Improvements in Communication Transformers *

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The rapidly advancing art of electrical communication and the increasingly wide variety of its applications have required marked improvements in the transformers used in communication circuits. These improvements, achieved partly through advances in design and partly through improvements in the constituent materials, are discussed in this paper.

THE rapid development of the art of electrical communication in the last decade has necessitated marked improvements in the transformers used in it. New applications for these transformers and the extension of old ones have imposed new and far severer performance requirements. The primary applications of communication transformers are in the telephone plant, in the various voice and carrier transmission circuits, and in a multitude of incidental services. They have also wide uses in radio broadcasting transmitters and receivers, in the amplifiers of sound motion picture equipment, in the radio equipment for aircraft, and in a variety of other circuits.

Although communication and power transformers have a common origin, the communication transformer now has evolved as a precision device which has only a general resemblance to the usual power transformer. Some voice-frequency transformers, such as those used in aircraft, weigh but 2 or 3 ounces, yet transmit speech substantially undistorted. Some used in program circuits transmit with negligibly small phase or amplitude distortion all frequencies from 20 to 16,000 cycles per second. Transformers also have been developed for transmitting narrow bands of frequencies and having associated with the normal transformer performance valuable frequency discriminating properties. A discussion of improvements in these narrow band transformers is outside the scope of this paper, which will be confined to those transmitting wide-frequency bands, that is, those for which the ratio of upper to lower limiting frequencies is at least 10 to 1.

The design of the modern communication transformer is based upon extensions of the familiar theory of transformers covered in numerous texts. However, this type of transformer is a more complex device, with its multiplicity of requirements and its transmission over a wide-frequency range. Its proper representation accordingly requires a

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more elaborate equivalent network than the customary II or T network. With the use of such a network, the performance of the transformer may be correlated mathematically with its constants in accordance with network theory.

Improvements in Low-Frequency Transmission

The great improvements in communication transformers, particularly at audio frequencies, are largely attributable to the invention and application of the permalloys as magnetic core materials. For convenience, the term "permalloy" has been applied to a group of nickel-iron alloys containing between 30 and 95 per cent nickel which have been developed by Bell Telephone Laboratories.[1, 2, 3] In addition to other desirable magnetic properties, some of these permalloys [4] when properly heat treated yield exceptionally high initial permeabilities. As a result of the use of these special alloys, telephone transformers may be designed to have less loss and distortion over wider frequency ranges than has been possible in transformers designed without the benefit of use of such materials.

Figure 1 illustrates the excellence of performance resulting from the use of a special permalloy consisting of approximately 4 per cent

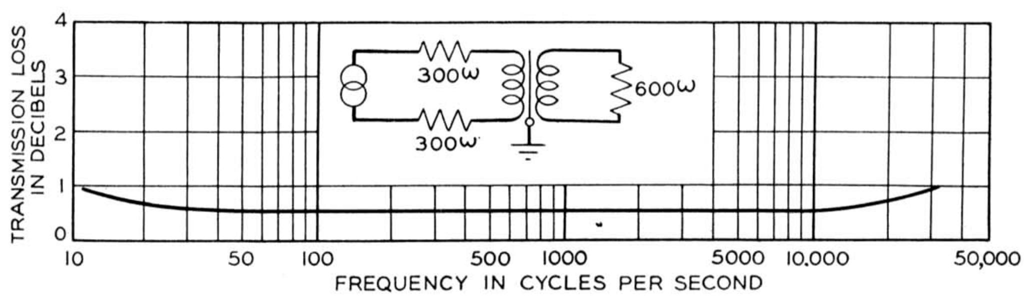

Fig. 1—Transmission-frequency characteristic of a transformer utilizing a permalloy core and designed to connect a telephone transmission line to a program repeater. Transmission loss shown is the loss relative to an ideal transformer of the same ratio.

chromium, 78 per cent nickel, and the remainder iron, in a transformer designed to connect a telephone transmission line to a program repeater. Figure 2 shows the voltage amplification characteristic of an interstage transformer for a high quality amplifier. As is well known,[5] superimposed direct currents generally decrease the effective a.-c. permeability of ferromagnetic materials. Therefore, to retain the full benefit of the permalloy core, an auxiliary circuit was used with this transformer for supplying the plate current to the preceding tube. Another illustration is a transformer designed for use as an input transformer (that is, one designed to operate into the grid circuit of a

