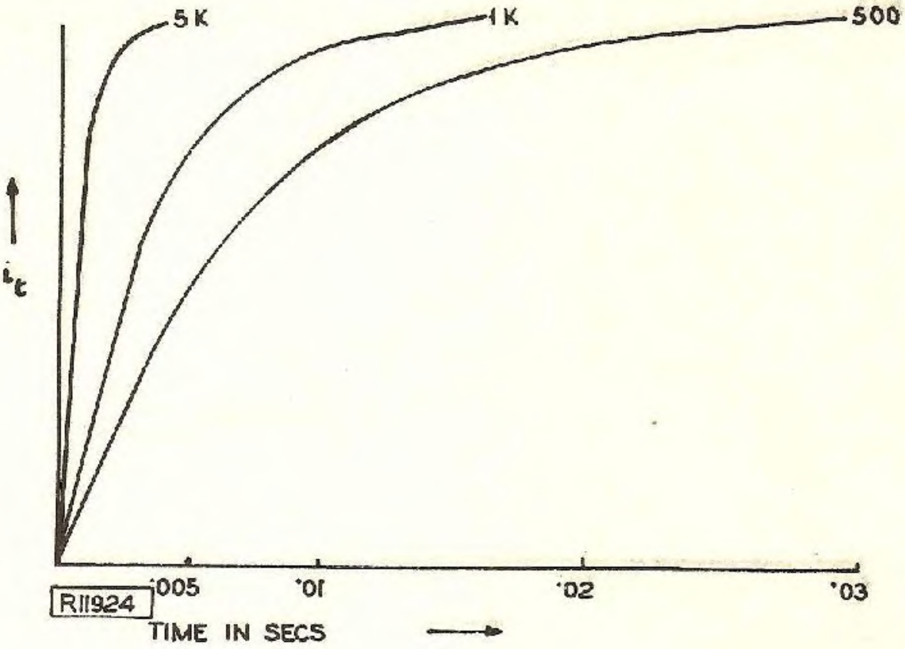


Fig. 11

The Shunted Capacitor

When the value of resistance has been increased to such a value that any further increase requires a greater signalling voltage than is available, a further increase in the rate of rise of current can be obtained by shunting the resistance with a capacitor. The circuit is shown in Fig. 12.

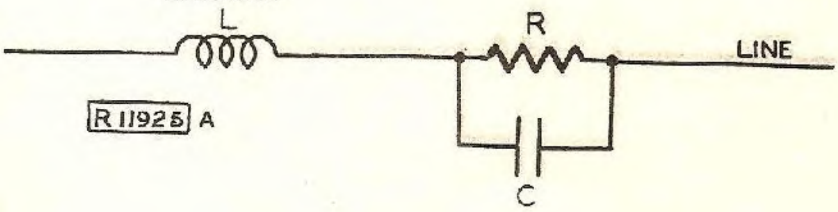


Fig. 12

As C increased the rate of rise of the current in the inductance is increased until a critical value of C is reached. If the capacitance of C be further increased, the instantaneous current will rise above its steady maximum value and then oscillate about this value until the oscillation is damped out, Fig. 13. The larger C is now made, the greater will be the amplitude of the transient.

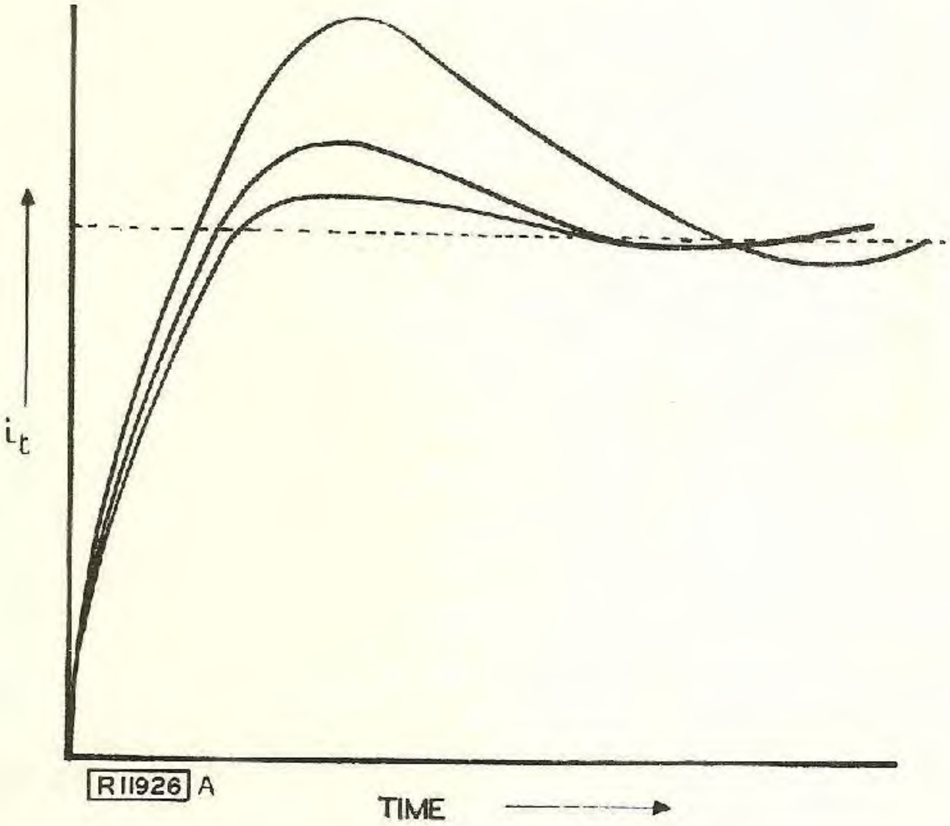


Fig. 13

The square-topped telegraph signal can be shown to consist of a sine wave of fundamental frequency, combined with a series of odd harmonics of the fundamental. The impedance of an inductive receiver rises at the higher frequencies and this results in a fall in its response to these components of the square-topped signal. By terminating the line in an impedance consisting of a shunted capacitor and the receiver, in series, the response to high-frequency components of the signal is considerably improved because of the falling impedance/frequency characteristic of the shunted capacitor. The final value of the received current is reduced because of the additional resistance in circuit. As the value of capacitance is increased the oscillatory condition shown in Fig. 13 is approached.

Fig. 14 shows a local circuit consisting of inductance with a shunted capacitor in series.

