Precision Methods Used in Constructing Electric Wave Filters for Carrier Systems

By G. R. HARRIS

Electric wave filters are used extensively in carrier telephone and telegraph systems. In order that such systems may be operated efficiently and economically, the requirements placed on the filters they employ are occasionally so severe in nature that new methods in design or construction must be developed to make the commercial production of the filters possible. The band filters for the Type "C" Carrier Telephone System are cases in point. This paper sets forth the requirements which were met in the design of the filters for this system, and describes a new manufacturing adjustment made necessary by these requirements. This feature consists essentially of an inductance continuously variable over a small range above and below its nominal value; the adjustment is not used to set the coil inductance at its specified value, but to locate correctly the series or parallel resonance of the mesh of which the coil is a part. The bridge and associated apparatus developed to facilitate this adjustment are also described.

ONE of the most important fields of usefulness of the electric wave filter in the Bell System is found in carrier current telephone and telegraph systems. A carrier telephone system transmits several messages over the same line by employing several carrier currents of frequencies higher than those in the ordinary voice band, and modulating these carriers with the messages to be transmitted. The messages are then transmitted over the line as side bands of their respective carriers, and are demodulated to their original voice frequencies at the receiving end.

Usually only one side band of a carrier is transmitted in order to reduce the frequency space required for each channel. Each message as it appears on the line occupies its own portion of the frequency spectrum, distinct from that occupied by any other message, and is transmitted without interference from other messages; but in order that the operations of modulation and demodulation may be carried on without interference and in order that unwanted side bands may be suppressed, it is necessary that each modulator and demodulator be equipped with some apparatus which will pass all the side band frequencies making up one message and reject all others. Electric wave filters are the instruments used for this purpose, since they possess the property of passing currents of certain chosen frequencies with very small loss, and of offering high attenuation to other chosen frequencies.

The theory of electric wave filters as used in carrier systems has been discussed in previous articles in this *Journal*, notably "Physical

Theory of the Electric Wave Filter" by G. A. Campbell, which appeared in the November, 1922 issue, and "Theory and Design of Uniform and Composite Electric Wave Filters" by O. J. Zobel, in the issue for January, 1923. It is not the purpose of the author to discuss further the theory of wave filter design or operation, but rather to discuss some of the problems that arise when an attempt is made to construct filters which must meet certain requirements of a carrier system with a very small margin of variation, and to describe the methods of solution adopted. It is assumed that the reader is familiar with the general principles of electric wave filter theory.

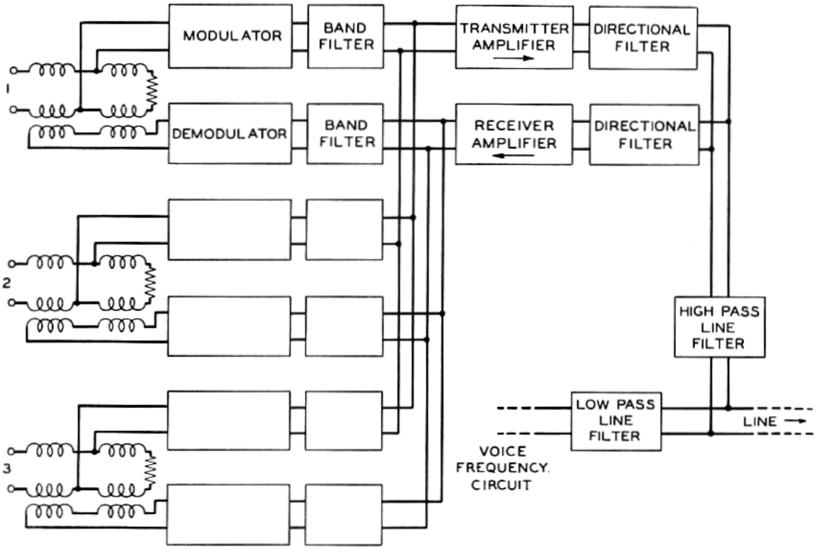

Fig. 1—Type "C" system terminal arrangement.

Different carrier systems require different numbers and designs of filters. A carrier system designed to provide three two-way telephone channels would have six band filters at each terminal. These filters would be of a type that passes all frequencies between certain upper and lower frequency limits, and provides a high attenuation or loss to all frequencies below and above these limits. A simplified diagram of such a terminal arrangement is shown in Fig. 1.

In addition to the band filters, a pair of directional filters is required at each terminal to separate the three incoming from the three outgoing channels. This directional filter pair is composed of a low-pass and a high-pass filter, which as their names imply, pass respectively all frequencies from zero up to the predetermined cut-off point and attenuate those above this point, or pass all frequencies above the cut-off point and attenuate all those below. The cut-off points of this pair of filters are so arranged that the passing region of the low-pass filter includes the three lower frequency channels and the passing range of the high-pass filter includes the three upper frequency channels. The location of the various filters in the frequency spectrum is shown in Fig. 2.

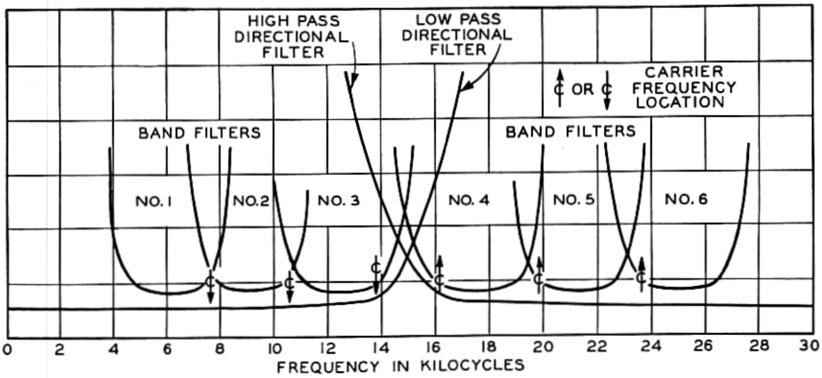

Fig. 2—Frequency spectrum of type "C" normal system.