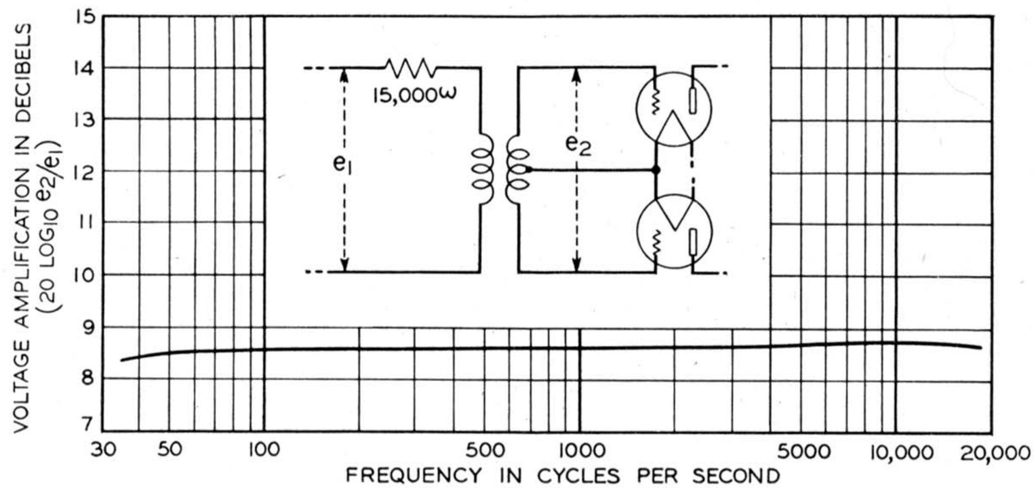

Fig. 2—Voltage amplification-frequency characteristic of an interstage transformer for a high quality program amplifier.

vacuum tube) for portable recording equipment where light weight is an important consideration. The voltage amplification-frequency characteristic of this transformer is shown in Fig. 3. There is shown also in this figure, for purposes of comparison, the very much poorer characteristic realized when an alloy of about 50 per cent nickel as commonly used is substituted for the special permalloy. In addition,

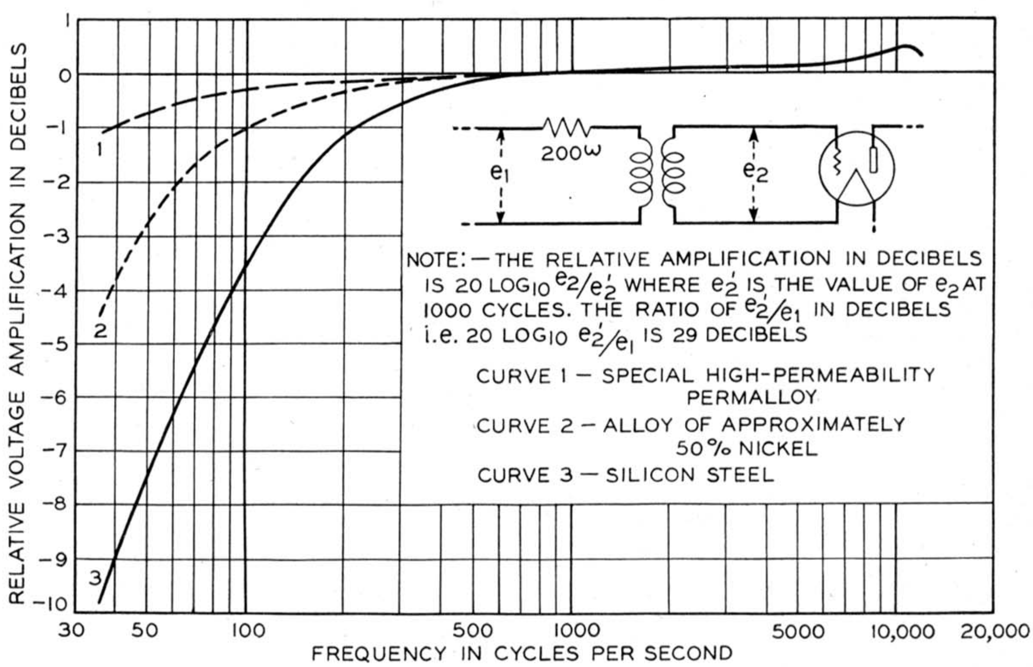

Fig. 3—Curves showing the relative effect of different core materials on the voltage amplification-frequency characteristic of a small transformer designed for portable recording apparatus. The composition of the special permalloy is approximately 4 per cent chromium, 78 per cent nickel, and the remainder iron.

there is shown the effect of using silicon steel as core material, which was the practice in older transformers.

An important limitation of high permeability alloys is their sensitivity to mechanical strain which may seriously impair their magnetic characteristics. Considerable care must be exercised to avoid strain during assembly operations after laminations are annealed. Telephone transformers are designed specially to provide a firm assembly without mechanical strain, thereby retaining the high permeabilities available.

Increase in Voltage Amplification

As may be seen from the foregoing curves, the voltage amplification of input transformers at the low end of the frequency band is directly dependent on the permeability of the magnetic core material. At the highest frequencies the voltage amplification of the above input transformers is controlled by leakage and capacitances, the latter including grid circuit capacitances as well as the transformer distributed capacitances. Over a wide range in the central part of the frequency band these effects are negligible and the transformer performs much as an ideal transformer of the same ratio. By proper proportioning of the leakage and capacitance effects, the shape of the characteristic may be controlled to a certain measure at will. For example, a rising voltage amplification-frequency characteristic can be obtained if desired to correct for a falling characteristic of other parts of the amplifier.