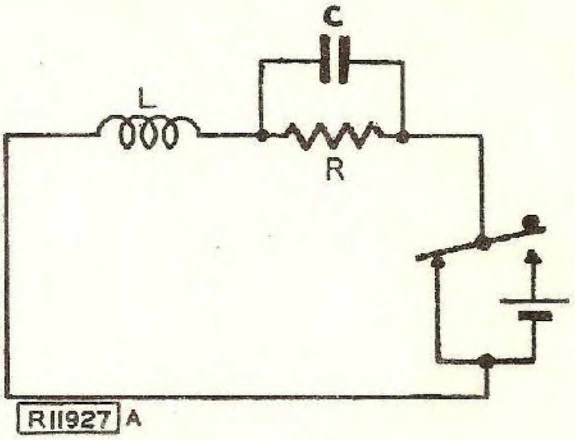


Fig. 14

Upon operation of the key in Fig. 14 the charging of the capacitor through the inductance will help to build up the current quickly. Upon releasing the key, the discharge, which is in the reverse direction, will take place partly through the inductance and so hasten the current decay in the inductance.

The effect on a dot signal of 0.04 seconds duration (equivalent to 30 words per minute in Wheatstone) is shown in Fig. 15. Notice the steep rise of current and the way in which the transient current exceeds the final value. This helps to move the receive relay armature quickly, after which the steady value is sufficient to "hold" the relay until the next signal arrives. The dotted curve shows the rise of current without the capacitor.

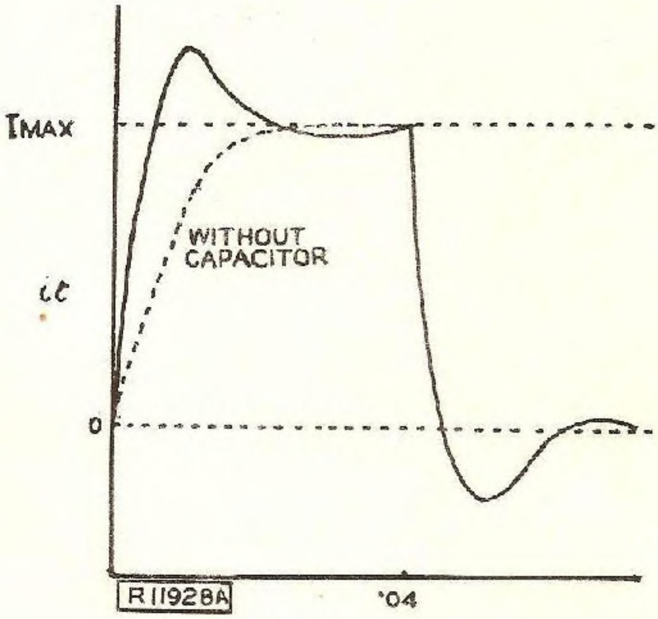
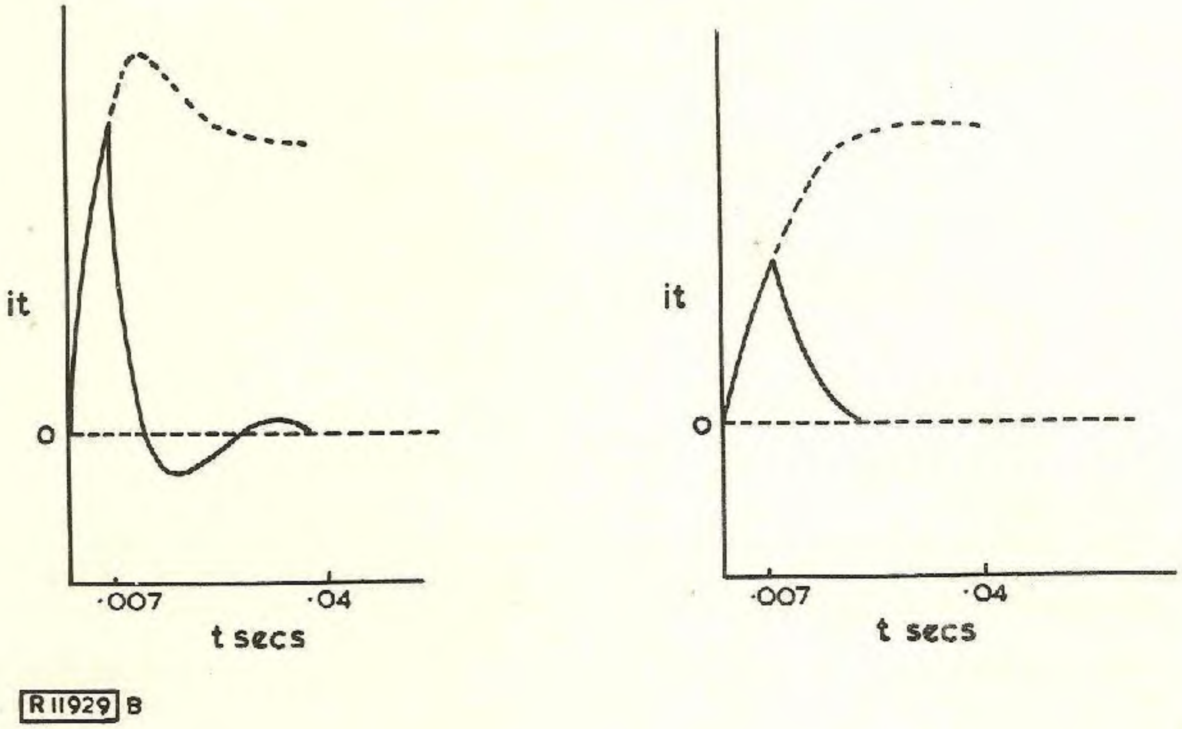


Fig. 15

For a speed of 180 words per minute, the duration of the dot signal would be 0.007 secs. The signal shape with and without capacitor are shown in Figs. 16(a) and 16(b) respectively.



(a) (b)

Fig. 16

A number of examples of the use of the shunted capacitor in telegraph circuits will be seen in subsequent pamphlets; the practice is sometimes called "signal shaping", the object being to make the wave front of the current in the receiver as steep as possible. The curves given should be taken as being illustrative rather than exact because the inductance of a relay or receiver is not a constant quantity due to the non-linear form of the magnetization curve; there will also be eddy current and hysteresis effects which are difficult to predict.

(ii) Line Capacitance

The effect of capacitance will necessarily be more pronounced as the length of the circuit increases; thus with long cable circuits the length of the cable is the determining factor in respect of time lag and signal distortion.

A long unloaded cable circuit may be considered as consisting of a large number of sections each made up of resistance shunted by a capacitance (neglecting G) as shown in Fig. 17.

