# Phase Distortion in Telephone Apparatus *

By C. E. LANE

This paper shows that if, over its transmitting range, the phase shift, $B$, in radians, of a four-terminal network may be written $B = a_0 + a_1\omega$ ($\omega = 2\pi x$ frequency in cycles per second), there is no phase distortion if $a_0 = N$, $N$ being any integer. However, there is a delay, for any signal, given by $dB/d\omega = a_1$ (seconds). If $N$ is not an integer, there is a delay, $a_1$, and in addition a distortion, which distortion, generally for speech and music, may be neglected. Typical phase characteristics for lines, filters and all-pass networks are shown. In general over their transmitting range, such phase characteristics which usually are curved, may be regarded as the sum of two characteristics, a straight line having a slope corresponding to the minimum slope of the original and which introduces a delay without distortion and a curved portion to which all of the distortion of the signal may be ascribed. Oscillograms are given showing the distortion for a loaded line and for band filters for a signal which is of the form $y \sin (\omega_0 t + \theta)$ between $t = 0$ and $t = T$ and zero for all other time. A description is given of the means employed for reducing the amount of phase distortion in telephone cable and in low-pass filters in circuits used for program transmission and regular telephone service. Also, phase distortion in repeaters and transformers is described. Brief reference is made to the problem of phase distortion in telegraph, picture transmission, and television circuits.

THE effects of amplitude distortion in the transmission of signals has been taken into consideration in the design of telephone systems for some time. Recently [1] increasing attention is being given to the phase changes which waves undergo in the process of their transmission. The necessity of this is, on the one hand, due chiefly to the use of long distance telephone systems involving greater lengths of loaded cable and numerous filters and repeaters in tandem, and, on the other hand, due to the demand for improved performance. One place where better quality has become particularly desirable is in circuits for interconnecting broadcasting stations.

This paper will present some general considerations of the relation between the phase characteristics [2] of telephone apparatus and signal distortion,[3] show the types of phase characteristics that most frequently require consideration and discuss the manner in which the amount of phase distortion is controlled. Brief reference will also be

* Presented at New York Section, A. I. E. E., May 1930.

[1] At the end of this paper, a bibliography is given containing references to previous publications on this subject.

[2] For a definition of phase characteristic see Appendix I. The "insertion" phase characteristic and "image transfer" phase characteristic are defined there.

[3] A companion paper by J. C. Steinberg deals specifically with the effects of phase distortion on the quality of speech and music. Another companion paper by H. Nyquist and S. Brand treats of the measurement of phase distortion.

made to phase distortion in systems for transmitting other than telephone signals.

## Interpretation of Phase Distortion

Telephone systems must be so designed that the received signal approximates in wave form the sent signal within limits found by experience to be tolerable. We are here concerned primarily with the departure of the received signal wave from the sent signal [4] which may be attributed to the phase characteristic [5] of such networks as lines, filters, repeaters, etc. which go to make up the complete system. Such distortion is called phase or delay distortion. The reason for the term, delay, will appear later. We shall summarize here some of the more general conclusions of the effect on signals of certain phase characteristics and discuss the validity of these conclusions in Appendix II.

If the phase characteristic of any network is of the type shown by any of the dotted lines in Fig. 1 the received wave will be an exact copy of the sent or reference wave (assuming no amplitude distortion). In the case of Fig. 2 the received wave differs from the reference wave only in that it is reversed in sign which is equivalent simply to reversing the terminals of the load. *In both cases the received wave is delayed with respect to the reference wave by a time interval that is given by the slope of the phase characteristic or* $dB/d\omega$. If $B$ is in radians, and $\omega = 2\pi f$, where $f$ is the frequency in cycles per second, the delay will be in seconds. There is no distinction in effect between the phase characteristics for any of the dotted lines and furthermore they are identical with any such solid broken line as that shown. Since this is true we may completely represent any of the phase characteristics of Fig. 1 if we choose by the single line passing through zero in which case the delay is $B/\omega$.

If the phase characteristics are straight lines and intersect the vertical axis at odd multiples of $\pi/2$ the received wave may be obtained from the reference wave first by delaying it by $dB/d\omega$ and then shifting the phases of all its steady state sinusoidal components as obtained by Fourier Integral or Series analysis by $\pi/2$.

If the straight line phase characteristics intersect the ordinate at intermediate values the received wave may be said to be the sum of

[4] See Appendix I. If one desires to be specific the sent or reference wave in the case of considering image transfer phase shift may look upon as the current entering the network and in the case of insertion phase shift the current through the load with the network omitted; and the received wave the current through the load in either case with the network in place.

[5] In actual apparatus certain general types of phase characteristics are associated with certain attenuation characteristics. For this reason it is difficult to separate to the extent one might sometimes desire the effects of the two types of distortion, attenuation and phase.

two parts as follows: The first part is an exact copy of the original wave modified in amplitude by a factor cos $a_0$ and delayed by $dB/d\omega$. The second part is obtained from the original wave by shifting all of the

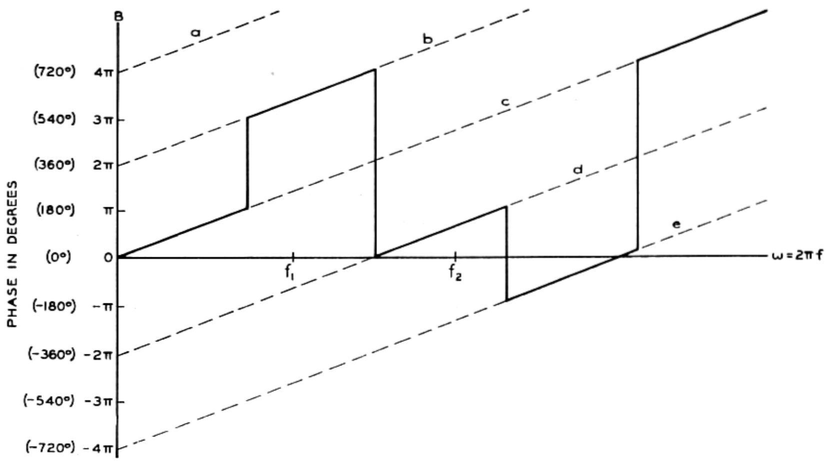


Fig. 1—Phase characteristics which introduce no distortion.

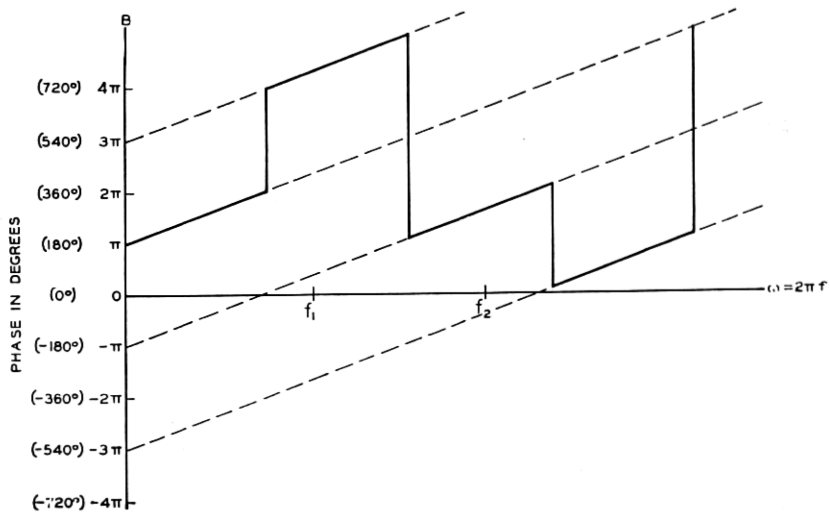


Fig. 2—Phase characteristics which introduce no distortion equivalent to those of Fig. 1 with connections to the load reversed.

components of the original by $\pi/2$, multiplying the result by sin $a_0$ and then delaying by $dB/d\omega$. $a_0$ is the value of the angle at the point of intersection of the vertical axis.

An important point to note here is that if a given signal has all its *important frequency components* falling in a region between $f_1$ and $f_2$ either because of the nature of the signal or as a result of attenuation in the system we are only interested in the phase characteristic in that region. *Thus for such a signal a sufficient condition for negligible phase distortion is that the phase characteristics be like those in Fig. 1 and Fig. 2 between* $f_1$ *and* $f_1$ *only.*

The phase characteristics actually found in telephone apparatus that frequently must be considered may for convenience be classified as follows: (1) those typical of the low pass filter and the loaded line,

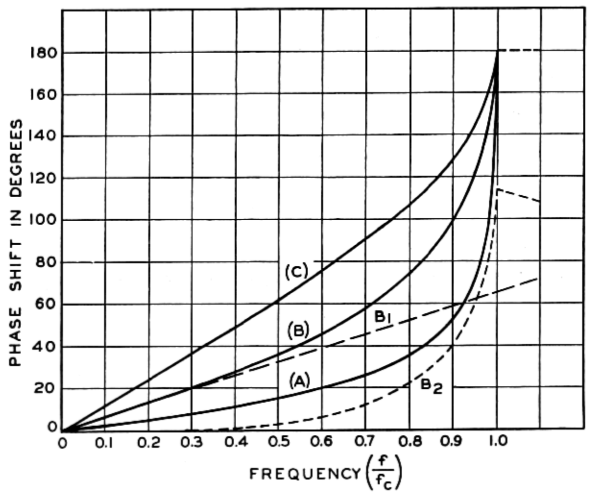


Fig. 3—Image transfer phase characteristics of typical low-pass filter sections. Same as insertion phase characteristic except in neighborhood of $f_c$. Curve *C* resembles closely the phase characteristic of a loaded line.

(2) those of band pass filters, (3) those of high pass filters, and (4) those of all pass networks.[6] The attenuation of all of these networks is fairly constant and small in the transmitting range.