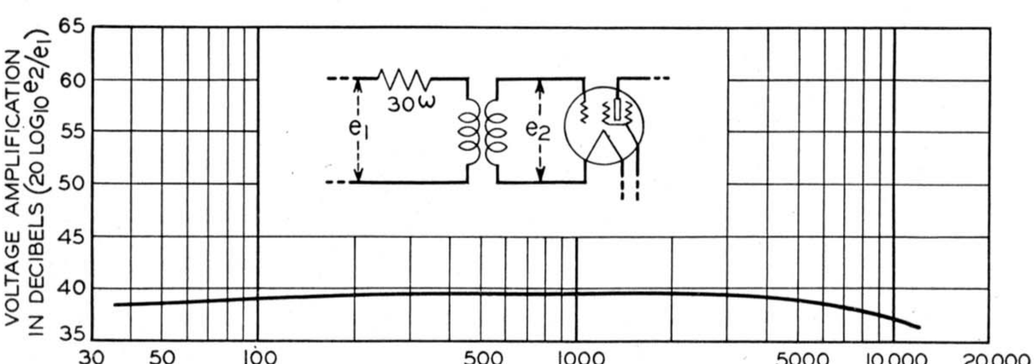

Fig. 4—Voltage amplification-frequency characteristic of an input transformer having an impedance ratio of 10,000 to 1.

In certain types of circuits the voltage amplification of input transformers is at a high premium, such as in the amplification of low-energy signals when a.-c. power is used for the tubes. Under these conditions the tubes tend to introduce appreciable noise. A high-voltage amplification in the input transformer serves to raise the signal voltage at the grid terminals so as to override the tube noises. Figure 4 shows that a high amplification, in this instance 10,000 to 1 in impedance level from a 30-ohm source, may be realized without undue restriction in either the low- or the high-frequency transmission.

Since transformers of this type are located at points of very low energy levels, special pains must be taken to avoid interference from stray magnetic and electrostatic fields. To prevent hum from nearby power apparatus, transformers are enclosed in cases or shields of high permeability material. The interference voltages induced in these transformers are some 30 or 40 decibels less than in older unshielded types of transformers. For higher frequency interference, effective shielding is obtained by cases made of high-conductivity material such as copper or aluminum.

Reduction in Size and Weight

The demand for lightweight equipment for aircraft communication and for portable apparatus for testing and recording has resulted in the development of communication transformers of unusually small size and weight. The smaller sizes weigh only $3\frac{1}{2}$ ounces and occupy a space of but 3 cubic inches. One of these used in aircraft receiving sets is illustrated in Fig. 5 contrasted with an earlier transformer also for lightweight service. The transmission loss-frequency characteristics are shown in Fig. 6. The corresponding characteristic of an input transformer for similar service is shown in Fig. 7.

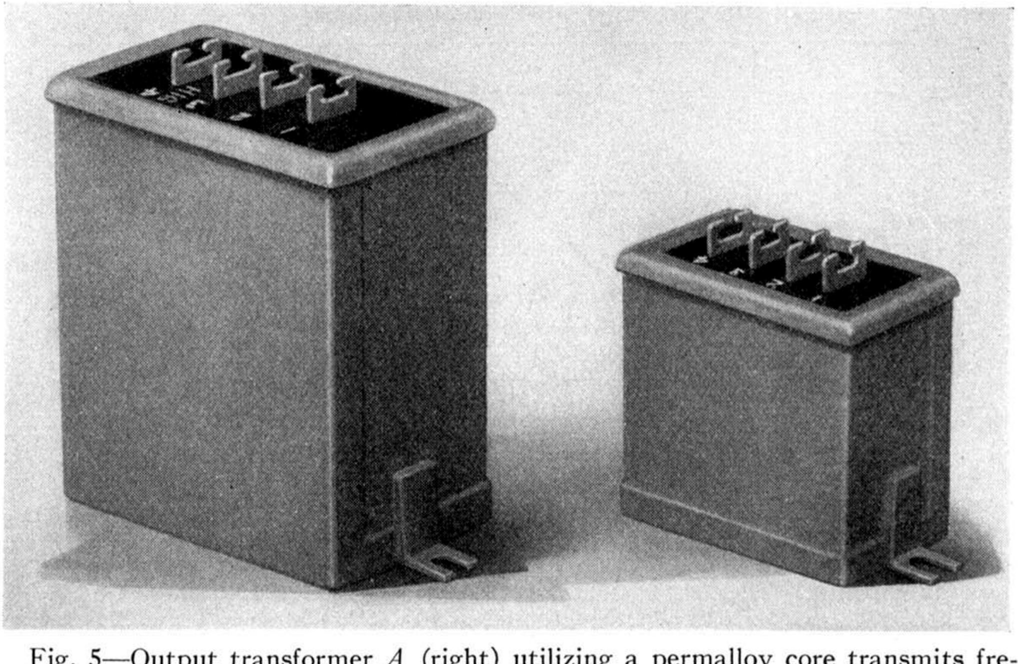

Fig. 5—Output transformer *A* (right) utilizing a permalloy core transmits frequencies from 40 to 3,000 cycles with greater over-all efficiency than the larger output transformer *B* (left) utilizing a core of silicon steel (see Fig. 6).