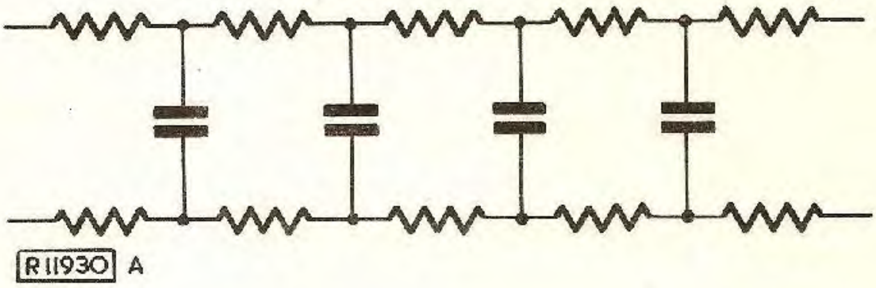


Fig. 17

When a signalling voltage is applied to one end of the line, the capacitance in all the successive sections in turn must be charged before the current reaches its maximum value at the receiving end. There is an initial rush of current into the line to charge the capacitance, but the received current is practically zero until the lapse of a short interval termed the silent interval. After this interval the current rises gradually until its maximum value is reached.

It was shown by Lord Kelvin that if the inductance and leakance be neglected (which is reasonable in the case of cables) and the receiving end is short-circuited, then the received current i_r at any instant is given by

$$i_r = \frac{2E}{Rl}\left[\frac{1}{2} - e^{-\mu t} + e^{-4\mu t} - e^{-9\mu t} + - - -\right]$$

where $\mu = \frac{\pi^2}{CRl^2}$

and E is the applied e.m.f.
R is the resistance per mile
l is the length in miles of the circuit
C is the capacitance per mile
t is the time elapsed since the application of E to the line.

For values of μt up to 0.23, the value of i_r will be practically zero and this accounts for the silent interval or delay time of the circuit. For large values of μt, the first two terms in the series are sufficient, and the expression for the current at the receiving end may be rearranged, thus,

$$i_r = \frac{E}{Rl}\left[1 - 2e^{-\frac{\pi^2 t}{CRl^2}}\right]$$

now $\frac{E}{Rl}$ is the final steady value of current; expressing the current at time t as a fraction of this final value

$$\frac{i_r}{E/Rl} = 1 - 2e^{-\frac{\pi^2 t}{CRl^2}}$$

Fig. 18 shows a curve of $\frac{i_r}{E/Rl}$ plotted against time t in secs., for a cable with a CRl^2 value of 2.4. This is known as an arrival curve and is used to determine the time required for the current to reach the operate current for the type of receiver in use. Notice how, after the initial delay period, the current rises steeply before flattening off to the steady value when the transient is completed. It is this steep portion of the curve which is used to operate the receiver. The time taken to reach the operate current will decide how quickly signals may follow each other if the operate value is to be reached for each signal. It follows that the Kelvin formula may be used to calculate the maximum speed of working and is the basis of what is known as the CR law.

The CR law is still used as a criterion for telegraph circuits but the limitations of the Kelvin formula, upon which it was based, should always be borne in mind, i.e. that inductance and leakance are neglected. The CR law should therefore only be used for calculations on unloaded circuits and cable circuits of low inductance.

The CR law states that the product of the capacitance and resistance per mile and the square of the length of the circuit in miles, is a measure of the maximum speed of working. The speed of working is inversely proportional to CRl^2.

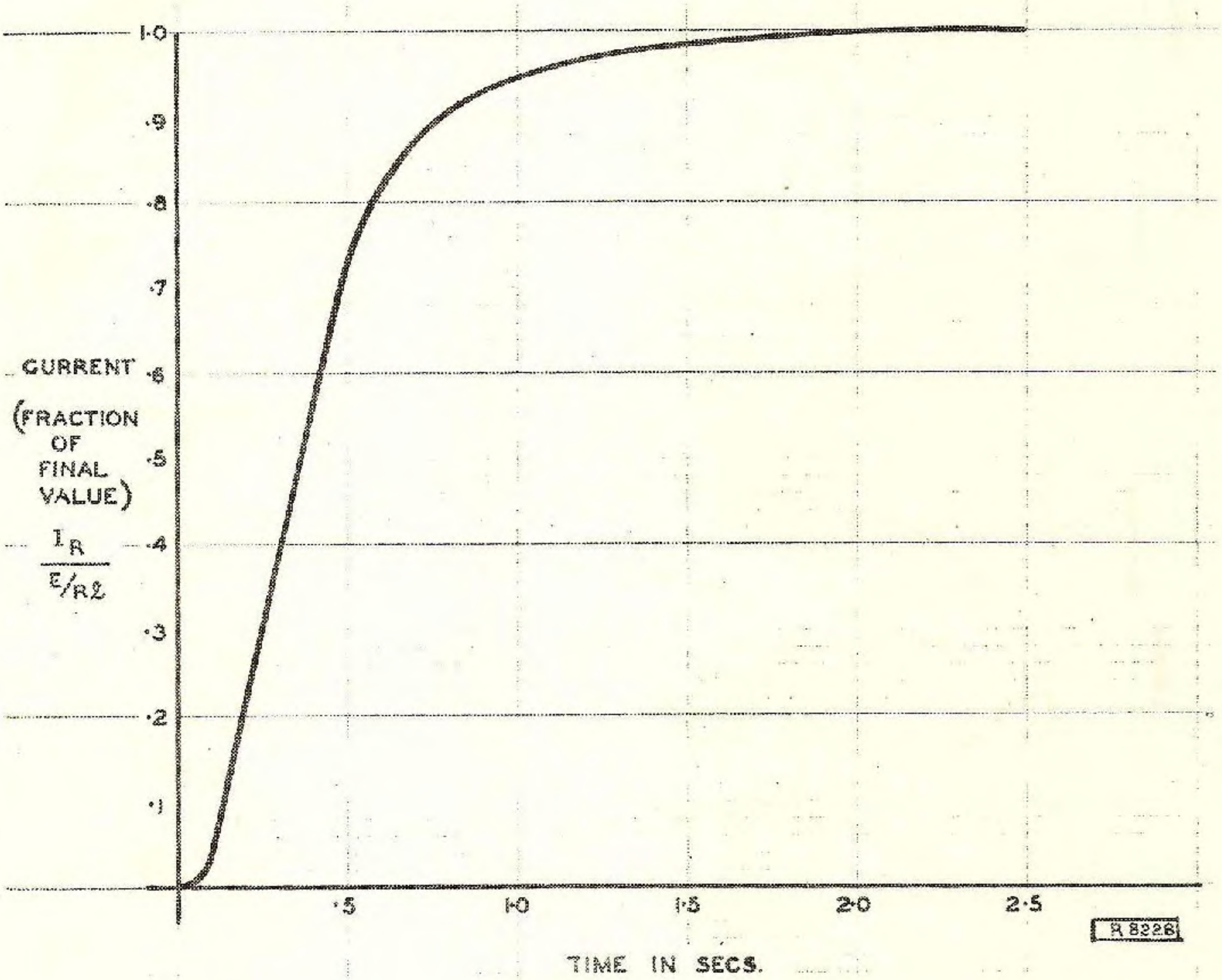

CURRENT
(FRACTION OF FINAL VALUE)
$\frac{I_R}{E/R_2}$
1·0
·9
·8
·7
·6
·5
·4
·3
·2
·1
·5
1·0
1·5
2·0
2·5
R 8226
TIME IN SECS.