The solid curves of Fig. 3 show the image transfer phase characteristics of typical low pass filter sections having a cut-off frequency $f_c$. The significance of these different type sections will be discussed later. The curve, *C*, resembles closely the phase characteristic of a loaded

[6] An interesting type of insertion phase is that obtained when these four types of apparatus are terminated over a considerable portion of their transmitting range in impedances that differ radically from their image impedances. The wavy phase curves obtained may be said to be chiefly responsible for the so-called reflection effects thus obtained though here too the attenuation plays an important part. If the attenuation in the network is large as in a line this waviness due to miss-match tends to disappear and the phase characteristic resembles closely in general shape that which would be obtained if no miss-match occurred.

line.[7] These curves as well as those in the following three figures are for non-dissipative networks terminated in their image impedances. However, the insertion phase characteristic with dissipation and the usual terminations, i.e. a resistance of fixed value, would not noticeably

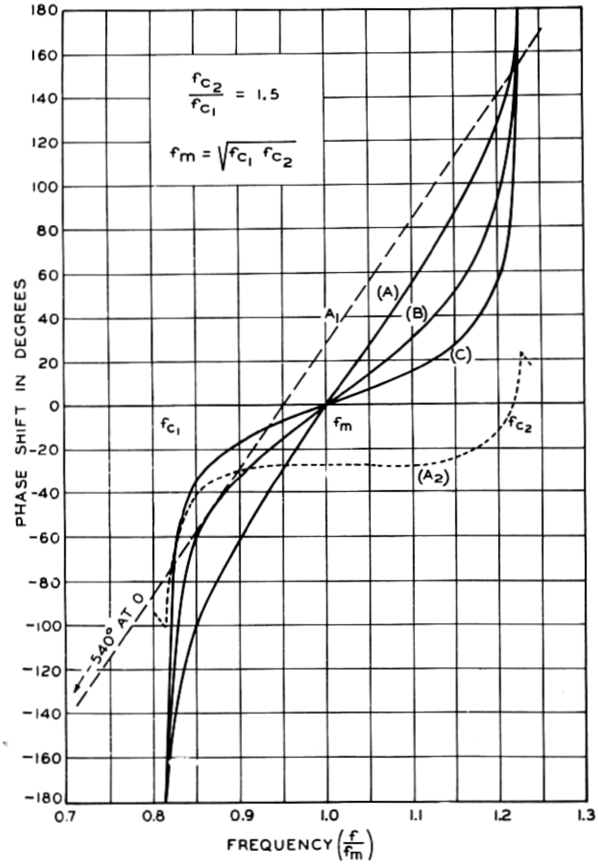


Fig. 4—Image transfer phase characteristics of typical band-pass filter sections

be different in most of the transmitting range. For filters in the latter case in the neighborhood of $f_c$ the slope would be modified so as to remain finite. This will be discussed further in the next section.

The curves of Figs. 4 and 5 show respectively the image transfer

[7] It will be noted that the second derivative of these low pass filter phase curves are positive at all frequencies. However, special sections exist for which this is not true and such sections are occasionally used as discussed later where it is desirable to keep the characteristic as a whole nearly straight over a wider frequency range but low pass filters when considered as a whole generally have phase characteristics of the type shown.

phase characteristics for typical band pass and high pass filter sections. The curves of Fig. 6 are for all-pass lattice type network sections. The frequency $f_r$ is the resonant or anti-resonant frequency of the series arms and cross-arms of the network.

The above four figures show that the phase characteristics are curved in every case over a considerable portion of the transmitted frequency range.[8] A curved phase characteristic like that shown in Fig. 3, curve $B$, for example, may be represented as the sum of a distortionless phase characteristic, $B_1$, of the type shown in Fig. 1 and another curved one, $B_2$, which is the difference between it and the

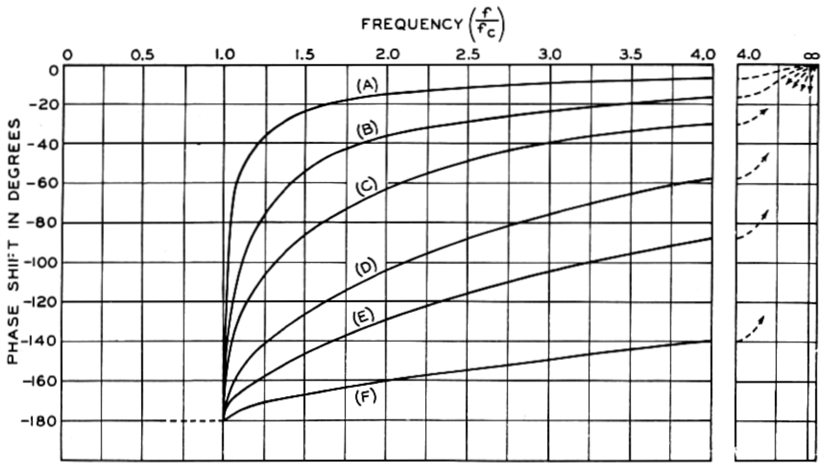


Fig. 5—Image transfer phase characteristics of typical high-pass filter sections.

original,[9] i.e., $B = B_1 + B_2$. The slope of the straight line characteristic is the minimum slope of the original, i.e. the slope at very low frequencies. $B_1$ introduces at all frequencies a definite delay without distortion given by its slope. $B_2$, to which no delay as a whole may be ascribed may be called the phase distortion characteristic of the network, and its derivative $(dB/d\omega)_f - (dB/d\omega)_{\min}$. the *delay distortion characteristic* or simply the *delay distortion*. This procedure is equivalent to regarding the low pass filter as consisting of two parts in tandem the first part introducing a delay without distortion and the second part a distortion. If, after subtracting such straight line portions from low pass filters the remaining curves are the same, the phase

[8] In discussing the phase characteristics of filters only the characteristics in the transmitting range are considered, since in general the frequency components in this range only contribute noticeably to the received signal.

[9] See Appendix II.

distortion would be the same even though the delays might be different due to different slopes of the subtracted portion.[10]

In the case of the band pass filter of Fig. 4 a distortionless portion may be subtracted having the slope of the original at the mid-frequency but only for special cases will it be tangent to the curve. Fig. 4 shows curve $A$ broken into two parts a distortionless part $A_1$ giving delay and a part $A_2$ responsible for the distortion, i.e., $A = A_1 + A_2$. It is doubtful if effects of $A_2$ on speech and music would be noticeably different than any other curve obtained by adding a constant angle to it at all frequencies. This type of variation occurs to the same ex-

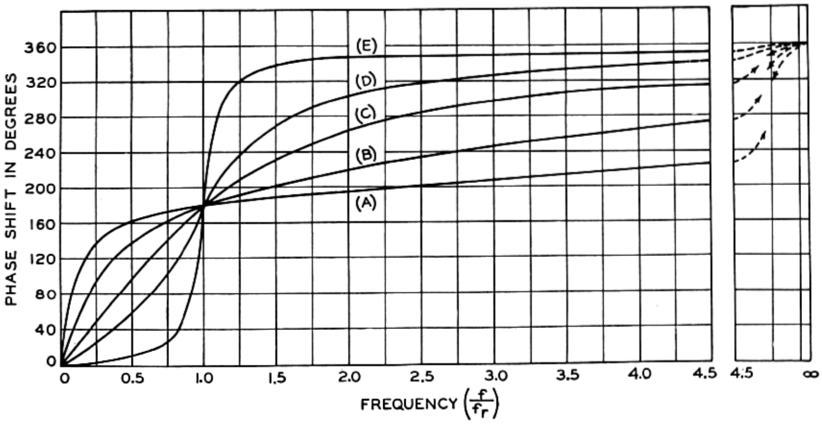


Fig. 6—Image transfer phase characteristics of typical all-pass lattice type network sections.

tent in apparatus observed to produce negligible phase distortion as where distortion is apparent. It is for this reason that the slope of the phase curve rather than the curve itself is generally taken as the criterion for determining the amount of phase or delay distortion in a network. In other words if two phase curves give the same $dB/d\omega$ or delay characteristics (sometimes called "envelope" delay characteristics) they are regarded as introducing the same phase distortion particularly for speech and music though such an assumption is not rigorously true.

In the case of the high pass filters and all pass networks of Figs. 5 and

[10] This procedure of breaking the phase characteristic into two parts one part introducing no distortion but a delay $T_0$ given by the minimum slope in the transmitting range and another part responsible for the distortion is perfectly rigorous, but it *must not* be interpreted to mean that for a signal starting at $t = 0$ absolutely nothing will be received before $t = T_0$. In the first place there is generally a small amount of energy outside the transmitting range that will come through earlier and in the second place, unless the residual phase characteristic is of a kind that can be produced by physical apparatus the distortion characteristic alone will cause the received wave to differ from zero prior to $t = T_0$.

6 the minimum slopes are zero hence no delay can be subtracted which applies to the signal as a whole.[11]

In order to observe the effects of phase distortion in some simple cases [12] we shall show oscillographs of some sent and received non-periodic waves. These waves are of the type that are zero up to time $t = 0$, take the form $y \sin(\omega_0 t + \theta)$ between $t = 0$ and $t = T$ and are zero for all future time.[13] A *Fourier Integral* analysis of these waves would show they contained energy over the entire frequency range, though most of it is confined to frequencies in the neighborhood of $f_0$ where $f_0 = \omega_0/2\pi$.