If the carrier system is long enough to require repeaters, additional directional filters must be employed. These filters are required because repeaters must amplify frequencies going in both directions. The arrangement of the repeater is shown in Fig. 3.

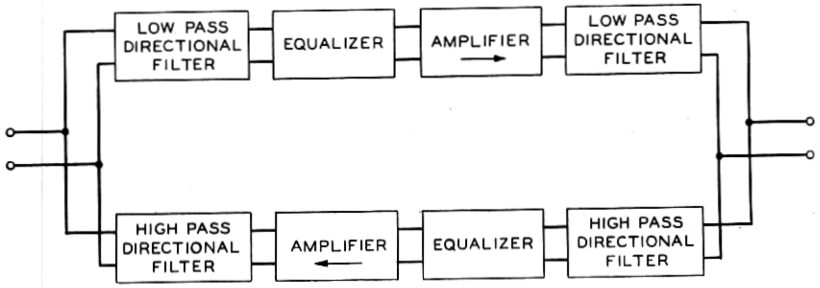

Fig. 3—Schematic of type "C" repeater.

This paper will be concerned with the filters for the Western Electric Type "C" Carrier Telephone System,[1] since the requirements placed on the apparatus for this system raised certain problems in filter

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[1] H. A. Affel, C. S. Demarest and C. W. Green, "Carrier Systems on Long Distance Telephone Lines," *Bell Sys. Tech. Jour.*, July, 1928.

design and construction which had not then been satisfactorily solved. The highest frequency to be used in this system was determined, of course, by the limitations of wire transmission as the frequency increases. The lowest was set chiefly by the desire to avoid interference from carrier telegraph systems on other wires of the same pole line. Between these limits, the six bands (three two-way channels) had to be located. At the same time it was desirable to provide a second system, with a frequency allocation offset or "staggered" with respect to the first, to permit operation of carrier systems on pairs in close proximity where the normal crosstalk would not permit operation of the same systems. This is shown graphically on Fig. 4. The crosstalk advantage thus obtained is rather critical with respect to the overlap between interfering channels. These two factors, first, interference between channels in the same system and, second, interference between channels in adjacent staggered systems, emphasized the need for a high degree of precision in the location of the individual bands.

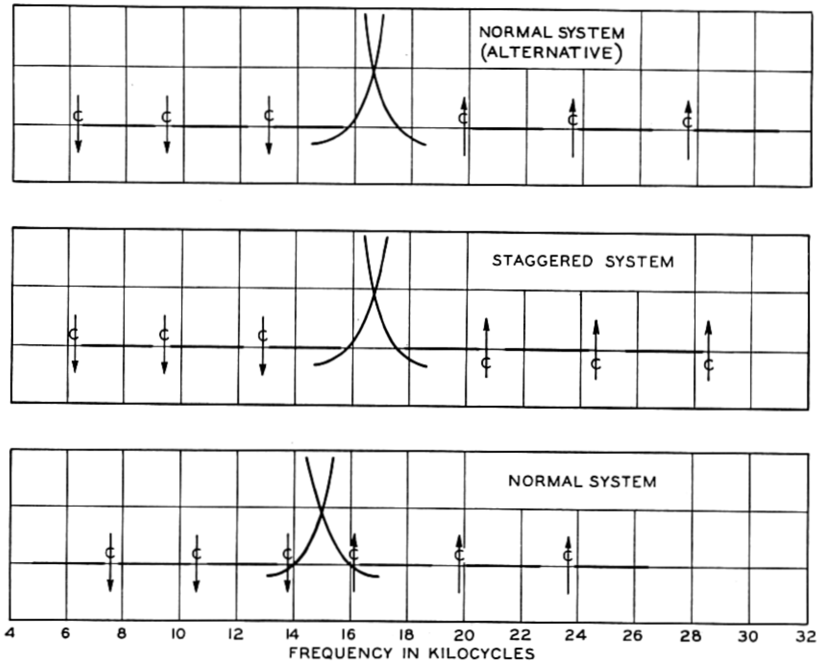

Fig. 4—Frequency spectra of type "C" normal and staggered systems.

The theoretical requirements of the filters, although severe, were met without any departure from conventional design practices. The calculated attenuation characteristics satisfied the minimum loss requirements and did not exceed the maximum loss requirements in the transmitting bands. The margins, however, were not very great.

It is evident, therefore, from Fig. 5, that a very small shift in the frequency location of the loss characteristic of a filter would throw it outside the required limits. The shift which would cause this to happen was, in fact, so small, ± 125 cycles, that the manufacture of these filters by methods currently in use resulted in enough rejections at the factory to warrant the development of a more precise method.