Fig. 18

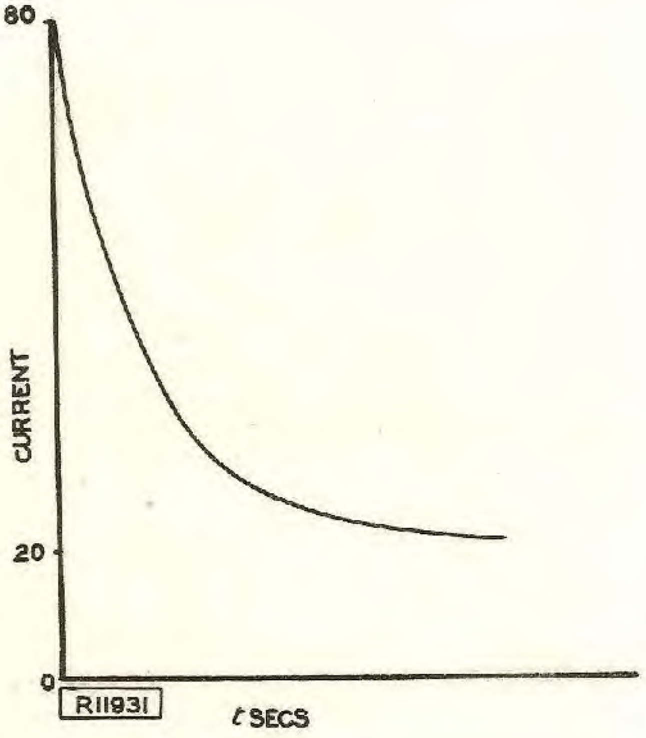


Fig. 19

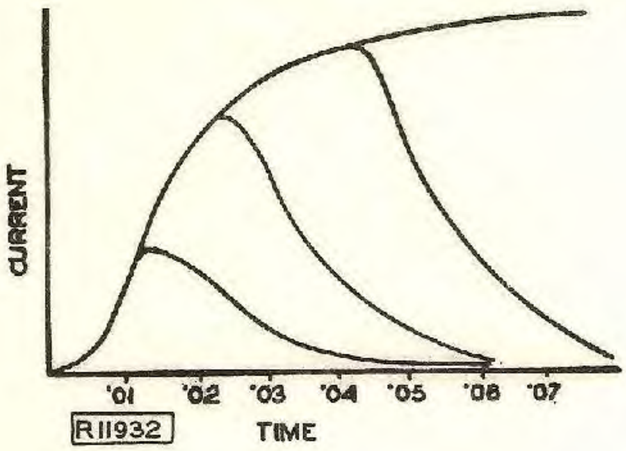


Fig. 20

Sending and current

The sending end current, plotted against time is shown in Fig. 19, it will be noticed that the initial current is much greater than the final steady value; this is due to the surge of current which charges the capacitance of the line.

Line capacitance and distortion

The effect of line capacitance on the distortion of signals is quite similar to that due to instrument inductance. The arrival curve is somewhat similar in shape to that of the current rise in an inductance so far as it affects signal distortion with single and double current working.

The received current form for dot signals of various lengths is shown in Fig. 20.

A shunted capacitor in series with the receiver enhances the speed of working because of its effect upon the charge on the line. At the instant when the signalling voltage is reversed, the capacitor discharges into the line. This prevents the line discharging bia the receiver - an effect which would prolong the signal - and by its conditioned action causes the current to rise rapidly in the opposite direction.

(iii) Transit time

The time interval during the actuation of the moving parts of the receiver is known as the transit time of the receiver. Receive-relay transit time may have any value from 0.5 milliseconds to 4 milliseconds; transit time can be reduced to a minimum by correct adjustment of the contacts and pole pieces of the relay. The effect of transit time on the received signal is shown in Fig. 21, in Part IV, where it may be seen that for a short period (2 ms) the relay tongue is not making a connexion with either battery contact and the current is consequently zero. It is evident from the diagram that the transit time will add to the distortion.

Telegraph Working Speed

In the past there have been a number of ways of indicating the effectiveness of a telegraph circuit and the speed of working was one of the early methods used. The speed of working of a circuit may be expressed as the number of words transmitted per minute. Calculations of speed in words per minute are based on an average number of characters for each word and upon the average number of unit signal elements per character. In the five unit code, the number of unit elements is the same for each character, whereas in the Morse code this is a variable quantity. Thus, while different codes are being used, employing varying numbers of signal elements for the same character, a true indication of the performance of a circuit is not obtained from the number of characters or words successfully transmitted per minute.

It is logical that the smallest interval of time used in any system should be used as a standard of measurement and the unit signal element is therefore the basis of speed measurements. The unit of telegraph speed is called the BAUD and is defined as the number of unit signal elements transmitted per second.

Signal elements in the Morse code consist of dots and dashes, the dot being the unit signal element and the dash consisting of 3-unit signal elements. The space between each dot or dash is 1 unit signal element, i.e. the length of 1 dot signal, and between each letter forming a word there is a space equal to 3 dots. Words are separated by a space equal to five dots. In order to convert a speed given in words per minute for Wheatstone (i.e. Morse) to speed in Bauds it is necessary to remember the following conventions. The average word is taken as having 6 characters (5 letters and a space) and the average length of a Morse character is 8 dot units.

$$\therefore \quad \text{Average word} = 8 \times 6 = 48 \text{ unit elements}$$

$$\therefore \quad 1 \text{ word per min.} = \frac{48}{60} \text{ unit elements/sec.}$$

$$\therefore \quad 1 \text{ " " "} = \frac{4}{5} \text{ " " "}$$

$$= \frac{4}{5} \text{ Baud}$$

To convert from w.p.m. (Wheatstone) to Bauds, multiply by $\frac{4}{5}$. The following table is a brief guide for convenience.

WPM (Wheatstone)	Bauds	Hertz
20	16	8
40	32	16
60	48	24
80	64	32
100	80	40
150	120	60
200	160	80

In systems in which the Morse code is used exclusively it is convenient and satisfactory to express the speed in words per minute.

With the growth of multi-channel voice frequency systems it is useful to know the speed of transmission in cycles per second. One complete reversal of current may be regarded as one cycle; this is equivalent to a dot signal (in Morse) followed by a space and thus consists of two elements. The speed in cycles per second is therefore half the speed in Bauds as indicated in the table given.