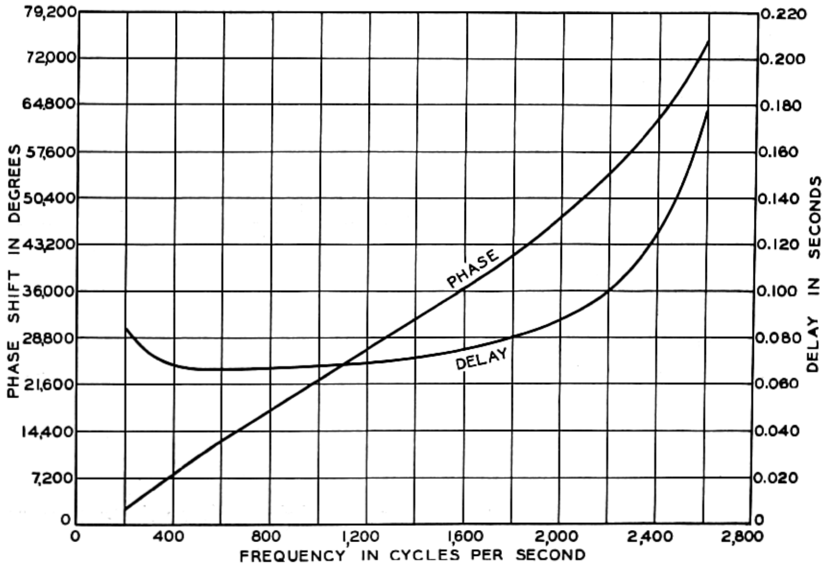


Fig. 7—Insertion phase and delay characteristics of a 600 mile length of medium heavy loaded cable (including repeaters).

Such waves as these are elementary waves which can readily be produced in the laboratory and the effects of distortion on them observed or in special cases the effect may be calculated.

[11] This assumes of course that energy falls in the frequency range where the slope approximates zero. If such were not the case for a particular signal a definite delay could be ascribed given by the minimum slope in the range where the frequency components of consequence fall.

[12] The effect of phase distortion on speech and music signals is discussed in the paper by J. C. Steinberg already mentioned.

[13] It is of interest to note that any complex wave which is zero at all times prior to $t = 0$ and also at all times after $t = T$ may be regarded as the sum of such finite components as these. Analyze it by means of *Fouriers Series* as though it repeated itself as a steady state wave for all time. Then multiply all of the steady state sinusoidal components by zero for all time prior to $t = 0$ and after $t = T$ retaining only the portion for the interval of time $T$. The resultant simple components will add up to give the original complex wave. After distortion the distorted components will add up to give the distorted wave as a whole.

Fig. 7 is the insertion phase and delay characteristic of a 600 mile length of medium heavy loaded cable including repeaters. This cable has a theoretical cut-off of about 2500 cycles. Fig. 8 shows the distortion for two simple waves[14] of the above type, for one $f_0 = 1000$ cycles and for the other $f_0 = 1500$ cycles. The oscillographs show as, predicted, that practically nothing in either case is received until after the time given by the minimum value of $dB/d\omega$, i.e. .0654 seconds. After this time a distorted form of the sent wave occurs. Since for $f_0 = 1000$ most of the energy of the wave as analyzed by the Fourier Integral method of analysis falls in the neighborhood of 1000 cycles

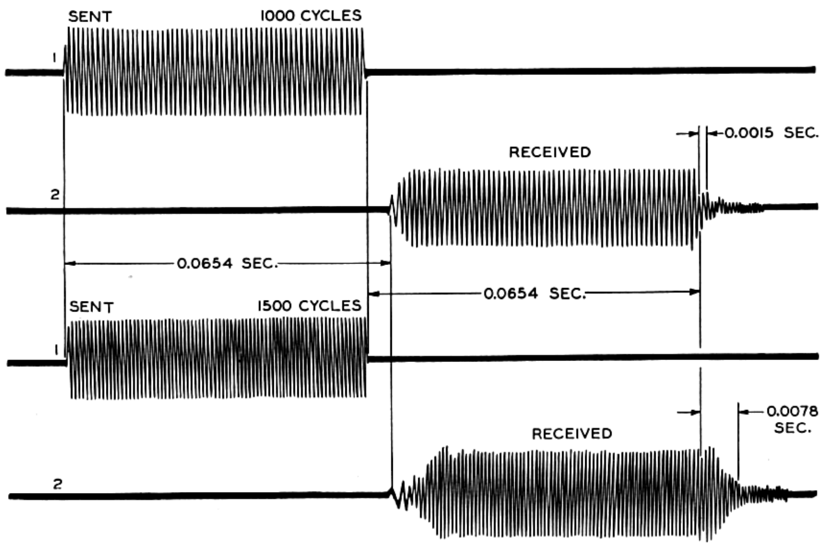


Fig. 8—Distortion resulting from 600 mile length of cable of Fig. 7 for signals of the form $y \sin \omega_0 t + \theta$ between $t = 0$ and $t = T$ and zero for all other time.

where the delay characteristic is reasonably constant this wave is not distorted much. In the case for $f_0 = 1500$ cycles a larger portion of the energy falls in the neighborhood of 1500 cycles where the delay characteristic is changing more rapidly and it is therefore distorted more. $(dB/d\omega)_{f_0} - (dB/d\omega)_{\min.}$ may be taken as a fair measure of the distortion of such simple waves although higher derivatives are also involved.

Fig. 9 shows the insertion delay characteristic for a system consisting of four band filters in tandem. The attenuation characteristic is also

[14] Reproduced from the paper by Sallie P. Mead, loc. cit.

shown. Fig. 10 shows oscillographs for waves of the above type for $f_0 = 260$, 300, 480 and 680 cycles per second. Notice that the distortion is much greater where $f_0$ falls near the edges of the transmitting band, although in every case the wave starts noticeably building up at about .0109 seconds after $t = 0$ for the sent wave. This is the value of $(dB/d\omega)_{\text{min.}}$ in the transmitting range of the filters. In both Figs. 8

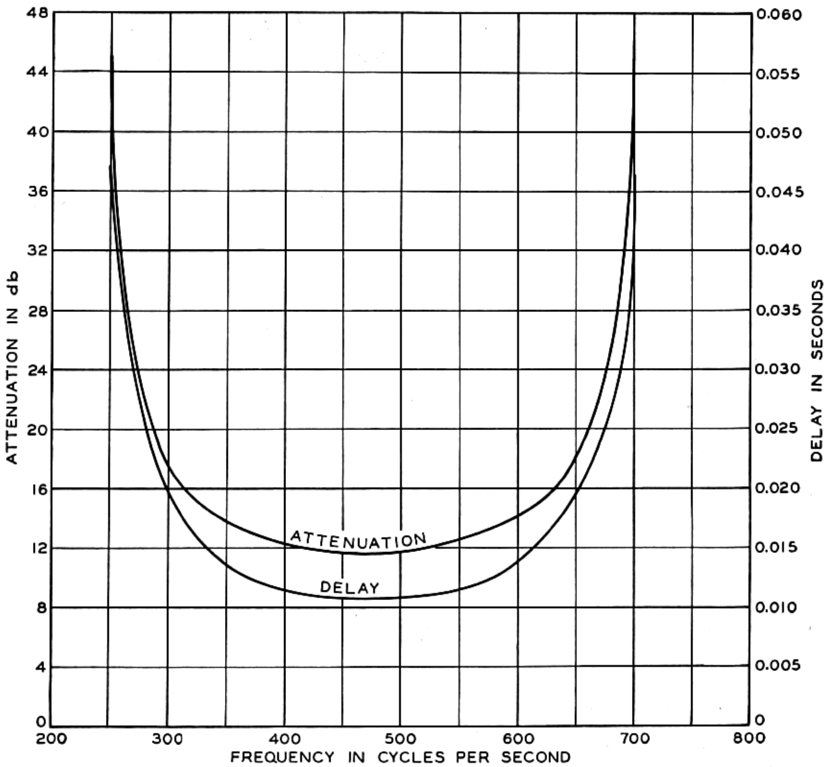


Fig. 9—Insertion delay and attenuation characteristics of 4 band-pass filters in tandem.

and 10 some of the distortion may be ascribed to attenuation although the *elongation effect* is primarily due to phase distortion. It is this elongation effect that is noticeable to the ear in speech and music.

## Phase Distortion and Its Correction

This section of the paper will contain a more specific discussion of the phase characteristics of apparatus and the means employed for keeping phase distortion within desirable limits.

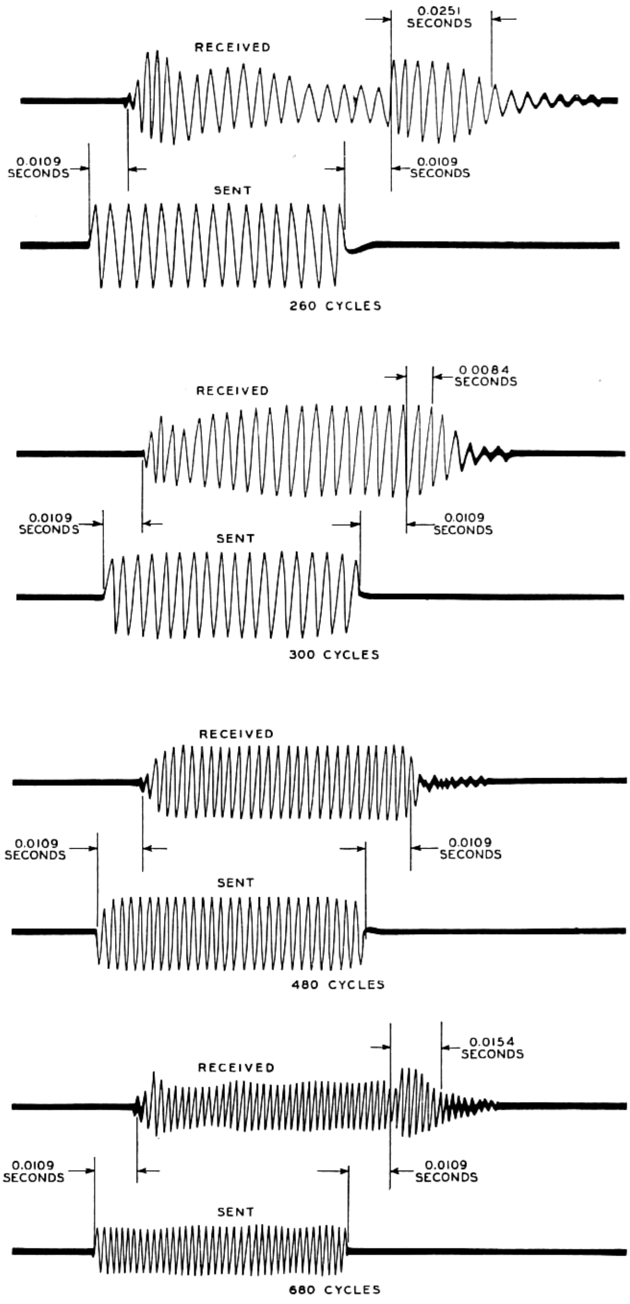


Fig. 10—Distortion resulting from four band filters of Fig. 9 for signals of the form $y \sin \omega_0 t + \theta$ between $t = 0$ and $t = T$ and zero for all other time.