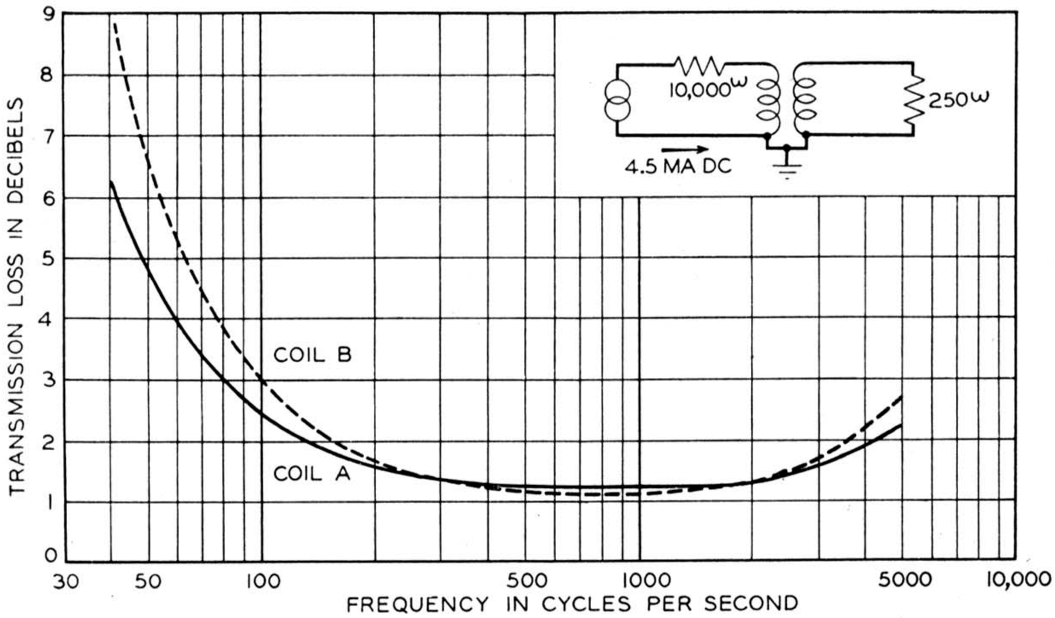

Fig. 6—Curves showing the transmission loss-frequency characteristics of (*A*) the small output transformer and (*B*) the larger output transformer shown in Fig. 5.

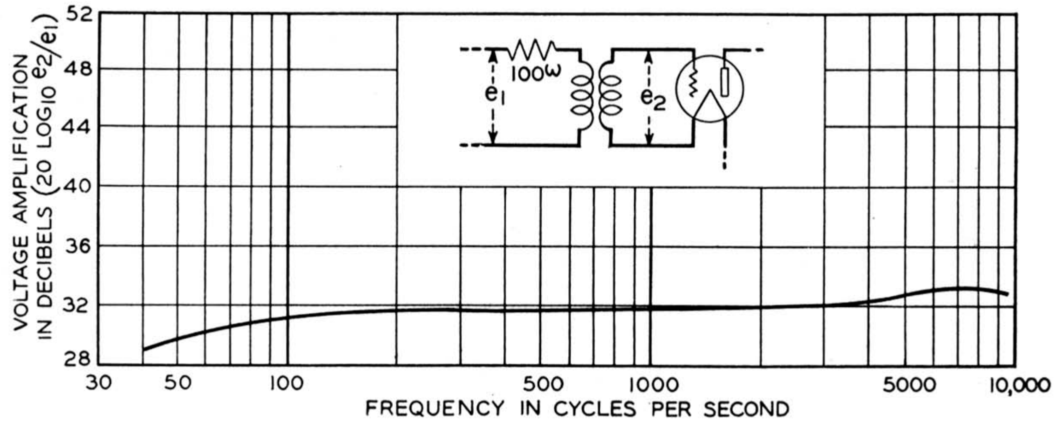

Fig. 7—Voltage amplification-frequency characteristic of an input transformer similar in size to the smaller output transformer shown in Fig. 5.

Extension of Range to Higher Frequencies.

The effective permeabilities of alloys of high initial permeabilities drop rather rapidly with frequency, a property which lessens the value of such alloys in transformers for carrier and higher frequencies. This effect, which is attributable primarily to eddy currents, can be greatly decreased, of course, by the use of thinner laminations. The use of these alloys, however, is limited by the rapidly increasing cost of reducing the lamination thickness and the less efficient use of the volume available for the core. This dropping off of effective permeability with frequency is not so important in audio-frequency transformers, since there the core characteristics limit the transmission only at low frequencies where the effective permeability is high.

At higher frequencies the voltage amplification is severely limited also by the grid circuit and transformer capacitances. It has been found advantageous to add correcting elements, such as inductances and capacitances, to increase the gain ordinarily available. These added elements and the equivalent elements in the transformer are designed together as configurations similar to low-pass filter sections terminated midshunt in the grid circuit capacitance. Figure 8 illus-

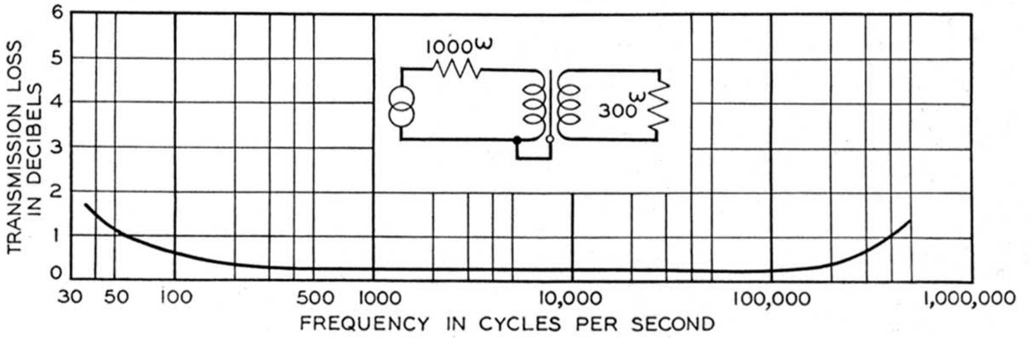

Fig. 8—Transmission loss-frequency characteristic of a transformer designed to transmit high frequencies in addition to audio frequencies.

trates the performance of a transformer designed for certain high frequency transmission experiments. The performance of this transformer in the frequency range of 30–500,000 cycles per second is similar to that of earlier types in the range of 30–60,000 cycles per second.