The teleprinter No. 7 is an example of a start-stop system employing the 5 unit code,

$$\begin{aligned} \text{Start signal} &= 1 \text{ unit} \\ \text{Stop signal} &= 1\tfrac{1}{2} \text{ units} \\ \text{Code} &= 5 \text{ units} \\ \text{Total} &= 7\tfrac{1}{2} \text{ units} \\ &= 3\tfrac{3}{4} \text{ cycles per cam revolution} \end{aligned}$$

Now the cam makes 400 rev/min.

$$\therefore \qquad \text{Speed} = \frac{400 \times 3.75}{60} \text{ Hz}$$

$$= 25 \text{ Hz}$$

(This, the maximum frequency, occurs when R or Y is transmitted).

Each cycle consists of two unit signal elements

$$\therefore \qquad \text{Speed} = 50 \text{ Bauds}$$

(The Baud speed is constant, whichever character is transmitted)

Transmission speed of the working circuit

Experiments show that the working speed of a circuit is inversely proportional to the product of its total resistance and capacitance. Thus if C microfarads is the total capacitance of the line and R ohms its total resistance then the speed of working (S) is given by the following formula

$$S = \frac{A}{C\,R}$$

Where A is some constant derived by experiment and depending on the particular line and type of receiving apparatus.

This formula has its theoretical foundation in the Kelvin formula discussed in Part III and is subject to the same limitations, i.e. circuits in which the inductance and leakance may be neglected. In any case it should only be used as a rough guide for comparing the speeds of working of circuits under different line conditions.

If C and R are in units per mile, the formula becomes

$$S = \frac{A}{CRl^2}$$

For a given type of line conductor and receiving apparatus C, R, and A are constants, hence the speed of working is inversely proportional to the square of the length of the circuit. Accordingly if the length of a circuit is halved, the possible speed of working over it is quadrupled. It will be seen, therefore, that by inserting a repeater at the centre of a line it should be possible to increase the working speed of a long circuit considerably, e.g. if a speed of eightly words per minute is the maximum obtainable over a certain circuit, then it should be possible to work at 320 words per minute by inserting a repeater near its centre.

There is a limit to the speed obtainable over a circuit, depending on the maximum speed at which the receiving apparatus will respond, and this in practice rarely exceeds 700 words per minute. This is the deciding factor on; aerial lines; on long underground lines, however, the speed of working of the line is usually much less than that of the apparatus.

Telegraph Signal Distortion

Introduction

Before the advent of direct-printing telegraph systems, employing start-stop principles, a satisfactory criterion of the transmission efficiency was obtained by stating the maximum speed at which a circuit or system could be worked. Constant-speed systems have rendered this method ineffective and modern methods of determining circuit efficiency are based on signal distortion. It would appear that the distortion produced by a given set of circuit conditions could be determined from the actual shape of the signal received on the line in conjunction with the assumption of a fixed operating current for the receive relay. Although desirable, this method does not work out very well in practice, probably because of the unpredictable effects of the magnetic circuit of the relay on its operate and release currents when subjected to non-continuously repeated signal elements. The precise time of operation of the relay is dependent to a certain extent on the amplitude of preceding elements and the rate of change of current in its coils. Distortion measurements are normally made on the output of the receive-relay tongue, at which point in the circuit the signals have been restored to the square-topped wave-form; any lengthening or shortening of the signal elements at this point compared with the shape of the signals transmitted constitutes distortion.

A line or voice frequency channel is said to be telegraphically distortionless if the interval of time separating a change at the transmitter from the corresponding movement of the relay armature at the receiving end is the same for every change which occurs during the transmission of signals. It follows that a circuit is distortionless if the lengths of the elements of the received signals are exactly the same as those of the corresponding elements in the transmitted signals.

It is found that the amount of distortion varies with the different combinations of signalling elements used for the different characters. For example, it may be more marked on a series of reversals rapidly following each other, than on one long signal with the current in the same direction for the whole time. Again, one reversal of short duration between two comparatively long signals may suffer more distortion than any other combination.

Classification of Distortion

Distortion may be classified under three headings,

(i) Characteristic distortion
(ii) Bias distortion
(iii) Fortuitous distortion

(i) Characteristic distortion

Characteristic distortion is that distortion arising from the inherent electrical characteristics of the transmission circuit including the normal sending and receiving terminations of the circuit, and is the distortion occurring consistently with any given series of or combination of signal elements. It is the distortion which would be measured at the output of the receiving relay, this relay being in perfect order, when perfect signals are applied at the sending end, the circuit being completely free of bias and with no interference from any other source.

(ii) Bias distortion

Bias distortion is the lengthening of the marking signals and the corresponding shortening of the spacing signals (or vice versa) during their transmission through a circuit. Lengthening of marking signals is known as marking bias and lengthening of spacing signals as spacing bias. Bias distortion can be observed by the sending of neutral reversals which are themselves perfect signals. If bias is present it can be corrected by adjustments to the apparatus until received signals are neutral. Bias distortion may also be caused by hysteresis effects, unequal signalling voltages or by earth currents.

(iii) Fortuitous distortion

Fortuitous distortion is that which arises from random influence upon the apparatus or circuit. It can arise from mechanical faults in the transmitting and receiving apparatus, a typical instance being the presence of magnetic particles in the air gap of a relay. In d.c. telegraph circuits the presence of parasitic currents set up by electromagnetic or electric induction will cause a certain amount of fortuitous distortion. Such interference may be caused by other telegraph circuits carried in the same cable on adjacent wires, and on overhead lines it may be caused by induction from neighbouring power lines or atmospheric disturbances. Interference on channels in a multi-channel v.f. system may be caused by cross talk from neighbouring telephone circuits or other v.f. systems, and from noise in the line arising from some external source.

The combined characteristic and bias distortion is sometimes known as the "System distortion" whilst the distortion due to all causes is known as the total distortion.

Distortion is measured by comparing the actual instant of restitution with the instant at which it should have occurred. The measured time difference between these instants is expressed as a percentage of the length of the unit element and this gives the distortion.

In Figs. 21(a), (b) and (c) the full lines indicate the ideal instants of restitution associated with a single element of a 50 baud transmission, while the actual instants of restitution are denoted by the dotted lines.