1. *Telephone Cable.*—Two of the cases where phase distortion in telephone cable has been considered objectionable will be discussed: (1) In the newly developed high quality cable circuit for transmitting programs to and between broadcasting stations [15] which circuit is

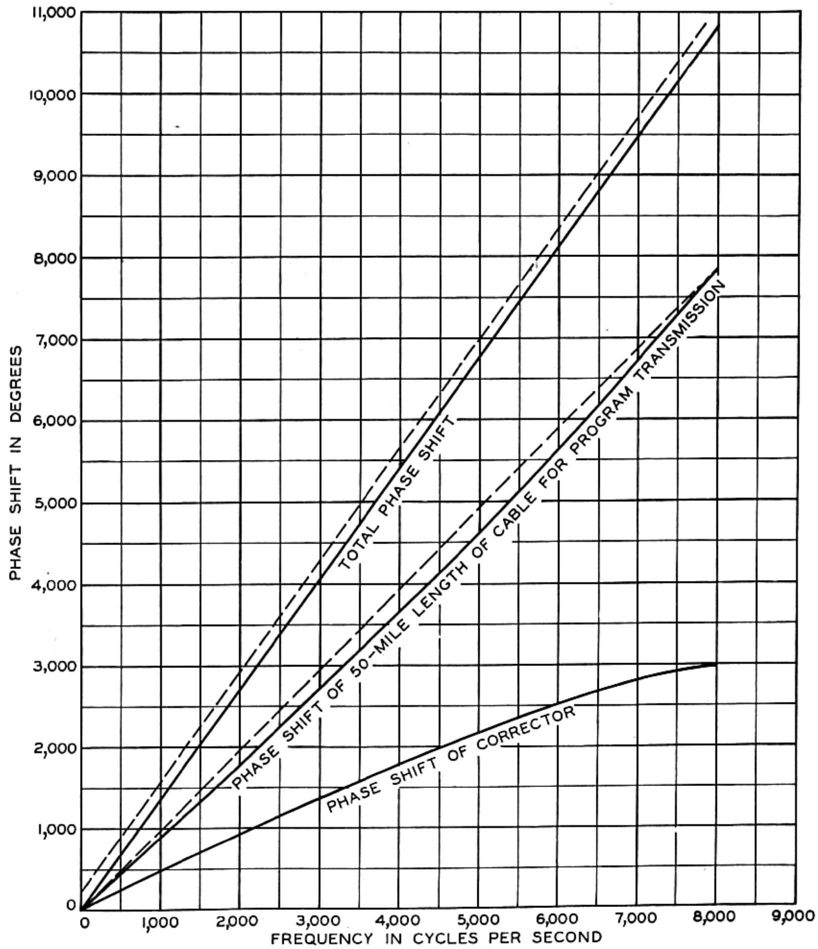


Fig. 11—Insertion phase characteristic of a 50 mile length of cable for program transmission. Also, phase characteristic of a phase corrector for this cable and for the sum of the two

designed to transmit with negligible amplitude and phase distortion all frequencies between 50 and 8000 cycles and (2) a proposed cable

[15] Long Distance Cable Circuit for Program Transmission, A. B. Clark and C. W. Green, to be presented at Summer Convention *A. I. E. E.*, Toronto, June, 1930. This cable consists of No. 16 gauge copper wire with 22 millihenry loading coils spaced every 3000 feet.

circuit [16] for regular long distance telephone message service designed to transmit with negligible distortion frequencies between 200 and 3000 cycles.

Fig. 11 shows the insertion phase characteristic of a 50 mile length of the cable for program transmission (exclusive of repeater). The broken line is drawn to bring out more clearly the curvature in the

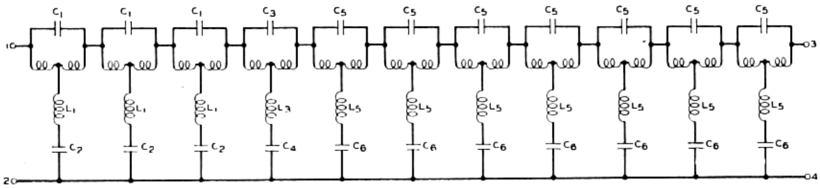

Fig. 12—Schematic of the phase corrector for a 50 mile length of cable for program transmission.

phase characteristic. Fig. 12 shows a schematic of the phase corrector used to correct for a 50 mile length of this cable. The insertion phase characteristic of this corrector as well as that of both the cable and corrector combined are also shown in Fig. 11. It will be noticed that a

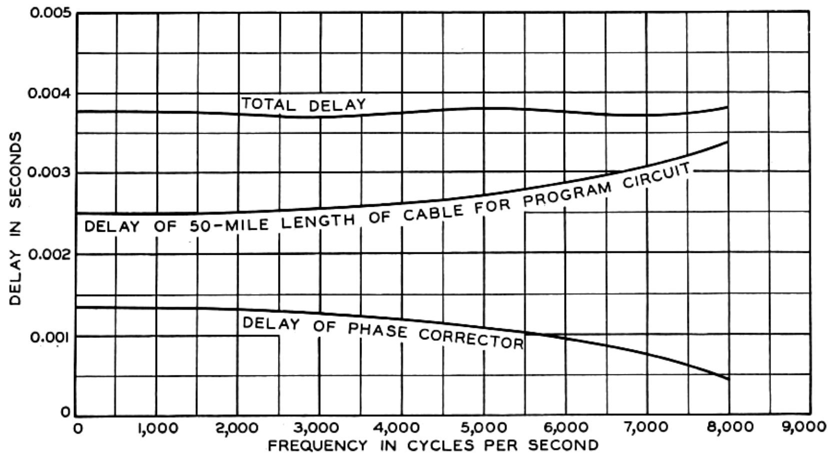


Fig. 13—Insertion delay characteristics corresponding to phase characteristics of Fig. 11.

single phase corrector consists of eleven sections, seven of one kind, three of another, and one of a third. Each section contains one two-terminal inductance coil and one three-terminal coil with mutual between the two windings and also two condensers. Fig. 13 gives

[16] This cable consists of No. 19 gauge copper wire with 44 millihenry loading coils spaced every 6000 feet.

$dB/d\omega$ for the cable, the phase corrector, and the two combined. A 50 mile length of corrected cable gives a delay of .00375 seconds. A 3000 mile length [17] of this cable such as would extend from coast to coast would give a delay of .225 seconds, with a difference between the

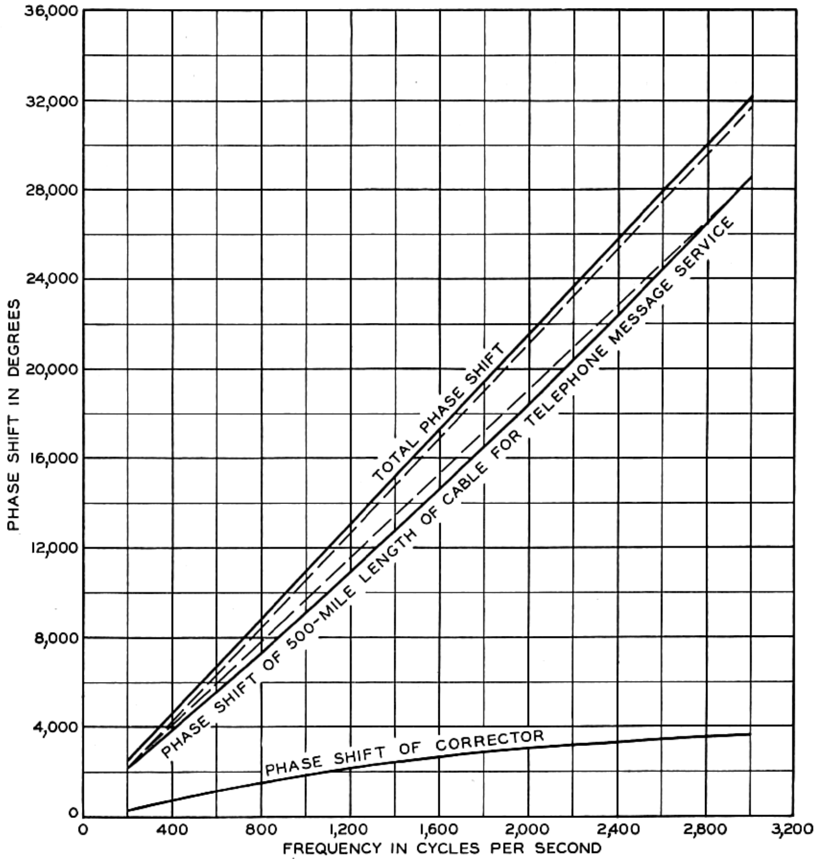


Fig. 14—Insertion phase characteristics of a 500 mile length of cable for telephone message service.

minimum and maximum value of .006 seconds in the corrected range. Without correction this difference would have been .055 seconds.