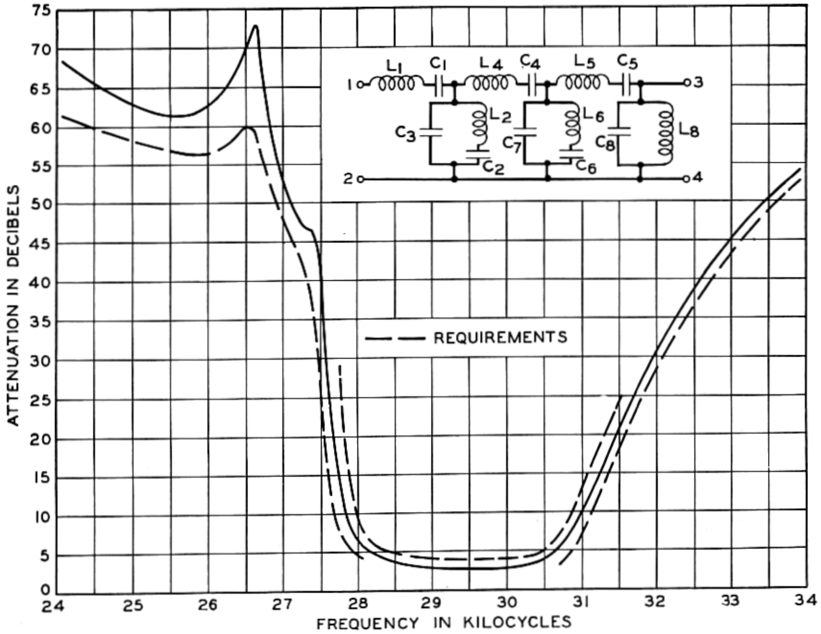

Fig. 5—Attenuation characteristic of 38–N filter, showing requirements.

The attenuation characteristic of a manufactured filter seldom conforms exactly with that desired because of manufacturing tolerances which must be allowed in its component elements. The inductances and capacitances of the coils and condensers which make up a filter differ somewhat from their specified values for several reasons. The precision of their adjustment can be no greater than the precision of the circuits in which they are measured. It is usually less than this figure because the coils and condensers used in precision filters are potted in a moisture-proofing compound, after adjustment, and this potting produces a small change in the capacitance of the condensers and the distributed capacitance of coils which is not uniform and cannot be allowed for exactly in advance. Coil adjustment is limited by another factor, as well; the adjustment of a single coil must be made in units of one turn. For these reasons it is very difficult to adjust condensers to better than about ± 0.3 per cent, and coils to better than a little over ± 1 per cent.

The effect of the variation in element values may be manifested in several ways. In a simple half-section low-pass filter, for example, the cut-off frequency

$$f_C = \frac{1}{2\pi\sqrt{LC}}$$

where L and C are the values of the series inductance and shunt capacitance. A variation in L or C will produce a change in the cut-off frequency proportional to the change in the element value. Changing the cut-off frequency is, of course, equivalent to shifting the whole attenuation characteristic upward or downward in frequency. A change in an element value also produces a change in the filter impedance. Suppose that in a network composed of a number of series and shunt arms, the impedance of one arm of the network, Z_q is increased by an amount ΔZ_q. The current through that branch is I_q. The change in impedance is approximately equivalent to introducing a voltage e in the circuit.

$$e = - I_q \Delta Z_q.$$

If E is assumed to be the voltage in series with the terminal impedance Z_s at the sending end of the network, and I_s is the input current,

$$- \frac{I_q \Delta Z_q}{\Delta I_s} = \frac{E}{I_q}$$

from the reciprocity theorem. But

$$\frac{\Delta I_s}{I_s} = - \frac{\Delta Z}{Z + Z_s},$$

where Z is the input impedance of the network, and ΔZ is the change in Z produced by the impedance change in the arm Z_q. Furthermore,

$$E = (Z + Z_s) I_s.$$

Therefore

$$E = - I_s^2 \frac{\Delta Z}{\Delta I_s}.$$

And

$$\Delta Z = \Delta Z_q \left(\frac{I_q}{I_s} \right)^2.$$

As a filter is usually designed to match two fixed impedances between which it must operate, a change in its impedance caused by element variation will produce a mismatch between the filter and its terminating impedances which will result in reflection loss in the transmitting region. However, the reflection loss arising from impedance deviation caused by element variation is usually much less troublesome than the shift in the attenuation characteristic produced by this variation.

A more complicated type of filter, such as the symmetrical "Constant k" band pass section exhibits a more involved relation between the cut-off frequencies and the values of the elements. L_1 and C_1 are the series arm inductance and capacitance, while L_2 and C_2 are the inductance and capacitance in the shunt arm.

$$\left.\begin{matrix} f_2 \\ f_1 \end{matrix}\right\} = \frac{1}{2\pi}\left[\sqrt{\frac{1}{L_1C_2}+\frac{1}{L_1C_1}} \pm \sqrt{\frac{1}{L_1C_2}}\right].$$

In the equation as written L_2 does not appear explicitly, but as in this type of section $L_1C_1 = L_2C_2$ the equation may be written with L_2C_2 as the denominator of the second term in place of L_1C_1, if desired. Therefore, three LC products influence each cut-off frequency; three resonant frequencies, therefore, must be held constant if the cut-offs are not to vary. The mid-band frequency of this section is given by the equation

$$f_m = \frac{1}{2\pi}\sqrt{\frac{1}{2}\left[\frac{1}{L_1C_1}+\frac{1}{L_2C_2}\right]},$$

from which it is seen that two LC products, L_1C_1 and L_2C_2, must be held constant if f_m is not to vary.