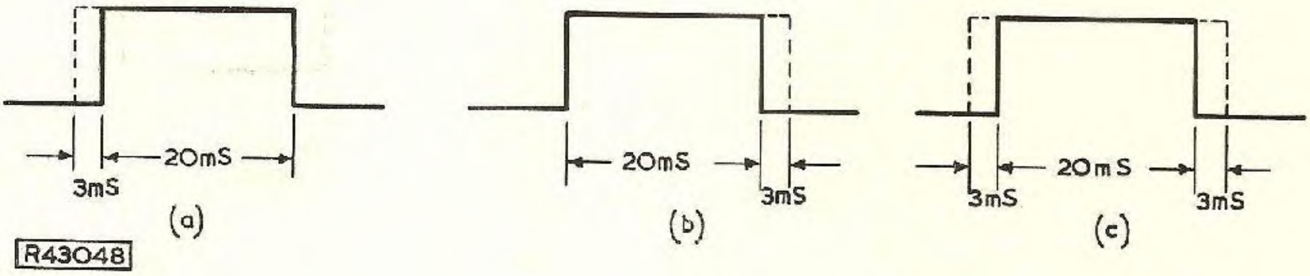


Fig. 21

In Fig. 21(a):-

$$\text{Distortion} = \frac{3}{20} \times 100 = 15\% \text{ early}$$

In Fig. 21(b):-

$$\text{Distortion} = \frac{3}{20} \times 100 = 15\% \text{ late}$$

The total distortion of the element is shown in Fig. 1(c):-

$$\text{Total Distortion} = \frac{3 + 3}{20} \times 100 = 30\%.$$

Isochronous Distortion

If the distortion of a train of telegraph signals is measured isochronously, as when lining-up voice frequency telegraph circuits, or on circuits using a synchronous form of line signal; then the isochronous distortion is given as the sum of the time difference between the transition which was earliest and the transition which was delayed the most compared with an ideal transition, and is expressed as a percentage of the unit element.

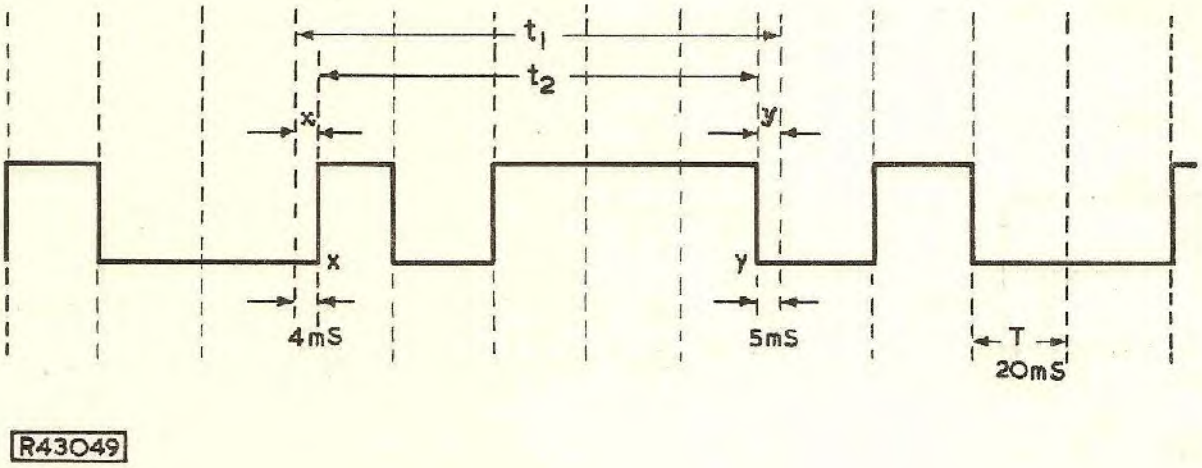


Fig. 22

As an illustration of isochronous distortion consider the 50 baud transmission shown in Fig. 22. Here it can be seen that the maximum early transition occurs at Y, and the maximum late transition occurs at X, therefore the maximum difference between the actual and theoretical intervals in this case is $t_1 - t_2$.

$$\text{Isochronous distortion} = \frac{(t_1 - t_2)}{T} \times 100\%$$

but

$$t_1 - t_2 = x + y$$

$$\therefore \quad \text{Isochronous distortion} = \frac{(x + y)}{T} \times 100\%$$

Substituting the values given in Fig. 22 this gives:-

$$\text{Isochronous distortion} = \frac{(4 + 5)}{20} \times 100 = 45\%$$

Start-Stop Distortion

The distortion of a start-stop signal is the ratio to the unit element, of the maximum difference between the actual and theoretical intervals separating any characteristic instant from the beginning of the start signal immediately preceding it. This ratio being expressed as a percentage.

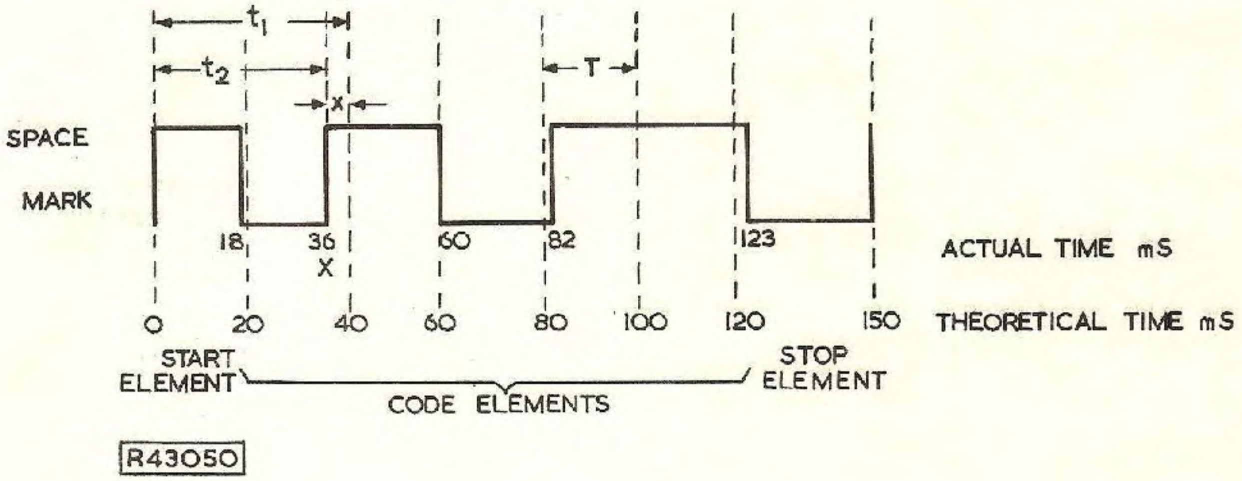


Fig. 23

Referring to the start-stop signal shown in Fig. 23, it can be seen that the maximum difference between the actual and theoretical characteristic instants occurs at X.

$$\text{Start-stop distortion} = \frac{t_1 - t_2}{T} \times 100\%$$

but $t_1 - t_2 = x$

$$\therefore \quad \text{Start-stop distortion} = \frac{x}{T} \times 100\%$$

Referring to Fig. 23, it can be seen that the maximum time difference ($t_1 - t_2 = x$) occurs at t_1 = 40 ms and t_2 = 36 ms.

Substituting the above values:-

$$\text{Maximum Start-stop distortion} = \frac{x}{T} \times 100\% \ (x = 40 - 36 = 4 \text{ ms})$$

$$= \frac{4}{20} \times 100$$

$$= 20\% \text{ (early)}$$

Teleprinter Margin

In order to obtain a measure of the transmission efficiency of a telegraph circuit working at some fixed speed it is necessary to determine two things.