Figs. 14, 15 and 16 correspond respectively to the previous three but are for a 500 mile length of the cable for regular telephone message service. The total delay for 500 mile length of this cable after correc-

[17] In designing apparatus going in long distance circuits in general the parts are so designed that if a circuit 3 or 4 thousand miles long is used the total accumulated distortion due to either amplitude or phase will be within tolerable limits.

tion is .029 seconds. A 3000 mile length would give .174 seconds delay. The difference after correction for 3000 miles between minimum and maximum value of $dB/d\omega$ is .007 seconds and before correction .035 seconds. This phase corrector (for 500 miles) consists of 12 sections, 8 of one kind and 4 of another. Each section contains four condensers and two four-terminal inductance coils with mutual between windings. Both this phase corrector and the previous one are formed by connecting together such all-pass network sections as to give the phase characteristic desired. In the first bridge T-sections are used and in the second lattice type.[18] The former are more economical when unbalanced apparatus may be used, though similar phase characteristics may generally be obtained with either.

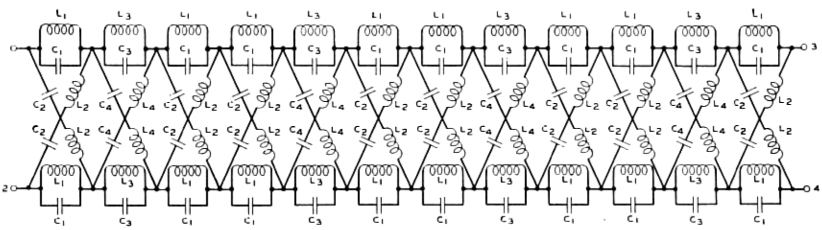

Fig. 15—Schematic of the phase corrector for 500 mile length of cable for telephone message service.

2. *Filters.*—The following factors influence the phase distortion in filters: (1) The width of the frequency band transmitted, (2) the amount of discrimination between transmitted and attenuated regions (corresponds to number of filter sections), (3) the rate at which the attenuation rises at the edges of the transmitting band, (4) the types of filter sections used, (5) the number of filters in tandem, (6) the amount of reflection due to impedance mis-match near the edges of the transmitting bands, and (7) the amount of dissipation in the filter elements.

The insertion phase characteristics of Fig. 17 and the insertion delay characteristics of Figs. 18 and 19 are for two low pass filters [19] of the usual type. As will be seen from their attenuation characteristics (insertion loss) each gives a discrimination of about 35 db, although the second requires an additional section in order to provide the rapidly

[18] Nyquist, U. S. patents Nos. 1,675,460 and 1,735,052 and Zobel patent No. 1,701,552; Maximum Output Network for Telephone Substation and Repeater Circuits, by G. A. Campbell and R. M. Foster, *Trans. A. I. E. E.*, Vol. 39, pp. 231–280.

[19] This note explains symbols used in these three figures and also the following three. $Z_I$ is the image impedance. $Z_0$ for a low pass filter is the value of $Z_I$ at zero frequency and for a high pass filter at infinite frequency. $Q$ is the ratio of the coil reactance to its effective resistance. Dissipation in the condensers is considered negligible. For a filter section having an attenuation peak at frequency, $f_\infty$, and a cut-off at, $f_c$, "a" is the ratio $f_\infty/f_c$ for a low pass filter and $f_c/f_\infty$ for a high pass filter.

rising attenuation at the edge of the band. These curves show that the delay distortion in the transmitting band is increased by increasing the slope of the attenuation curve at the cut-off although the minimum value—i.e. the delay which applies to the signal as a whole, does not increase appreciably. The effective band width transmitted depends upon both the delay and attenuation characteristics since especially

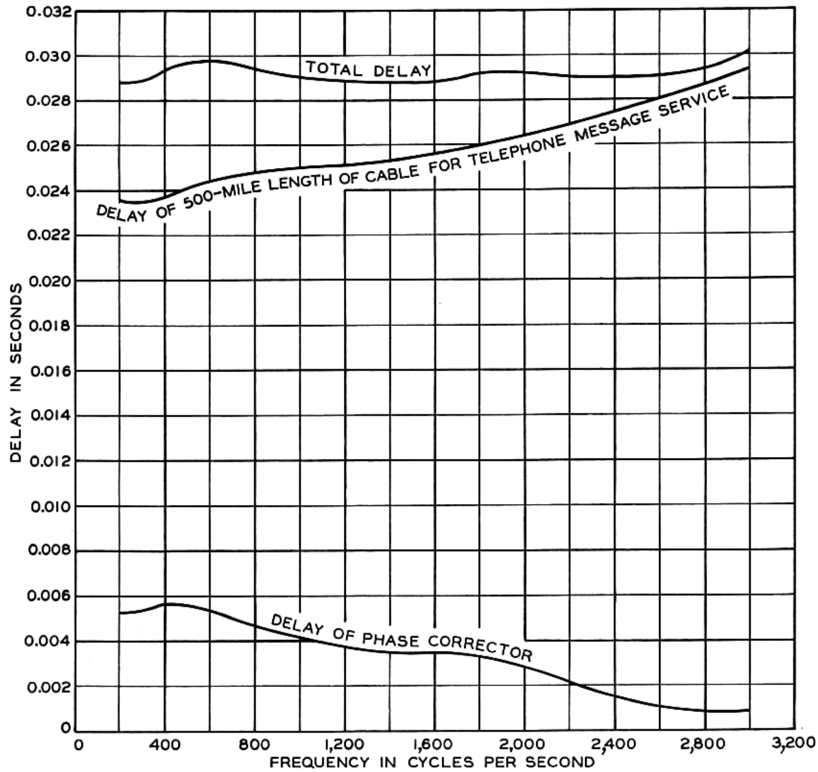


Fig. 16—Insertion delay characteristics corresponding to the phase characteristics of Fig. 14.

for a number of filters like these in tandem the delay of the frequency components of the wave near the cut-off may be so great that these components contribute little to articulation. Therefore in the design of filters a proper balance must be determined between the rate of attenuation and the delay distortion. A more complete discussion of the relation between delay, attenuation, and the effective cut-off is given in the paper by J. C. Steinberg.[20] When low pass filters are to be designed with sharper cut-offs from the standpoint of both delay and attenuation, there are two ways in which this is usually done, one

[20] Loc. cit.

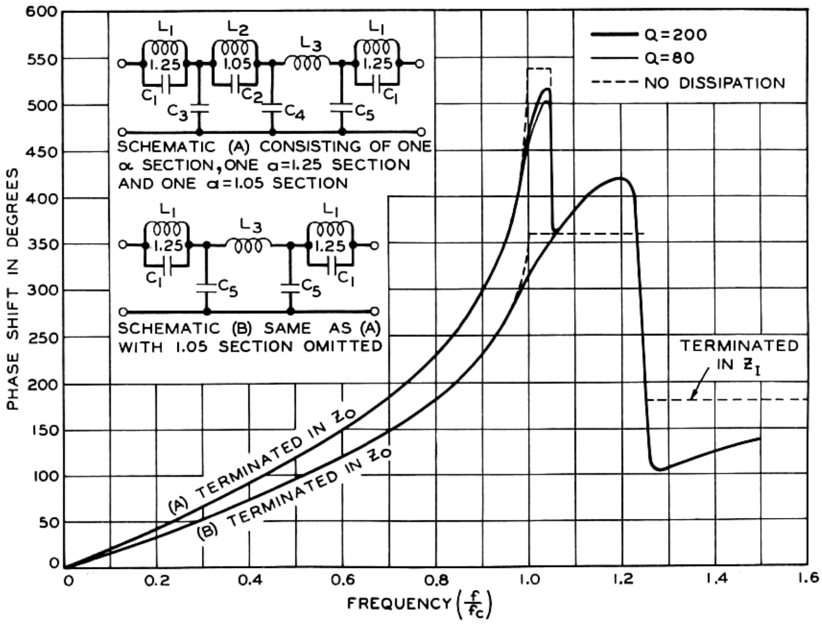


Fig. 17—Insertion phase characteristics and schematics of low-pass filters. (*A*) For a filter consisting of 3 full sections, one section having no attenuation peak, one with a peak at $1.25f_c$ and another at $1.05f_c$. (*B*) Same as (*A*) with the 1.05 section omitted.

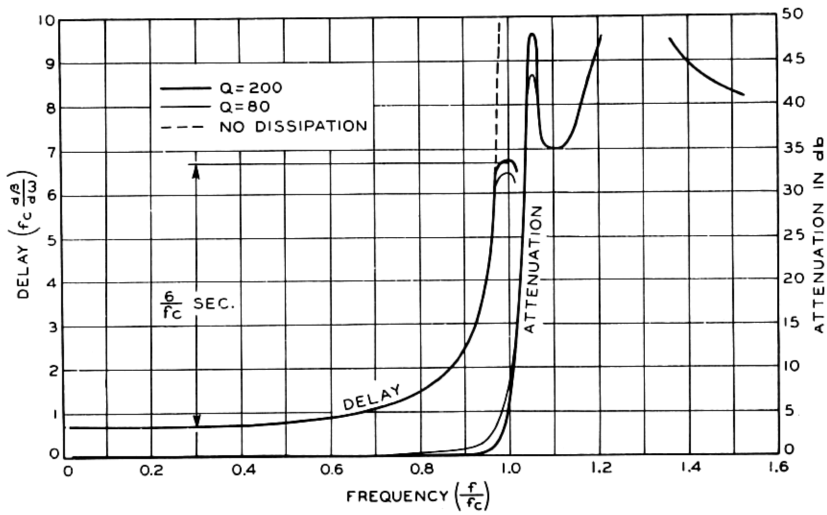


Fig. 18—Insertion delay and attenuation characteristics for filter *A* of Fig. 17.

is the use of a few filter sections of a type different from the usual types above having phase characteristics with a negative second derivative rather than positive so that the combination will postpone the occurrence of phase distortion until very near the theoretical cut-off and the other is the addition of all pass network sections which accomplish the same general result.