Element variation may cause a shift in the cut-off points and thus a displacement of the attenuation or impedance characteristic of any type of section, but it may have another effect on the characteristics of M type sections. An M type section provides a peak of attenuation at some finite frequency, which is determined, in most sections of this type in common use, by a single pair of elements; either a series resonant combination shunted across the filter or a parallel resonant combination in a series arm. Variation in either of the elements determining the location of the peak will cause a shift in the location of this peak proportional to the element variation. Changes in these elements would affect the cut-offs of the section as well as the peak or peaks, but it may happen that variation in the opposite direction of other elements in the section will result in negligible shift of the cut-offs, while the peaks are shifted noticeably. Thus the attenuation characteristic of an M type section may be distorted as well as displaced by element variation.

The critical region of the type "C" system band filter requirements was the slope of the attenuation characteristic from the cut-off to the peak nearest the carrier side of the transmitting band. The system was designed to transmit one sideband only, and the band filters were required to suppress the carriers at least 15 db. The transmitted sideband for each filter extended from 250 to 2750 cycles from the carrier, so that in every case the filter had to offer at least 15 db suppression to the carrier frequency, which was only 250 cycles away from the edge of the transmitting band. Where the carrier frequency was 25 kc., the separation was only 1 per cent. This requirement necessitated very steep slopes of the attenuation characteristic, especially for the higher frequency filters; at these slopes a frequency shift of 1/2 per cent produced a change in attenuation of 9 or 10 db, as may be observed in Fig. 6.

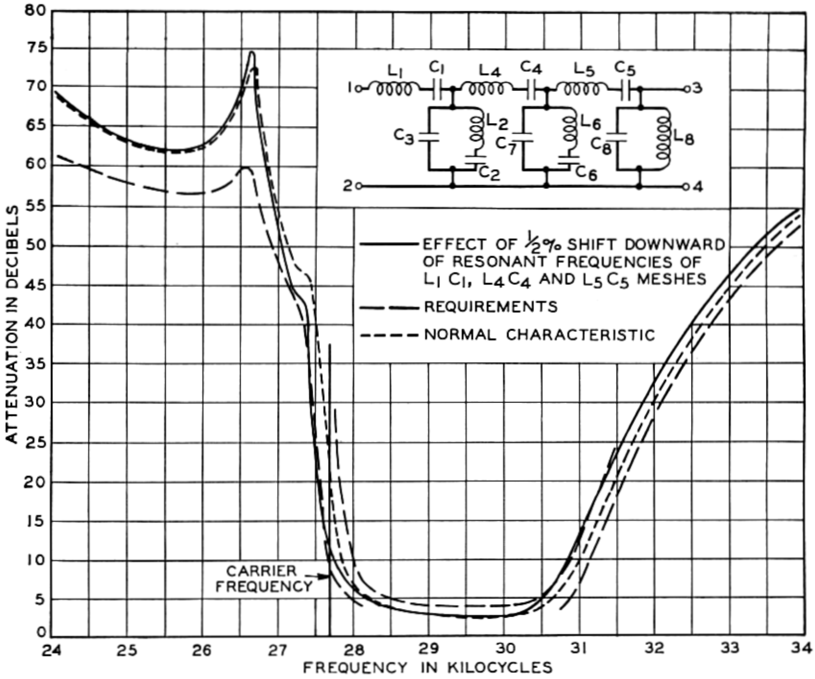

Fig. 6—Attenuation characteristics of 38–N filter, showing effect of element variation.

As the precision of adjustment for condensers was three or four times that for coils, it was obvious that some improvement in coil construction or adjustment would have to be made. Furthermore, since the important limiting factors in the adjustment of both coils and condensers were the precision of the bridge standards and the bridge operating technique in the shop it seemed unlikely that more precise location of the filter characteristics could be obtained until these factors were improved. However, another way was found. It has been pointed out in preceding paragraphs that critical points, such as cut-off points and attenuation "peaks" are usually dependent upon the resonant frequency of a pair of elements, or perhaps of several pairs. It is much more important that these critical frequencies be correctly located; that is, that the L–C product of the elements be of the correct value, than that either element alone be of the correct value. Therefore, if some way could be found of adjusting a combination of elements associated together in a filter so that the L–C product would be of the correct value, a considerable improvement in the precision of the attenuation characteristic location might be expected. If the elements could be adjusted so that a negative deviation in condenser capacity, for example, could be compensated for by a positive deviation in coil inductance, the L–C product, and therefore the resonant frequency, would be correct, and the effect of the individual element deviation would be greatly minimized, though not entirely eliminated. Either an adjustable coil or an adjustable condenser would make this procedure possible; and, as such a resonant frequency adjustment could be made to the precision of an oscillator calibration, or about 0.05 per cent, if necessary, the errors of inductance and capacity bridge standards, as well as initial adjustment error and variation due to potting would be eliminated at the resonant frequency, and their effects minimized greatly at other frequencies.

Development was therefore started on an adjustable type of inductance. As the simplest and most inexpensive coil was, of course, the most desirable, efforts were made to modify the solenoidal air core coil used in previous carrier filters. One scheme considered was to mount a small copper vane in such a way that it could be moved into or out of the field of the coil; the eddy-currents in the vane set up a small counter field that neutralized a part of the field of the main coil and thus reduced its inductance. Another method made use of a small "pancake" wound coil mounted vertically on the side of the main coil so that it could be moved up or down, into or out of the field of the main coil. This small coil was short-circuited, and therefore produced an effect similar to that of a copper vane. The model finally adopted, however, although using the same principle of adjustment, was made in a somewhat different form. A rectangular rotor was constructed to fit around the main coil. This rotor was pivoted to the main coil on its short sides and could be rotated through an angle of approximately 60° about its horizontal axis. On this rotor was wound a large number of turns of small gauge wire, and the winding was short-circuited. A coil of this type is shown in Fig. 7. The coupling between the rotor in its horizontal position and the main coil is very small, and therefore the effective inductance between terminals is practically that of the main coil. However, if the rotor is rotated in such a way that its plane becomes more nearly parallel with that of the main coil the coupling between it and the main coil is increased, and the effective inductance of the whole is reduced. It is possible to vary continuously the inductance of a coil of this design over a range of about $3\frac{1}{2}$ per cent.