(a) The maximum effective signal distortion which occurs during transmission.

(b) The maximum amount of signal distortion which may be permitted before the receiving mechanism fails to operate correctly. This has been given the name of "margin".

The amount by which (b) exceeds (a) is a measure of transmission efficiency of the circuit. This is known as the "excess margin".

In start-stop systems the limit of distortion is determined by the time displacement of the code elements with respect to the commencement of the start signal that precedes them.

Considering the teleprinter, it will be appreciated that there must be a definite time relationship between the mechanical operations and the received electrical pulses, if the teleprinter is to operate correctly. When the start signal commences, the receiving cam sleeve begins to rotate at a constant speed. It is essential that the start signal lasts at least for the length of time necessary to withdraw the cam sleeve pawl from the cam sleeve ratchet in order to set the cam sleeve rotating, otherwise the receiver mechanism will not start. Once the mechanism is started the start signal may terminate since it has fulfilled its function. The finger setting pin is moved from its normal central position behind the comb-setting fingers until it is opposite the middle of the first finger. The finger setting blade now starts to move from its maximum backward position towards the finger setting pin. As the finger setting blade moves towards the striker pin it will come to a position in which the blade is just about to pass beneath the pin, provided that the electromagnet armature is still over to spacing. That moment is the latest time at which we can decide to change over the electromagnet so that the blade will strike the pin. Furthermore, it must be held in the marking position until the striker pin has moved the selecting finger beneath the end of the comb setting finger, or the mark selection will fail. Thus there is a definite period in each signal, as timed from the commencement of the start signal, during which the electromagnet must be held stationary in position if the teleprinter is not to fail; there times are indicated by the shaded areas in Fig. 24. The unshaded areas indicate the periods during which the electromagnet armature may change over from working to spacing and vice versa without causing a failure to record correct signals.

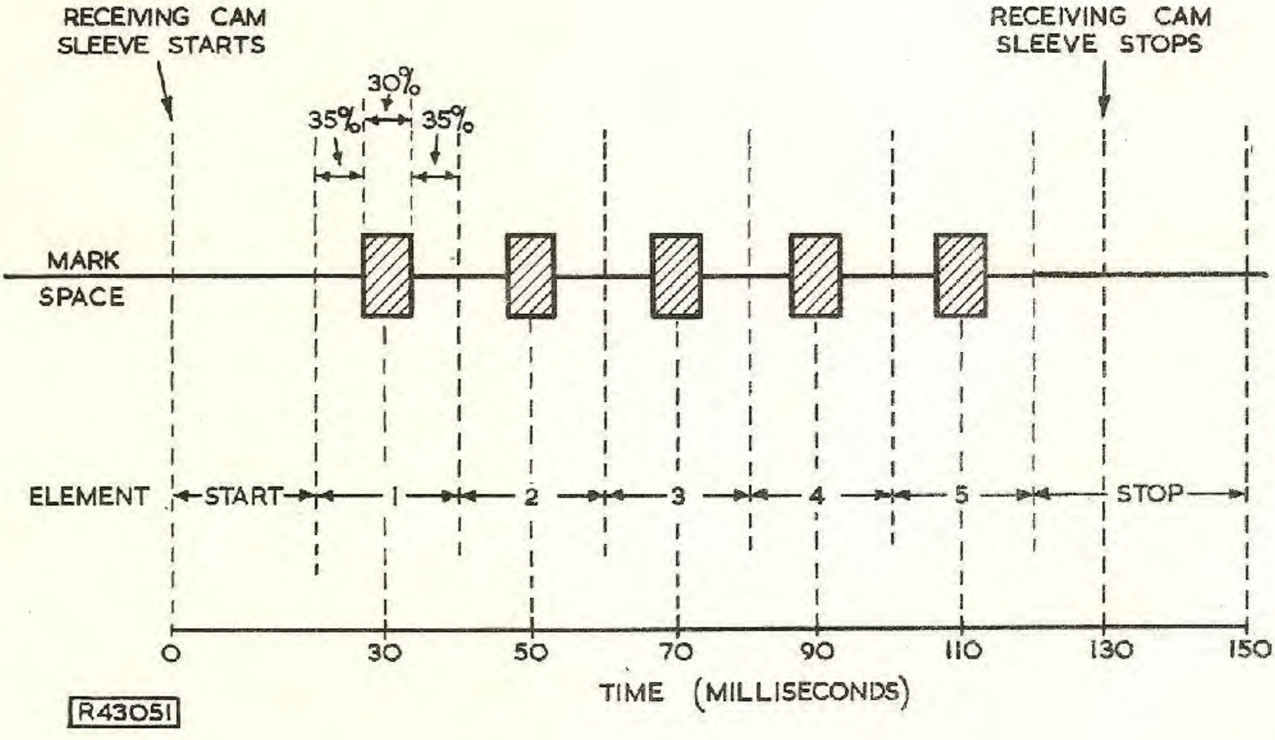


Fig. 24

Consider the finger setting blade commencing to move from its maximum backward position; a certain period of time elapses before the blade touches the pin and a further period is occupied in moving the comb setting finger under the comb extension. Movement from the maximum forward to the maximum backward position occupies a further period of time. The total of these times is equivalent to the period of time of a unit signal element. A representation of the movement of the finger setting blade in relation to the reception of a perfect signal is shown in Fig. 25.

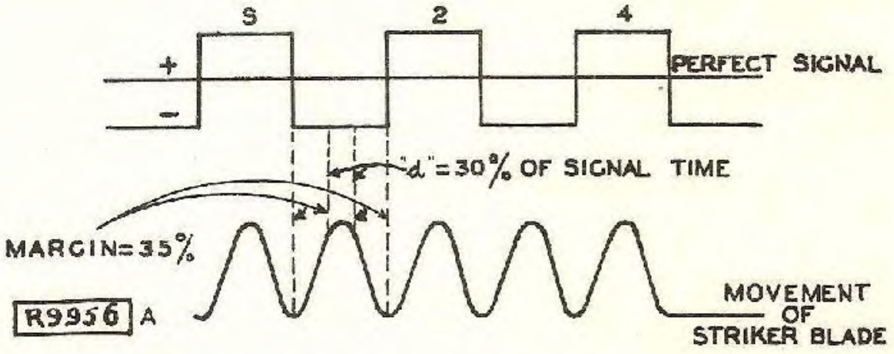


Fig. 25

In the diagram, "d" represents the portion of the signal time during which the finger setting pin is actually moved. In a correctly adjusted teleprinter the movement of the finger setting pin is timed to occur at the centre of a perfect signal and occupies 30% of the total signal time. If the signal is not a perfect one (i.e. if it suffers distortion) or if the teleprinter is not perfectly adjusted then the period of time "d" may not occur at the middle of the signal time but may be either early or late. The selection will only fail however if the portion "d" occurs early or late by more than 35% of the total signal time. This is therefore the theoretical margin of the teleprinter 7B using a $7\frac{1}{2}$ unit code. In practice the margin is quite often in excess of the theoretical value of 35%.