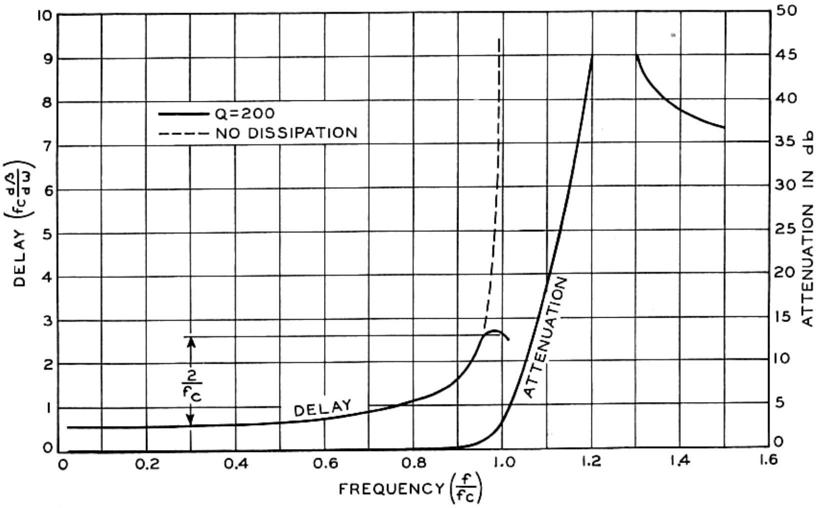


Fig. 19—Insertion delay and attenuation characteristics for filter *B* of Fig. 17.

One other point should be noted here. The shape of the insertion phase curve as shown at the cut-off frequency owes its departure from the image transfer phase shift without dissipation shown by the dotted line more because of the reflection than dissipation. The value of the $Q$ so long as it is within the usual range makes little difference.

Figs. 20, 21 and 22 correspond to those of 17, 18 and 19 but are for high pass filters. High pass filters introduce no initial delay to signals as a whole. The distortion of the signal is dependent upon sharpness of cut-off, $Q$ etc. just as for low pass filters.

Band pass filters give an initial delay defined by the shape of the phase curve. Other factors remaining the same this delay as well as the amount of phase distortion is inversely proportional to $f_2 - f_1$ the band width in cycles and is independent of the position of the band on the frequency scale. The effect of reflection, dissipation, sharpness of cut-off, etc., are about the same at the lower cut-off as for a high pass filter and at the upper cut-off as for a low pass. As already noted one distinguishing feature of the phase characteristic of a band pass filter

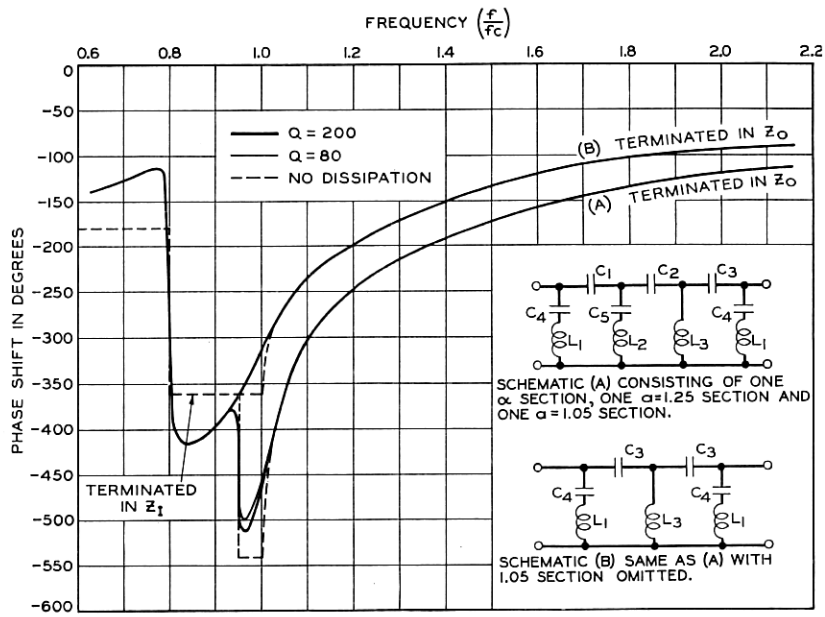


Fig. 20—Insertion phase characteristics and schematics for high-pass filters. ($A$) For a filter consisting of 3 full sections, one section having no attenuation peak, one with a peak at $1/1.25f_c$ and another at $1/1.05f_c$. ($B$) Same as ($A$) with the $1/1.05f_c$ section omitted.

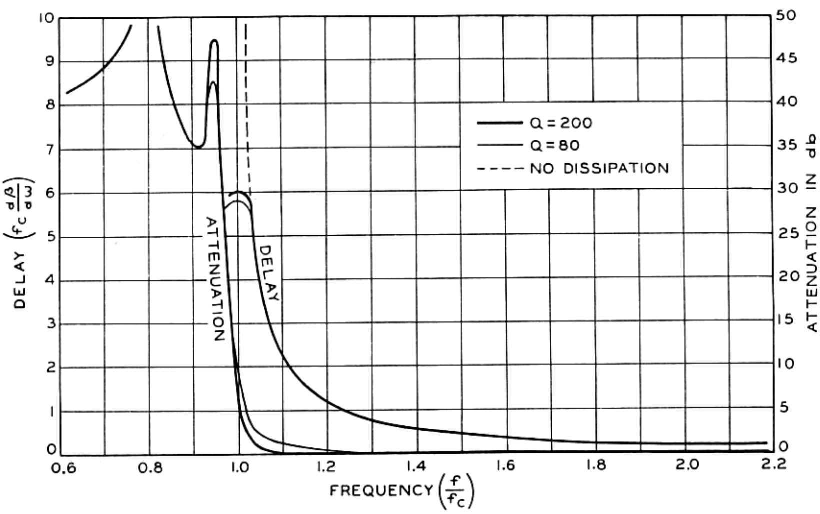


Fig. 21—Insertion delay and attenuation characteristic for filter $A$ of Fig. 20.

is that the straight portion of the phase curve may if extended intersect the vertical axis at any point and does not like the low pass filter pass always through $N\pi$.

As an example of a condition where it has been found necessary to take phase into consideration in designing low pass filters let us consider the case of line filters used in open wire circuits transmitting simultaneously both programs for broadcasting and carrier telephony. Here as many as 40 or 50 filters may be used in tandem.

Fig. 23 shows the measured delay and attenuation characteristics

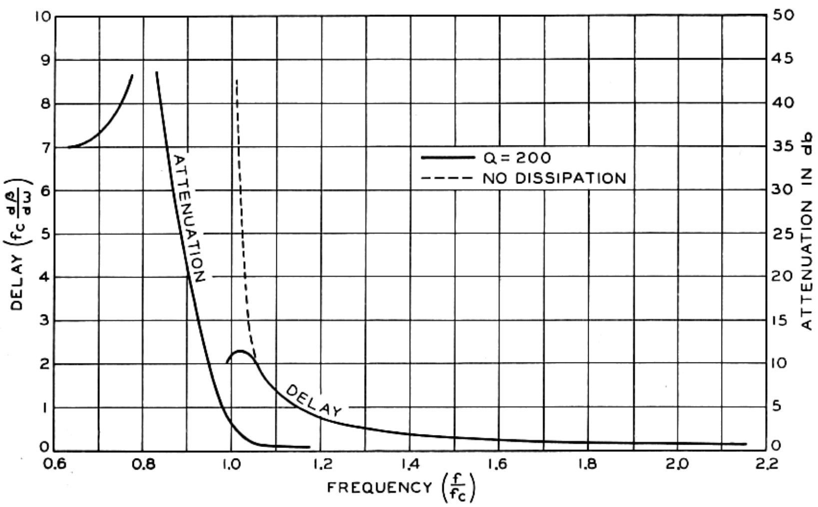


Fig. 22—Insertion delay and attenuation characteristic for filter *B* of Fig. 20.

for 25 of the present 5000 cycle quality line filters now in use, these filters being connected in tandem. The circuit is so designed that it practically equalizes up to 5000 cycles for the attenuation distortion. When a number of these filters are used in tandem as in the longest "hook ups" the phase distortion of these filters is somewhat noticeable but not seriously so and their effective cut-off is appreciably lowered because of this phase distortion.[21]

Fig. 24 gives the calculated delay and attenuation of twenty-five 8000 cycle low pass line filters connected in tandem. This filter is being considered for use in place of the 5000 cycle line filter of Fig. 23. The delay for 25 of these filters in tandem is approximately constant up to 7500 cycles (within .001 seconds). The attenuation is also constant up to this frequency. The attenuation

[21] J. C. Steinberg, loc. cit.

distortion between 7500 and 8000 cycles is purposely left uncorrected so that if these filters are used when a number of them are connected in tandem on a line, the effective cut-off will be lowered therefore eliminating the effects of any accumulating delay over this range. Thus for short distances 8000 cycle quality will be realized, and for very long circuits 7500 cycle quality, and for intermediate lengths something in between. In any case the effects of delay distortion will be negligible. Special filter sections are used in order to meet the unusual delay and attenuation requirements. The same results could

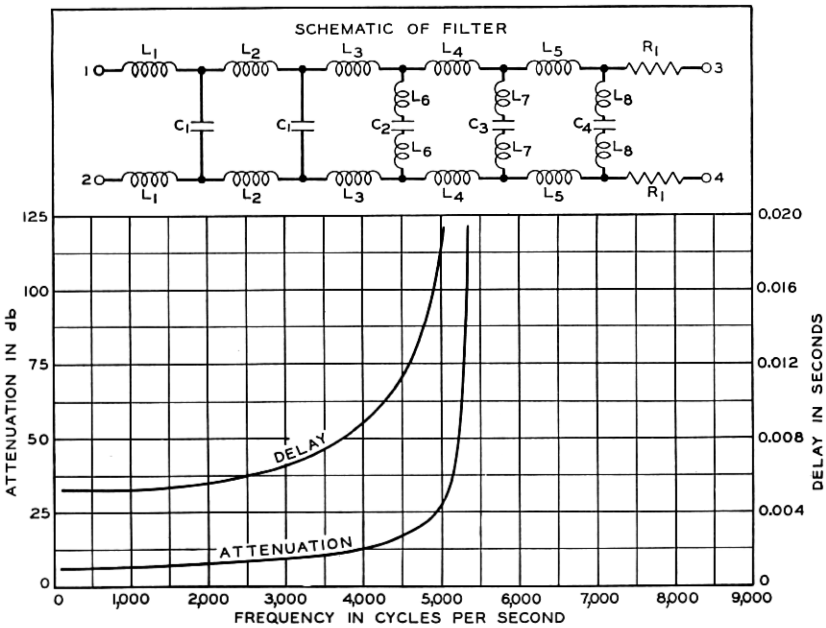


Fig. 23—Schematic, insertion delay and attenuation characteristics of twenty-five 5000 cycle low-pass line filters connected in tandem.

have been obtained using the usual type sections like those used in the 5000 cycle filter and then correcting for phase by an all-pass structure. Such a method would have resulted in a somewhat more expensive filter and one giving more overall delay.