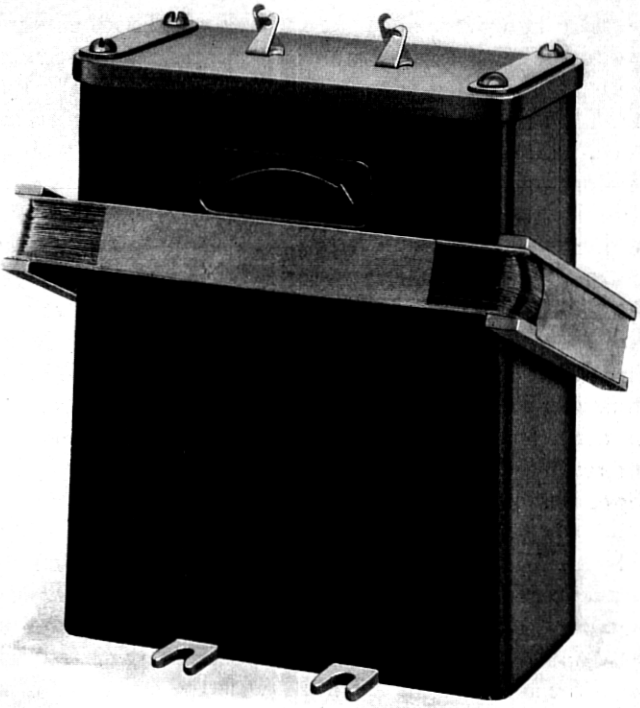

Fig. 7—Photograph of "AA" coil.

When coils of this type and their associated condensers are connected together as they would appear in a filter, their resonant frequency or frequencies are located by an adjustment of the coil or coils in the mesh. If the mesh contains more than one adjustable coil, more than one resonant frequency may be located. As many of these resonant frequencies may be located in this way as there are adjustable elements in the mesh. Since the condensers are not adjustable, all of the frequencies of series and parallel resonance in a complex mesh, will not, in general, be capable of adjustment. If the mesh is composed of n condensers and m coils, and the difference between m and n is not more than 1 (if this condition is violated the mesh can be reduced to an electrically equivalent one containing a smaller number of elements), the number of resonant and anti-resonant frequencies is clearly $(m + n - 1)$. However, since the number of adjustments possible is equal only to the number of coils, m, the number of frequencies which cannot be exactly located is $(n - 1)$, or one less than the number of condensers. This condition is not very objectionable in practice as the mesh configuration is usually chosen to be of a form which permits the more important critical frequencies to be adjusted. In a four-element mesh, the largest usually encountered in an ordinary filter structure, two of the three resonant frequencies may be adjusted, and furthermore, the adjusted frequencies may be any two of the three; in most cases the adjustment of two frequencies is sufficient.

The frequency adjustment is actually made on a bridge circuit, the schematic of which is shown in Fig. 8. Two of the bridge arms are, of course, ratio arms; the mesh to be adjusted is connected in circuit as a third arm, and the fourth arm is a variable resistance. For series resonance adjustment, the desired frequency is impressed on the bridge, and the inductance of the adjustable coils varied so that the impedance of the mesh becomes a pure resistance, which is balanced by an adjustment of the resistance in the opposite bridge arm. For a parallel resonance measurement, a resistance of 10,000 ohms is shunted across the mesh being adjusted, and the coil varied until the reactance component of the mesh impedance vanishes, when the resistance of the 10,000 ohms in parallel with the resistance of the mesh can be balanced in the fourth bridge arm.

This frequency adjustment of filter arms involved a change in filter manufacturing procedure. Ordinarily the coils and condensers for the filter are individually adjusted, then mounted, wired, and the filter finally tested as a whole, but an additional step is required in the construction of filters employing adjustable coils. It is necessary to adjust the resonant frequencies of meshes after the elements are mounted, but before the filter is finally wired and tested, and furthermore, it is necessary to adjust these elements under exactly the same conditions that obtain during filter operation if the full benefit of the adjustable feature is to be realized. This requirement presented a difficulty, as the filters for the type "C" carrier system are assembled in copper boxes or shields as shown in Fig. 9 and are completely soldered all around, including the lid. This type of assembly was made necessary by the requirements on cross-talk between filters mounted next to each other on a vertical rack. The cross-talk between two filters mounted side by side was required to be 135 db below the signal currents, or, in other words, the ratio of the desired signal to the cross-talk had to be a little over 5,000,000 : 1. The chief cause of such cross-talk between two pieces of apparatus is electromagnetic coupling between them; to reduce this coupling eddy-current shielding is employed. Eddy-current shielding is accomplished by surrounding the source of a varying electromagnetic field—a coil, say, or the coils in a filter—by some metal, such as copper, brass or aluminum, which has good conductivity.