In most telephone applications the design of input transformers is complicated greatly by circuit functional requirements in addition to those of direct transmission. For example, as discussed in a succeeding section of this paper, phase distortion requirements demand self-impedances far higher than those required by transmission loss considerations, thermal [6] noise requirements demand lower dissipations, and impedance requirements limit the voltage amplification obtainable. For feed-back type amplifiers [7] the input transformers in addition to the forward amplification must meet transmission and phase requirements in the regenerative path. These special requirements apply not only for the transmitted frequency band but also at frequencies remote from this band in order to insure stability of the amplifier.

Reduction in Phase Distortion

Since transformers are reactive devices, they introduce phase shift in the circuits in which they are used. If the phase shift introduced be a linear function of the frequency it will not produce any distortion in the shape of the transmitted wave. However, departures from linearity change the wave shape, and this form of distortion is referred to as phase or delay distortion. The delay at any frequency is a measure of this departure from linearity, and is dependent upon the frequency derivative of the phase shift at that frequency. Differences in delay of the various frequency components of the signal wave which transformers tend to produce result in distortion that may be especially serious in circuits intended for program transmission.

For wide-band transformers the delay caused by the shunting effect of the mutual impedance usually predominates. In fact for audio transformers the delay at higher frequencies is relatively so small that the delay distortion is practically equal to the mutual impedance delay at the lowest transmitted frequency. Delay distortion is also of importance in transformers to be used in television and telephotography. In these circuits phase distortion causes a space shift in the image of certain frequency components with respect to others with consequent blurring of the image.

The delay characteristic of a transformer used in program circuits to connect a telephone transmission line to the grid circuit of a repeater amplifier is shown in Fig. 9. This characteristic is compared in the same illustration with the delay characteristic of a repeater transformer developed some years ago for use in what then was re-

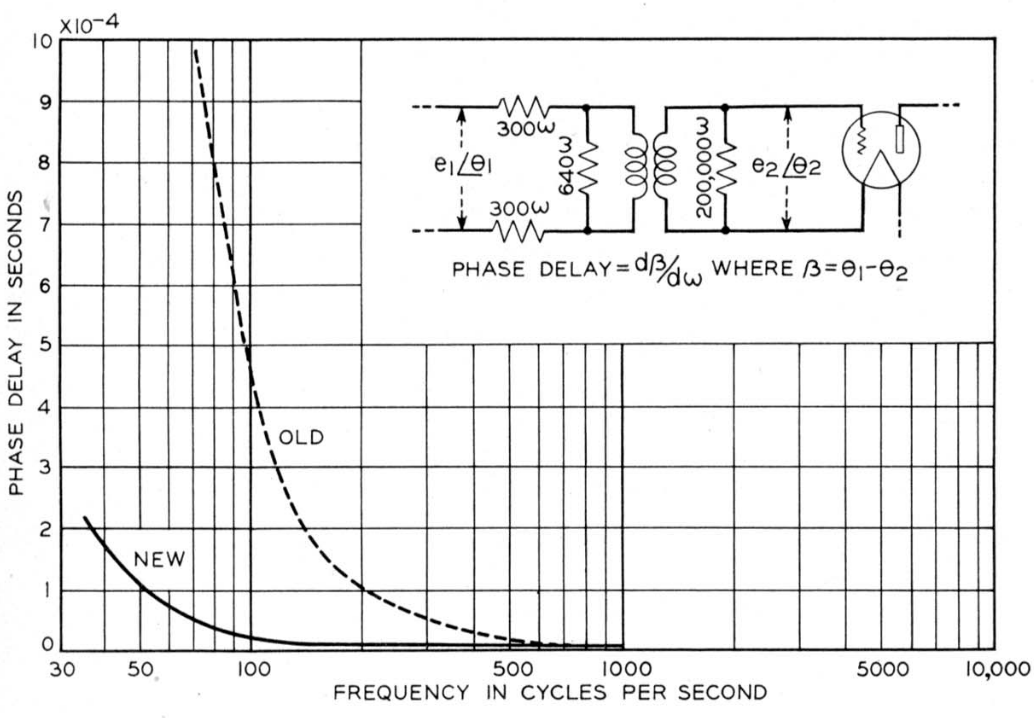

Fig. 9—Phase delay-frequency characteristic of an input transformer used in recent program repeaters, compared with that of an input transformer used in an older repeater.

garded as a high quality circuit. The delay characteristic of a high frequency transformer is shown in Fig. 10.