3. *Repeaters.*—The chief sources of delay in telephone repeaters are the transformers. However, some additional low frequency delay is caused by shunt retard coils and series condensers. This is kept within negligible limits by using large values of both. Conversely inductance in series and capacitance in shunt cause high frequency delay but this effect can easily be made negligible in any frequency range in which one is interested. Fig. 25 is a schematic of the telephone repeater

used in the cable circuit previously referred to for program transmission. A repeating coil and input transformer at its input and the output transformer at its output are shown. These will be discussed in the next paragraph.

4. *Transformers.*—As an example of phase distortion in transformers we shall consider those shown in the telephone repeater of Fig. 25. Here, the phase shift of a small number of transformers would be of little importance but where a large number are connected together as in long toll circuits their effect cannot be overlooked. The delay caused by a transformer is similar to that of a high-pass filter. The

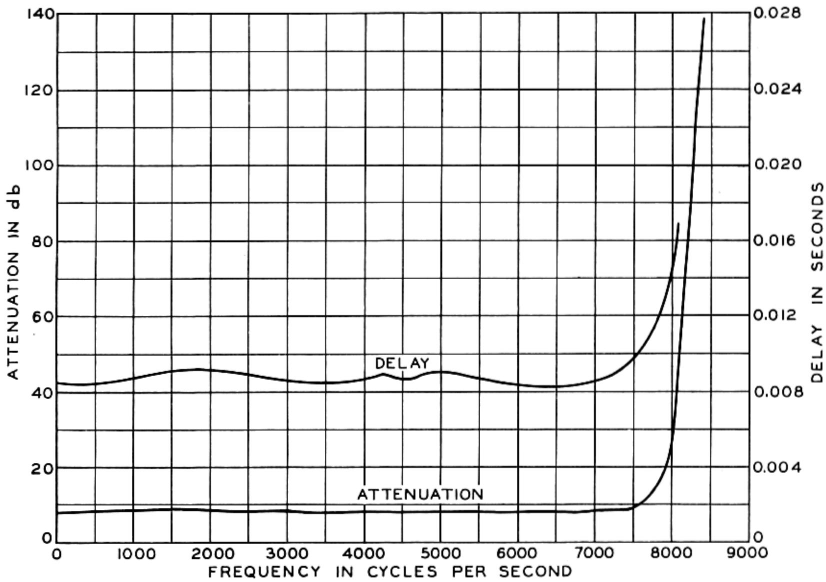


Fig. 24—Insertion delay and attenuation characteristics of twenty-five 8000 cycle low-pass line filters connected in tandem.

insertion phase characteristics of these three transformers between impedances for which they were designed are shown in Fig. 26 and their insertion delay characteristics, $dB/d\omega$ in Fig. 27. It will be noticed that practically all of the delay occurs below 100 cycles. The three together give at 40 cycles a value of $dB/d\omega$ of .0008 seconds. 25 sets would give .020 seconds delay. Experience has shown that this amount of delay for speech at low frequencies is negligible whereas at high frequencies such would not be the case.[22]

5. *Attenuation Equalizers.*—Attenuation equalizers introduce some phase distortion but the amount is so small that it can generally be

[22] At high frequencies $(dB/d\omega)_{\text{max.}} - (dB/d\omega)_{\text{min.}}$ must generally be kept under .005 to .010 seconds if its effect can be neglected for speech.

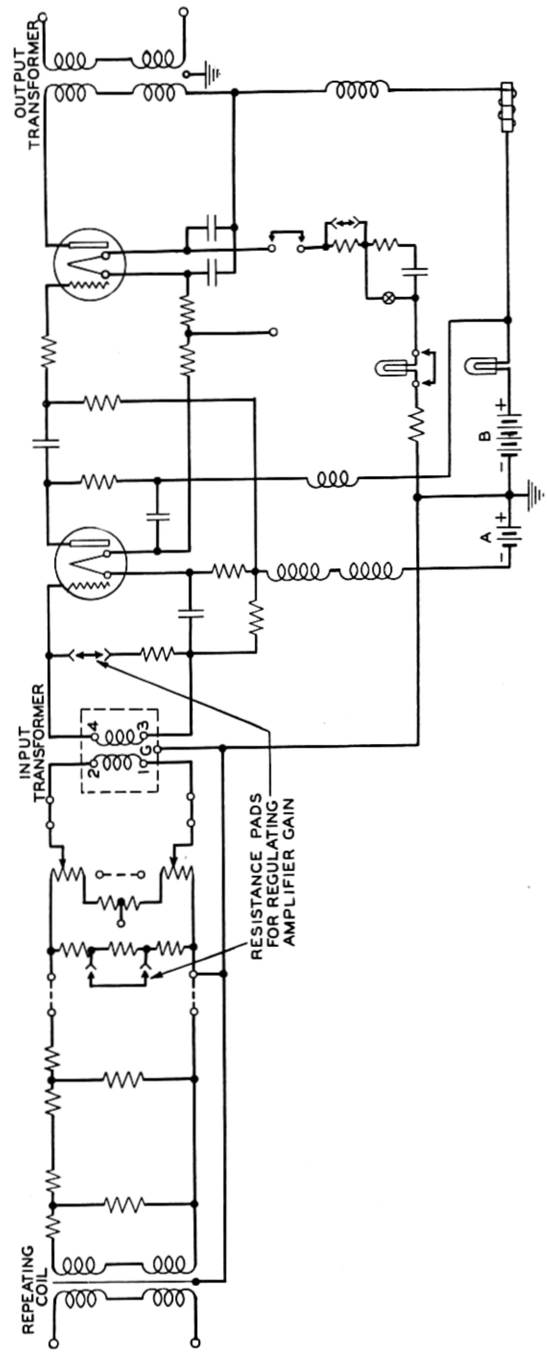


Fig. 25—Schematic of repeater used in the cable circuit for program transmission.

neglected. The presence of such equalizers in the circuit for program transmission did not influence the design of the phase correctors. However in considering the design of the equalizers the particular structure used was chosen on the basis of its giving a minimum amount of phase distortion.

## Phase Distortion in Other Communication Systems

Phase distortion has for some time been considered a real problem in submarine cable telegraphy. If the highest reversal frequency of a telegraph signal is $f_v$ it has been found expedient to correct for both

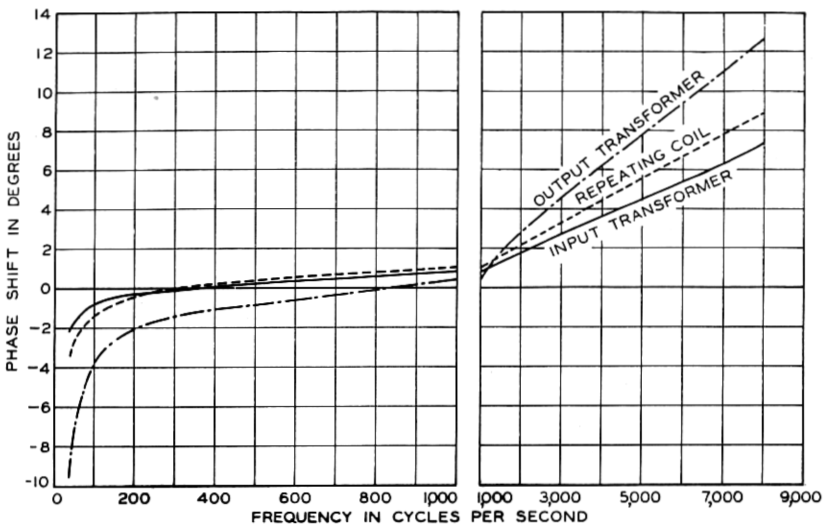


Fig. 26—Insertion phase characteristics of repeating coil, input transformer and output transformer used in repeater shown in Fig. 25.

amplitude and phase distortion over a frequency range of from zero to between 1.4 and 1.6 $f_v$. More phase distortion can be tolerated when the signal is read by the operator from a siphon recorder slip than for automatic printing. In the case where $f_v$ is 60 cycles per second a 45° departure (at 60 cycles) from the low frequency characteristic if continued as a straight line it has been found in some cases to cause errors to be printed.