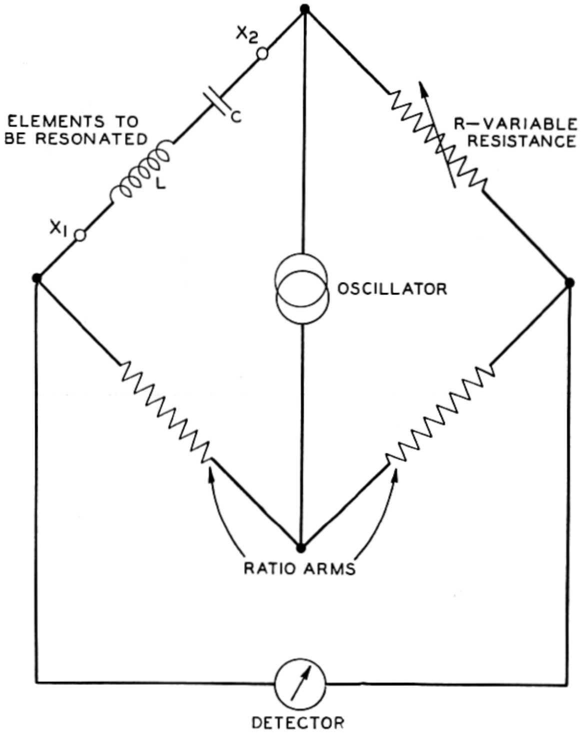

Fig. 8—Simplified schematic of L–C bridge.

To make clear the effect of a shield on an inclosed inductance, a brief discussion of shielding may be of interest. If a coil through which an alternating current is flowing is enclosed in such a shield, one part of the flux lines from the coil will encounter the shield; the remaining part will not. Let every line $\Delta\varphi$ of the flux which encounters the shield be divided into components perpendicular to the shield and parallel to it. If Θ is the angle between such a line and the plane of the shield, the component perpendicular to the shield, which is effective in setting up eddy currents in it is $\Delta\varphi \sin \Theta$. The other component, $\Delta\varphi \cos \Theta$, makes no coupling with this shield, and sets up no eddy currents. To every line $\Delta\varphi \sin \Theta$ the shield presents a certain inductance and resistance, and the average inductance and resistance presented to all the linking lines may be taken as the inductance and resistance of the shield. The equivalent circuit of a coil surrounded by a shield may be indicated, then, as a coil L_1 of two sections coupled to a second coil L_2, in parallel with a resistance R_2. This parallel circuit is the equivalent circuit of the shield. The coil L_1 has a total inductance equal to that of the coil in the shield, and is considered to be divided into two sections, the first of which, "A," makes no coupling at all with L_2, and the second, "B," which makes perfect coupling with L_2. If K is the coefficient of coupling between the coil L_1 as a whole and L_2,

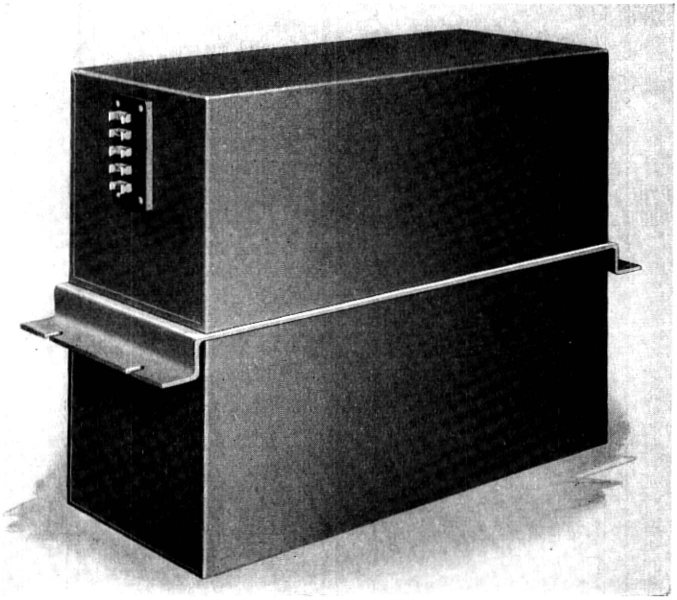

Fig. 9—Photograph of filter in soldered shield.

the portion "B" of L_1 is equal to K^2L_1. Now let a current I_1 be assumed to be flowing in L_1 and, I_2 in L_2. The mutual inductance between the coil and the shield is $-K\sqrt{L_1L_2}$. If e_1 is the voltage drop across the portion "B" of L_1

$$\begin{cases} e_1 = j\omega K^2L_1I_1 - j\omega K\sqrt{L_1L_2}I_2 \\ 0 = j\omega L_2I_2 + R_2I_2 - j\omega K\sqrt{L_1L_2}I_1, \end{cases} \tag{1}$$

from which

$$e_1 = \frac{I_1K^2R_2L_1\omega}{R_2^2+L_2^2\omega^2}(L_2\omega + jR_2).$$

Suppose $R_2 = 0$, which would be the case if the shield were made of a perfect conductor. Then $e_1 = 0$. If, however, R_2 is assumed to be infinite, $e_1 = I_1j\omega K^2L_1$, the voltage which would appear if the shield were not present. Since the portion "B" of L_1 is the only inductance coupled with the shield, it is the only source of a field which might extend beyond the shield. Therefore, when R_2 is 0, and e_1 the voltage across "B" is also 0, there is no energy in the field, and it obviously cannot make coupling with anything beyond the shield. This condition would obtain for perfect shielding, but R_2, of course, is never zero in practice.

When R_2 is finite, "e_1," the voltage across "B" is finite, and a certain amount of energy is transferred to the equivalent circuit of the shield. Part of this energy is dissipated in the equivalent resistance of the shield, and the remainder is stored in the field of the equivalent inductance.