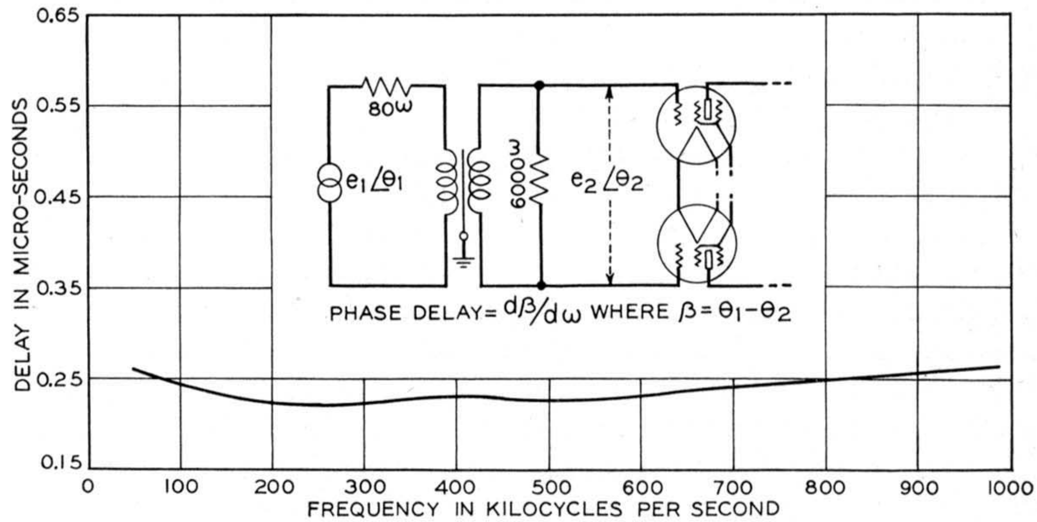

Fig. 10—Phase delay-frequency characteristic of an input transformer designed to transmit radio frequencies.

Reduction in Audio Frequency Modulation

The present exacting requirements for transformer performance have made it necessary to lessen greatly certain second-order distortion effects inherent in transformers having magnetic cores. Nearly all core materials tend to generate extraneous frequencies because of magnetic non-linearity—a property referred to as magnetic modulation. In audio-frequency circuits intended for high quality service, magnetic modulation may cause serious distortion in that harmonics of the lower frequencies appear higher in the audible range. The energy present at the lower frequencies is usually so much greater than that over the rest of the band that the modulation products may approach the order of magnitude of the signal components at higher frequencies.

This form of distortion in no way is revealed by the ordinary transmission loss characteristic; in fact, a transformer having a very flat loss characteristic over a wide-frequency range may nevertheless be definitely objectionable from a modulation standpoint. In present audio-frequency transformers, the total modulation products are some 40 to 80 decibels down from the energy of frequencies around 35 cycles per second producing them. This represents an improvement of about 30 decibels over older types.

Another second-order effect resembling modulation is microphonic noise caused by magnetostriction phenomena, that is, changes in magnetization accompanying the physical deformation of the magnetic material. For instance, slight jarring of input transformers used in very high-gain amplifiers (100 decibels or more) may induce in this manner disturbing noise voltages. Freedom from magnetostriction is a unique characteristic of permalloys containing approximately 80 per cent nickel, and their use accounts for the superiority of telephone transformers from this standpoint.

Reduction in Carrier Frequency Modulation

Magnetic modulation is even more serious at carrier frequencies where a transformer may transmit many channels, frequently at widely different levels. The modulation from the higher level channels may produce very objectionable interference in other channels. Carrier transformers now have been improved to such an extent that highly sensitive testing circuits are required to detect and measure the modulation products contributed by them. Representative values of these modulation products expressed as current ratios to the fundamentals are of the order of one-millionth of the fundamental frequencies, compared to one-thousandth in older types.

It is of interest to point out that in such transformers the presence of magnetic material, other than the special permalloys, in the vicinity of the transformer must be avoided with great care. For example, a small steel screw near the field of the transformer will seriously impair its performance from a modulation standpoint. Common practice is to use brass parts for the assembly and to confine the field of the transformer by completely enclosing it in a copper or aluminum case. The transformer then may be mounted by any convenient means without affecting its performance.

Improvements in Shielding and Balance

In the very nature of the service that it renders, the telephone plant involves many independent communication circuits in fairly close proximity. The minimizing of interference between these independent communication circuits has constituted a major problem in telephone engineering. Where such interference occurs between like circuits, that is, between two voice circuits or between two carrier circuits of overlapping frequency bands, the interference commonly is referred to as crosstalk, as distinguished from the interference from other types of circuits such as power and telegraph circuits.

In order to avoid crosstalk and other interference, balanced * cir-

* The new coaxial cable circuits under development are an interesting exception. In this type of cable a grounded outer conductor completely encloses the central conductor, and shielding rather than balance is relied upon to protect the circuit from interference. The shielding depends upon the size, thickness, permeability, and conductivity of the outer conductor and the frequency of the disturbance. If the frequency band used in the transmission over coaxial circuits is chosen properly, the circuit may be made substantially immune to effects from outside fields.

cuits are used almost exclusively in the telephone plant. For simplicity, some of the terminal apparatus connected with these circuits is constructed unbalanced, so that it is necessary to interpose transformers between the lines and the office equipment, these transformers providing a barrier to the propagation of the relatively large longitudinal currents from the line circuits. (Longitudinal currents, in contrast with the usual circulating currents, are currents that flow equally and in the same direction in both sides of the line.) In order to insure that the voltage impressed on the office equipment is attributable to the voltage between the wires of the line circuit and not to that between the wires and ground, it is necessary that the transformers be balanced very carefully; and for certain types of circuits, shields must be interposed so that the direct capacitance between the line winding and office winding is reduced to a very small value.