An encroachment diagram of a Creed Teleprinter together with some distorted signals is shown in Fig. 26.

(a) This is the encroachment diagram for a Creed Teleprinter in perfect adjustment. The shaded portions indicate the periods during any part of which the electromagnet armature may change over from mark to space and vice versa. The unshaded portions indicate the periods during which the armature must remain on the required contact to ensure correct selection.

(b) Shows a hypothetically distorted fourth signal element which would give correct registration. Any further distortion would, of course, cause a failure and hence the excess margin in this case is zero.

(c) Shows the start signal with 70% distortion which would give correct registration. No further distortion can be allowed.

(d) Is the actual characteristic distortion (obtained in test) due to an unloaded telegraph line. The distortion of the fourth element is 35% and correct registration would be given, but again, no further distortion is permissible; the "excess margin" is zero. The character is "Q".

(e) Is the actual distortion obtained over the same line but with the 'carriage return' signal on the Teleprinter No. 7. The distortion in this case is 19% late and 17% early giving a total distortion of 36%, but a further distortion of 16% late and 18% early may be permitted without causing failure. The "excess margin" being 16% on the late side and 18% on the early side.

The foregoing cases show that a knowledge of the total distortion (i.e. sum of maximum early and maximum late operations) does not give sufficient information for obtaining a value for the "excess margin" which will be of practical use. In cases (d) and (e) the total distortion is almost the same but in order to derive a value for the "excess margin" which will be properly expressive of the working efficiency, we must consider the additional distortion that may be allowed, not the difference between the total distortion occuring (35% and 36% respectively) and the teleprinter margin as suggested earlier.

In practice, therefore, it is necessary to find the amount by which the signal elements, as measured at the receiving relay contacts, are lengthened and/or shortened, as compared with a perfect signal, together with the "early" excess margin and the "late" excess margin, of the teleprinter being used.

As far as the signals are concerned, various character combinations are tried but the one which suffers most distortion is the only one of importance from a practical working point of view. If the worst signal is recorded correctly then signals which are less distorted will also be recorded correctly.

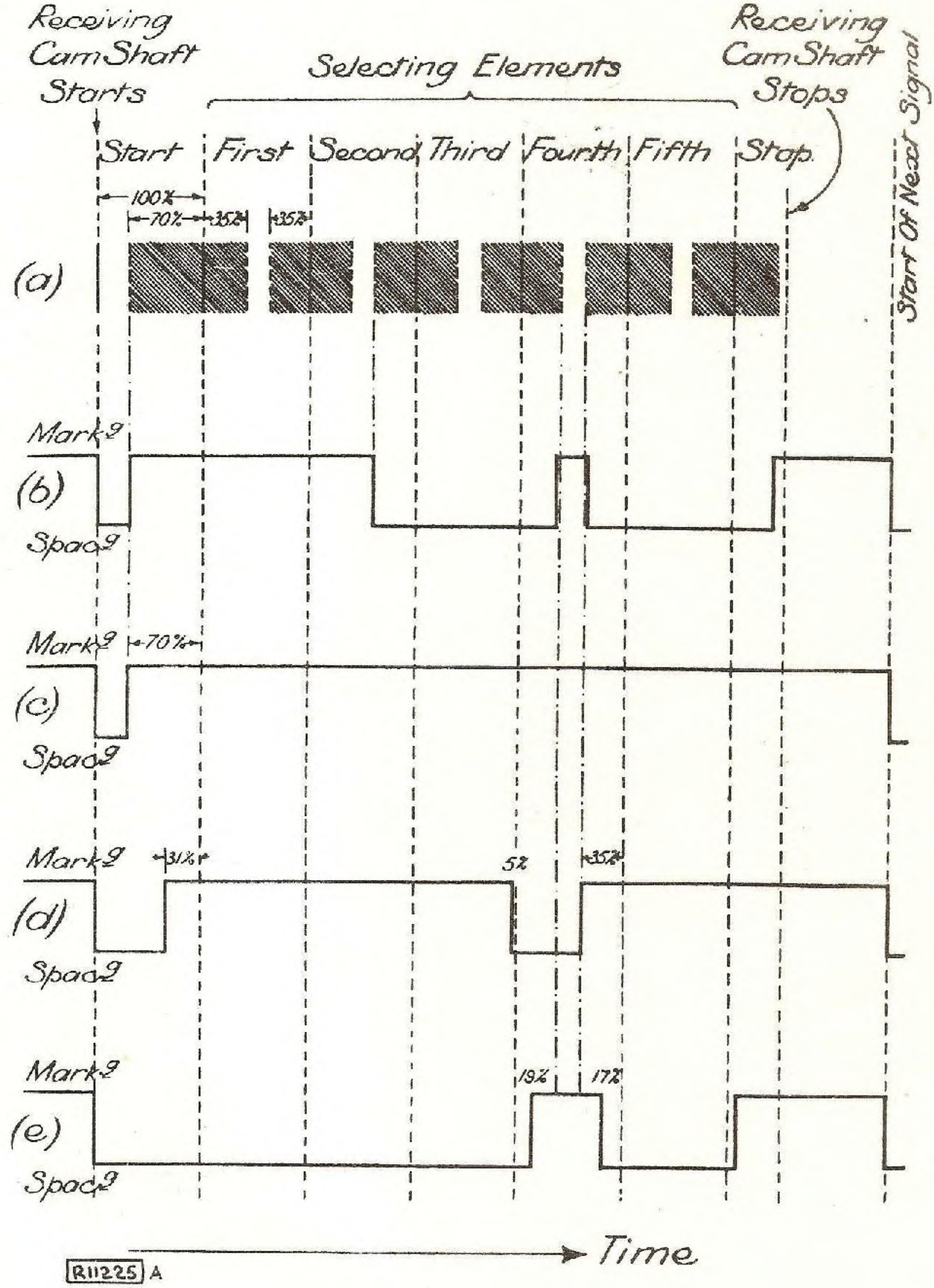

Receiving Cam Shaft Starts
Selecting Elements
Receiving Cam Shaft Stops
Start Of Next Signal
Start
First
Second
Third
Fourth
Fifth
Stop.
100%
70%
35%
35%
(a)
Mark^g
(b)
Spac^g
Mark^g
70%
(c)
Spac^g
Mark^g
31%
5%
35%
(d)
Spac^g
Mark^g
19%
17%
(e)
Spac^g
Time
R11225 A

Fig. 26

END