The reactance, or "j" term of Equation 1 is a measure of the energy stored in the shield and is, therefore, also a measure of the field which may exist outside the shield. As the flux is proportional to the ampere-turns, and the reactance is proportional to the square of the turns, the square root of the ratio of this reactance value when R_2 is infinite to its value when R_2 is finite is the average ratio of the flux φ_0 with no shield present to the flux φ_s with the shield present.

$$\frac{\varphi_0}{\varphi_s} = \sqrt{\frac{\frac{1}{R_2^2}}{R_2^2 + L_2^2\omega^2}} = \sqrt{1 + \frac{\omega^2}{P^2}}, \tag{2}$$

where $P = \frac{R_2}{L_2}$.

The efficacy of the shielding in reducing the external field is therefore seen to be dependent upon the frequency, and a parameter "P," the ratio of resistance to inductance of the shield itself. As the voltage induced in some coil beyond the shield is proportional to the flux, the reduction in cross-talk caused by shielding may be written

$$a = 20 \log_{10} \frac{\varphi_0}{\varphi_s} = 10 \log_{10} \left(1 + \frac{\omega^2}{P^2} \right) . \tag{3}$$

In the 1/32 inch copper shields ordinarily used for filters, the parameter "P" has been found to have values from 1250 at 500 cycles to 2500 at 15000 cycles.

From Equation 1, the change in impedance, ΔZ of the coil, caused by the presence of the shield, may be written

$$\Delta Z = + \frac{[\omega^2 K^2 L_1 L_2 R_2]}{\omega^2 L_2^2 + R_2^2} - j\omega \frac{[\omega^2 K^2 L_1 L_2^2]}{\omega^2 L_2^2 + R_2^2} . \tag{4}$$

This change is made up of a decrease in reactance and an increase in the effective resistance of the coil. The percentage change in both resistance and reactance may be written

$$\frac{\Delta R_1}{L_1} = - \frac{\omega^2 K^2 P}{P^2 + \omega^2}, \tag{5}$$

$$\frac{\Delta L_1}{L_1} = - \frac{\omega^2 K^2}{P^2 + \omega^2}, \tag{6}$$

and

$$\frac{\Delta R_1}{\Delta L_1} = - P. \tag{7}$$

The percentage change in the inductance of the solenoidal air-core coils mounted inside ranged from 2 per cent to 4 per cent, depending upon the proximity of the coil to the shield. Since these changes depended upon the distance of the coils from the shield, slight variations in the winding diameters of the coils caused variation in the magnitude of this cover effect, so that although this change in inductance was taken into account by specifying inductance values for the filter coils 2 to 4 per cent higher than indicated by the design computations, the corrections were only approximate. No such correction was, of course, necessary for the condensers; the condensers, therefore, as measured outside the filter shield, were still correct, but the coils under the same conditions, measured higher than specified values. It was obvious that the resonant adjustment should not be made with the coils outside their shields, as the approximate nature of the cover correction would vitiate the precision of the adjustment, but it was equally obvious that it would be very difficult to make a coil adjustment inside the soldered cans, as the elements would then be inaccessible.

As mentioned above, the purpose of the filter shielding was to reduce the cross-talk between filters mounted side by side; the effect of the shield upon the coil inductances was an unwelcome incidental. When the coil adjustment was considered, however, the shielding effect of the copper can was of no interest, but its effect on inductances was of paramount importance. Efforts were made to devise a dummy shield which would simulate the standard filter shield in its effect upon the inductances of the coils mounted inside but in which the coils would be readily accessible for adjustment. As it was expected that the adjustable coil would enable resonant frequencies to be located at their desired values within limits of ± 0.1 per cent, it was necessary that any dummy shield developed for use in the adjusting process should reproduce on the coils the effect of the filter shield to at least this figure. In the ideal case, it would have been desirable that the difference between the dummy or adjusting shield and the standard shield be no greater than the difference between two standard shields.

Several different designs of adjusting shields were tried in the attempt to realize this ideal. The model finally adopted was constructed in the following manner: A box of the same height and width but slightly shorter than the standard shield was built, open at one end. Laboratory tests showed that for coils placed inside the shield near the closed end, the reduction in inductance caused by the shield was almost entirely unaffected by conditions at the other end of the shield. The far end could be closed or left open with an effect which was negligible in comparison with the total inductance change caused by the shield. This condition, of course, held only for coils in the closed end or at a distance of at least three coil diameters from the open end of the shield. Since the maximum number of solenoidal coils mounted on a panel in the type "C" system filters was four, it was necessary only that the adjusting shield simulate the standard for two coil positions, as a filter panel could be turned end for end and the other two coils inserted in the shield after the first two coils were adjusted. The method of adjustment employed was the same for all the preliminary models as for the final design. Small holes were drilled in the top of the shield corresponding to the standard coil locations in the filters, and through these holes the coils were adjusted by means of hard rubber rods with small buttons at their ends. For each coil position a pair of these rods was provided, so arranged that one could be rested on each of the long sides of the coil cradles. Then, by pushing on one rod or the other, the operator could move the cradle to the desired position.

The adjusting shield as finally constructed, and as now used both by the Bell Laboratories and by the Western Electric Company, consists of two of the open shields previously described, mounted on an angle iron frame with the open ends facing each other, as illustrated in Fig. 10. The two shields, which are separated by a distance great enough to allow the filter assembly to be inserted between them, are equipped with a number of adjusting tools sufficient to adjust coils in any of the standard positions. The right hand shield was arranged to accommodate only the coils mounted on the right of the sub-panel center line, and the left hand shield was arranged to care for the coils mounted on the other half of the panel. Resonant frequency adjustments made in the shield have been checked to within a maximum of about ± 0.05 per cent against the frequency of the same combination in a standard soldered shield.