With a greater emphasis on carrier frequency transmission, a higher degree of balance is required between certain transformer windings, and highly effective shielding is frequently necessary. It is necessary also that the line windings be balanced very closely with respect to capacitances to the shield and case. The unbalance effects in carrier transformers now have been reduced to values in the order of 1 or 2 microamperes in circulating current per volt between the line windings and ground at 30,000 cycles per second, which compares with values of 50 microamperes or more for older transformers. At the same time the electrostatic shielding between the windings has been improved to such an extent that the direct capacitance between windings has been reduced to 1 or 2 micromicrofarads instead of 30 or 40 as before. The shields are arranged to intercept the dielectric flux lines tending to connect the primary and secondary windings, so that the direct capacitance between the two windings is attributable only to stray flux which bypasses the shield. One of the windings usually is enclosed completely in lead or copper foil with overlapping edges insulated to prevent a short-circuited turn. Still further improvements are obtained by covering the leads with grounded metal braiding, and in special cases by enclosing the terminals of the shielded winding in a separate shielded compartment. In certain transformers designed for high precision testing equipment, the direct capacitance between windings has been reduced to values less than 0.001 micromicrofarad.

In connection with phantom circuits, severer crosstalk requirements have necessitated more precise balances in the associated voice frequency transformers. In these transformers the turns are so arranged that the various distributed capacitances, flux linkages, and d.-c. resistances are disposed symmetrically with respect to ground. It has been found in practice that this symmetry is realized most readily by close coupling between the various parts of the windings. By improvements in design, the crosstalk between phantom and side circuits has been reduced to values in the order of 20 millionths in current ratio, compared to values 5 times as large, formerly tolerated.

Reduction in Impedance Distortion

As a further consequence of the extension of carrier systems, it has become necessary to match the impedance presented by transformers, when terminated in the succeeding circuits, to particular values over the frequency range. For example, the transposition schemes used on open wire lines are such as to minimize crosstalk primarily for carrier signals propagated in one direction in any line. If the transformer terminating such a line does not present an impedance under load equal to the characteristic impedance of the line, a portion of the wave is propagated in the reverse direction, that is reflected, causing crosstalk into adjacent circuits. This reflection effect increases with the vector difference in the impedances of the transformer and the line, the latter impedance approaching a pure resistance as the frequency increases.

The impedance of transformers has become increasingly important where such transformers terminate filters that require a nearly constant resistance termination to maintain proper attenuation characteristics. Another example is in transformers terminating screen grid tubes where the plate impedances are relatively very high. Here the energy abstracted from the plate circuit and transmitted by the transformer is directly dependent upon the resistance component of the impedance of the transformer when terminated in its load.

Better impedance characteristics of transformers for these various applications have been obtained by increasing the mutual impedance and decreasing the leakage and capacitance effects. This procedure is made difficult by the necessity for meeting at the same time other and newer requirements, as, for example, modulation limits. Correcting elements consisting of capacitances and inductances usually are added and are proportioned with the transformer elements in accordance with network theory. Typical impedance characteristics of such transformers are shown in Figs. 11 and 12.

Input transformers operating into the grid circuits of vacuum tubes inherently have impedances that depart widely from the nearly pure resistances usually desired, because of the reactive termination provided by the grid circuit. This makes it necessary to add resistances to serve in place of the usual load resistance. The required dissipation

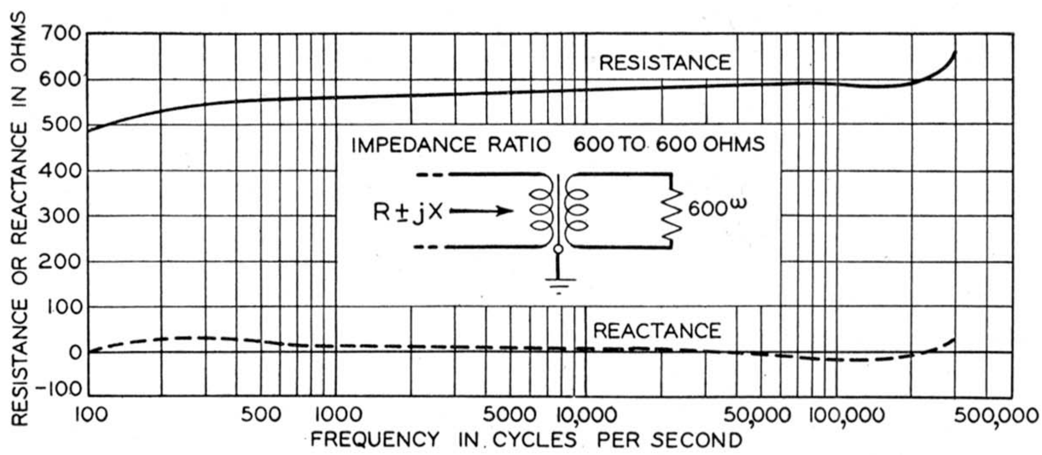

Fig. 11—Impedance-frequency characteristic of a transformer designed to operate between 600-ohm terminations and to transmit high frequencies in addition to audio frequencies.