While no two telegraph cables are alike all except very short ones require that some means of phase correction be incorporated in the terminal apparatus. Although the general principles of correction have been investigated mathematically and the results have been very useful as a guide in indicating the relative effects of factors involved, the practical solutions so far have been largely empirical. This is due to the comparative simplicity of the experimental method. The results of a number of adjustments in the terminating apparatus may be observed experimentally while one is investigated mathematically. This is due to the fact that one can tell, using an oscillograph, from the direct observation of the received signal when a proper adjustment is reached. It is not necessary, as in telephony, to make complete

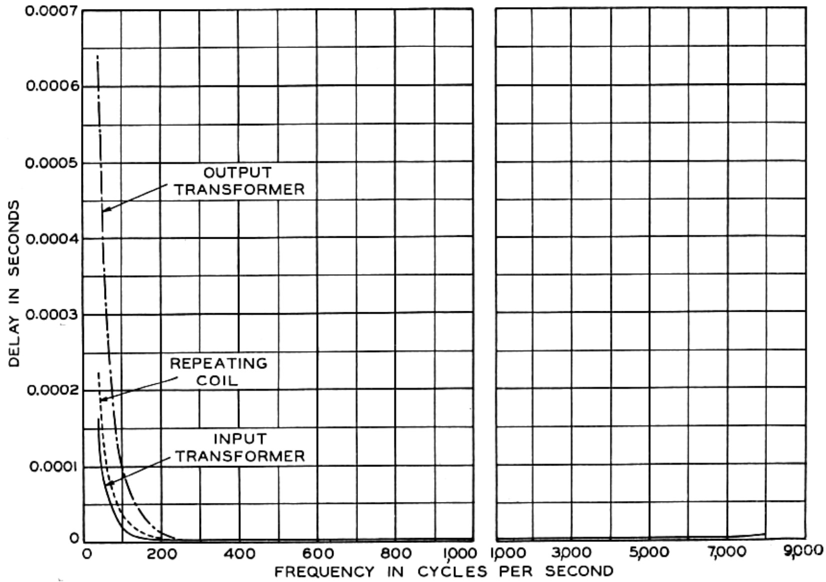


Fig. 27—Insertion delay characteristics corresponding to the phase characteristics of Fig. 26.

articulation tests or a large number of single frequency measurements. The advent of the continuously loaded cable made possible by the use of permalloy has simplified the problem. A discussion of detailed methods of phase correction in telegraph cable cannot be gone into here. Circuits in general use have been described in previous publications.[23]

Two other important places where it has been necessary to control phase distortion are (1) in circuits for picture transmission [24] and (2)

[23] The Loaded Submarine Cable, O. E. Buckley, *Bell Sys. Tech. Jour.*, July, 1925; High Speed Ocean Cable Telegraphy, O. E. Buckley, *Bell Sys. Tech. Jour.*, April, 1928; The Application of Vacuum Tube Amplifiers to Submarine Telegraph Cables, A. M. Curtis, July, 1927; Automatic Printing for Long Loaded Submarine Telegraph Cables, A. A. Clokey, *Bell Sys. Tech. Jour.*, July, 1927; J. R. Carson (U. S. Patent 1,315,539) and R. C. Mathes (U. S. Patent 1,311,283).

[24] Transmission of Pictures over Telephone Lines, H. E. Ives, J. W. Horton, R. D. Parker and A. B. Clark, *Bell Sys. Tech. Jour.*, April, 1925.

television circuits.[25] The necessity in both cases is similar. In picture transmission the frequencies between 900 and 1700 cycles were involved and a maximum departure for the system as a whole of $dB/d\omega$ from a constant value of .0005 seconds in this frequency range was found permissible. In television it was considered desirable to transmit frequencies over the range from 10 cycles to 20,000 cycles such that the value of $dB/d\omega$ as a function of frequency was constant about $\pm$.00002 seconds over all but the lowest part of the range. There at the very lowest frequency $\pm$.001 seconds was considered permissible.

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## Appendix I

### *Phase Shift Defined*

Networks with a pair of input terminals and a pair of output terminals such as lines, filters, equalizers, phase correctors, transformers, etc., are designed to work between a source of e.m.f. $E_a$, of impedance $Z_a$, and a receiving device of impedance, $Z_b$. The source of e.m.f. is generally spoken of as the generator and the receiving device as the load. Such a network, $N$, connected to a generator and a load are shown in Fig. 28. Terminals 1 and 2 are the input terminals and 3 and 4 the output terminals.

For any frequency let $Z_a = W_a$ be the image impedance[26] at ter-

[25] Production and Utilization of Television Signals, F. Gray, J. W. Horton and R. C. Mathes, *Bell Sys. Tech. Jour.*, October, 1927; Wire Transmission Systems for Television, D. K. Gannett and E. I. Green, *Bell Sys. Tech. Jour.*, October, 1927.

[26] The image impedance at either end of a four terminal network is given by the square root of the product of two impedances at that end, one measured with the opposite end short circuited and the other with it open circuited.

minals 1 and 2 and $W_b$ at 3 and 4. For these terminating conditions let the input current be $I_a'$ and the output current $I_b'$. The image transfer constant, $\theta$, of the network then is

$$\theta = \log_e \frac{I_a'}{I_b'} \sqrt{\frac{W_a}{W_b}}\,. \tag{1}$$

Let

$$\theta = A' + jB' \tag{2}$$

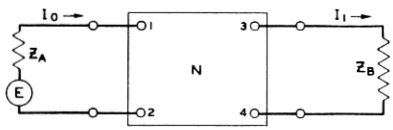


Fig. 28—Network connected between a generator of impedance $Z_a$ and a load of impedance $Z_b$.

$A'$ is the real part of the image transfer constant and $B'$ is the imaginary part. We have

$$\frac{I_a'}{I_b'} \sqrt{\frac{W_a'}{W_b'}} = e^{\theta} = e^{A'} \underline{|B'}. \tag{3}$$

$B'$ is the *image transfer phase shift* of the network.[27] Its value as a function of frequency gives the *image transfer phase characteristic* of the network.

There is another type of phase shift of more frequent use. Let $I_b$ be the current through the load before insertion of the network, i.e., when the generator and load are connected directly together or connected together by means of an ideal transformer of the best turns ratio. Let $I_b''$ be the current through the load with the network in place as shown in Fig. 28. Then

$$\frac{I_b}{I_b''} = e^{A''} \underline{|B''} \tag{4}$$

$B''$ is the *insertion phase shift.*[28] It will be noted that when the terminating impedances are the image impedances that $B'$ and $B''$ are the same.[29]

In most practical cases the phase shifts as defined above are determined for pure resistance terminations hence the phase shifts may equally well be said to relate the applied voltage to the received current. The angle of lag of the received current is regarded as positive.

[27] 20 $\log_{10} e^{A'}$ gives the image transfer loss in decibels.
[28] 20 $\log_{10} e^{A''}$ gives the insertion loss in decibels.
[29] The term insertion loss and insertion phase shift is here extended to include cases where apparatus is designed to work between resistance impedances of different values.

## Appendix II

### *Analytical Discussion of Phase Characteristics*

By means of the Fourier Integral any signal or wave whatever may be regarded as the sum of an infinite number of steady state sinusoidal frequency components which have existed and will exist for all time. Their amplitudes are infinitesimal and they are separated by differentially small amounts in their frequency spectrum. The finite wave is the sum of the infinitesimal components and is determined by their relative amplitudes and phases. The general Fourier Integral for the wave $I_a$ may be written

$$I_a = \int y \cos (\omega t + \theta) \, d\omega, \tag{5}$$

where $\omega = 2\pi f$, $f$ being the frequency. $y$ and $\theta$ are functions of $\omega$. If the amplitude is altered by a constant factor at all frequencies there is no amplitude distortion. For the purpose of discussing phase distortion we shall assume this factor unity. Let the angle be modified by any network by an angle $B$ which is a function of frequency. The expression for the received wave will then be

$$I_b = \int y \cos (\omega t + \theta - B) \, d\omega. \tag{6}$$

Let us assume a simple case where $B$ is proportional to frequency, i.e.

$$B = a_1 \omega. \tag{7}$$

Then

$$\begin{aligned} I_b &= \int y \cos (\omega t + \theta - a_1 \omega) d\omega \\ &= \int y \cos (\omega(t - a_1) + \theta) d\omega \\ &= \int y \cos (\omega t' + \theta) d\omega, \end{aligned} \tag{8}$$

where

$$t' = t - a_1. \tag{9}$$

This then is identical with the original wave form but occurs at a time $a_1$ later given by

$$\frac{B}{\omega} = \frac{dB}{d\omega} = a_1. \tag{10}$$

Such a phase curve then gives no distortion but a *delay*.[30]

The phase characteristic of a low pass filter or cable in the transmitting range may be written

$$B = a_1 \omega + a_2 \omega^2 + a_3 \omega^3 \cdots. \tag{11}$$

[30] It can be readily seen that for any portion of the phase characteristic we may have $B = a_1\omega \pm N\pi$. $N$ is an integer where $N$ is even the results will still be the same as for $N = 0$ since $\cos (N\pi + \theta) = \cos \theta$. If $N$ is odd the only difference is a change in sign of $I_b$.

We may consider the signal as operated on successively by different portions of the phase characteristic. The first term $a_1\omega$ delays the signal without distortion by time $a_1$, the remaining terms distorting it.

The phase characteristic of a constant $K$ band pass filter and those derived from it may, in the transmitting range, be written

$$B = a_1(\omega - \omega_m) + a_2(\omega - \omega_m)^2 + a_3(\omega - \omega_m)^3 \cdots. \quad (12)$$

Let $a_0 = a_1\omega_m$. $a_1$ again defines delay of the signal without distortion provided $a_0 = N\pi$. If $a_0 \neq N\pi$ there is a delay $a_1$ and in addition every component is shifted through an angle $a_0$ and then distorted by the remaining terms. Let us see what the constant phase shift $a_0$ of itself does to the signal.

We may write

$$I_b = \int y \cos(\omega t + \theta - a_0)d\omega \quad (13)$$

or

$$I_b = \cos a_0 \int y \cos(\omega t + \theta)d\omega + \sin a_0 \int y \sin(\omega t + \theta)d\omega. \quad (14)$$

The wave resulting from this distortion only may be resolved into two components one undelayed and exactly like the original but modified by the amplitude factor $\cos a_0$ and another which may be derived from the original by shifting all of the components through an angle $\pi/2$ and modifying by a factor $\sin a_0$.

The phase characteristics of a high pass filter may be written

$$B = a_1{}^1\omega^{-1} + a_2{}^1\omega^{-2} + a_3{}^1\omega^{-3} \cdots. \quad (15)$$

Here there is no term producing a delay without distortion to the signal as a whole nor is there a constant term producing a constant phase shift at all frequencies as in band filters. The distortion depends upon the values of $a_1a_2$ etc.

The phase characteristic of an all pass network may in the lower frequency range be represented by the same expression as for the low-pass filter and in the upper frequency range as for the high-pass filter but no such series as above will cover the entire range.