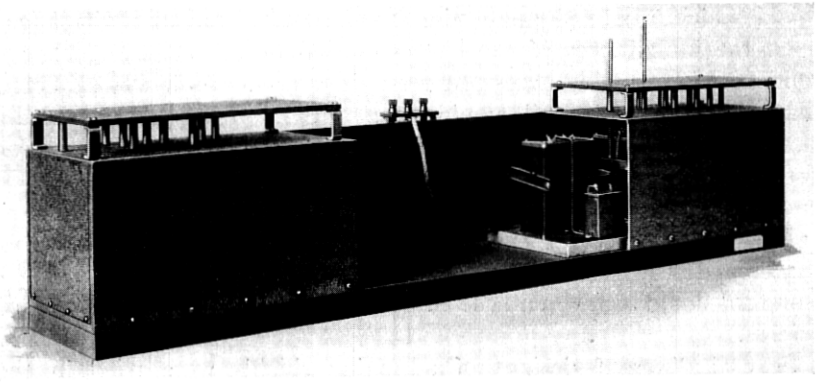

Fig. 10—Photograph of apparatus adjusting shield.

The shield is used with a special bridge and associated oscillator and detector, designed for the purpose. The bridge is very similar to the standard current bridges employed for measuring impedances at carrier frequencies, and the complete circuit is shown in Fig. 11.

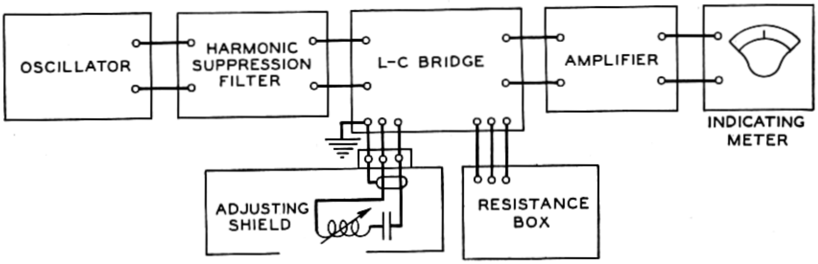

Fig. 11—L-C circuit arrangement.

A complete circuit for resonant frequency adjustment is set up at the Kearny, N. J. Works of the Western Electric Company where carrier filters are manufactured. There, after the coils and condensers in the filter are mounted upon their sub-panel (or panels), but before they are wired, the assemblies are brought over to the resonant frequency adjusting circuit, familiarly known as the *L–C* circuit. The sub-panel is placed in one end of the adjusting shield and the coils on that end of the sub-panel are adjusted in the manner previously outlined, after which the sub-panel is brought over to the other end of the shield, and the remaining coils are adjusted. After the coil rotors have been set at the positions for correct adjustment, they are locked by tightening the four screws which hold the coil terminal strip in place. The coil top presses down on the wedges (one of which is visible in Fig. 7) on each side of the coil case, and these wedges in turn clamp the rotor bearings firmly. Then the sub-panels are removed from the circuit, wired, and assembled in their shields.

This method of obtaining increased precision in filter manufacture was first employed in the band filters and equalizers for the Type "C" Carrier Telephone System. Previously, the ± 1 per cent limit on solenoidal air-core coils, the ± 0.3 per cent limit on mica condensers, and the additional ± 0.7 per cent variation in the effect of the filter shield in the coil inductance, caused by variation in the coil diameter, variation in the shield dimensions, and variation in mounting location, which added up to ± 2 per cent *L–C* variation, imposed a ± 1 per cent limit on the precision of frequency location. When the *L–C* method of adjustment is employed, the resonant frequency of a coil and condenser combination may be adjusted to ± 0.05 per cent, the precision of oscillator calibration, plus the ± 0.1 per cent limit on the adjustment process, or ± 0.15 per cent. In the laboratory it is possible to adjust the resonant frequency of an element combination to limits closer than ± 0.1 per cent, but the ± 0.1 per cent limits were set in the shop in order that production might proceed without undue delay occasioned by the process of adjustment. The ± 0.7 per cent tolerance caused by variation in coil diameter, shield dimensions and coil location is reduced to a variation of ± 0.1 per cent in *L–C* product, or ± 0.05 per cent in frequency; the difference between the adjusting shield and a filter shield caused by the variation in dimensions of filter shields. The precision of manufacture of filters using the *L–C* method of adjustment is, therefore, ± 0.15 per cent, the limits for the adjusting process, plus ± 0.05 per cent, the margin for variation in filter shield dimensions, or ± 0.20 per cent in frequency.

At 30 kc., this figure represents a variation in the location of the attenuation characteristic of ± 60 cycles. However, variations in the effective resistances of the filter coils, and variations in the reflection loss caused by small changes in the filter impedance produce changes in the attenuation of a filter which must be taken into consideration. The sum of these variations amounted to about ± 15 cycles. The ± 60 cycle precision at 30 kc., the highest frequency of the type "C" system, became, therefore, ± 75 cycles; a figure well within the ± 125 cycle maximum shop limit required by the system, and considerably less than the ± 300 cycle limits formerly obtainable.

The adoption of this method of filter construction has made it possible to realize in commercial manufacture the high precision of characteristic location which was formerly limited to laboratory construction.