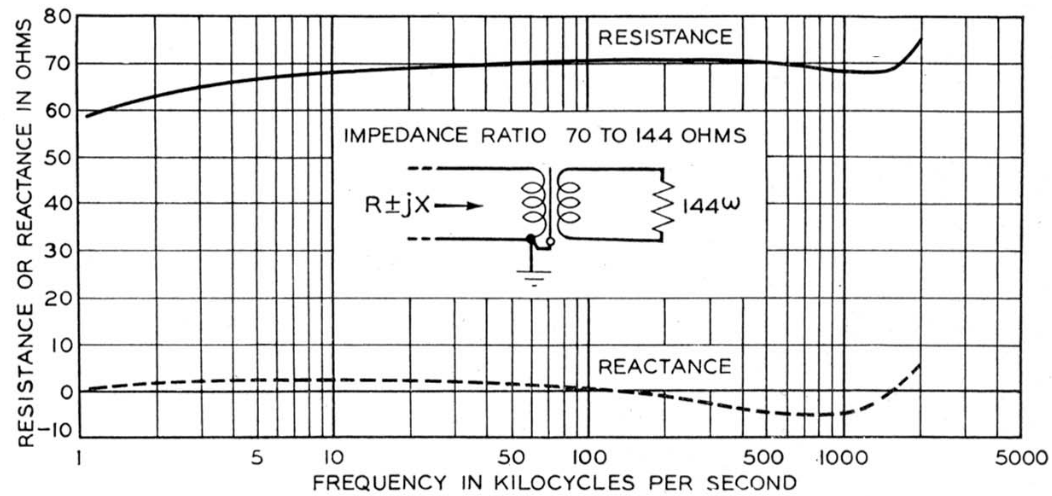

Fig. 12—Impedance-frequency characteristic of a transformer designed to operate between resistance terminations of 70 ohms and 144 ohms.

may be provided in many ways in the input transformer, which consideration allows much wider latitude in the design than in the ordinary transformer; there the major part of the dissipation for low transmission loss necessarily must occur in the load. A typical impedance characteristic of such an input transformer is shown in Fig. 13.

Testing Precautions

As a necessary concomitant to improvements in transformers, more precise testing circuits have been developed for accurately determining transformer performance. In estimating the performance of the transformer from its characteristic, care must be taken to make sure that the service conditions were reproduced carefully in the measuring circuit. In particular, certain precautions must be observed in the measurement in order to avoid obtaining a misleading characteristic. For example, the permeability of magnetic core materials tends to rise rapidly from its initial value with increasing voltages. If in the measurement, the low-frequency voltages used are materially higher than they are under service conditions, the low-frequency response will appear to be much better than the true response.

As another example, the transmission of input transformers at the high-frequency end may be critical with the termination of the high-

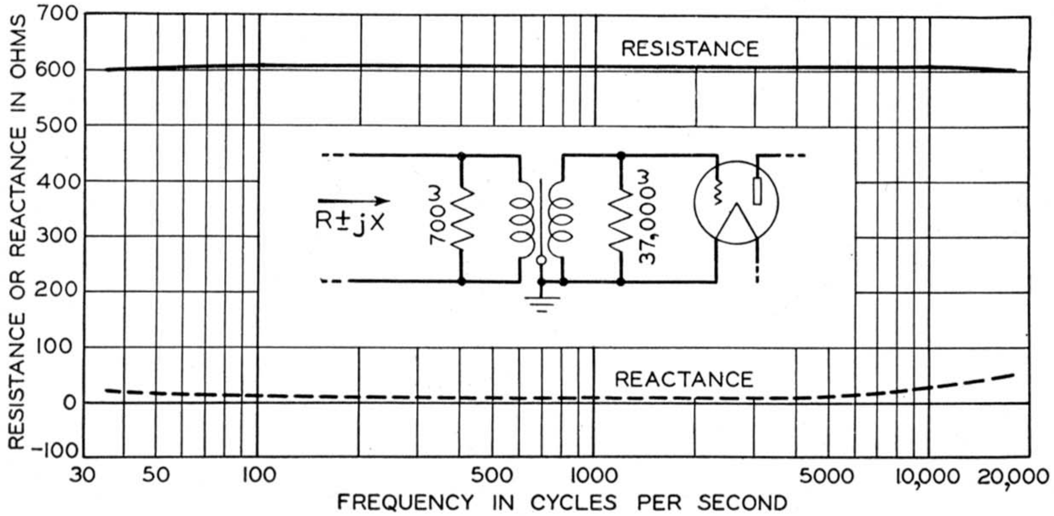

Fig. 13—Impedance-frequency characteristic of an input transformer used to operate from a telephone transmission line into a high quality program repeater. Impedance ratio is 600 to 15,000 ohms.

voltage winding. If the grid capacitance and conductance conditions are not reproduced faithfully in the measuring circuit, the high-frequency voltage amplification may appear to be much better than the true value.

In addition to more precise transmission measuring circuits, various other special circuits have been developed for measuring transformers, such as modulation, impedance, and crosstalk measuring circuits. The design of these circuits is of necessity a specialized art.

In the foregoing, various types of improvements in communication transformers have been discussed. Wherever applicable, several such improvements have been incorporated in an individual design. The improved performance of transformers as described has been an essential step in the development of the communication art.

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