Shielding In High-Frequency Measurements[1]

By J. G. FERGUSON

In this paper the purpose and usefulness of shielding in high-frequency measurement are outlined. General principles of electrostatic shielding are developed as applied to simple impedances and to networks of impedances, particularly to bridge networks. Practical applications of these principles to the shielding of adjustable impedances, and in the construction of actual bridge circuits, are described.

SHIELDING of high-frequency measurement apparatus has for its immediate object the control of certain electromagnetic and electrostatic couplings unintentionally introduced in the usual high-frequency circuit. These couplings are represented by stray admittances between the various parts of the system, either direct or to ground, and mutual impedances resulting from stray magnetic fields. In general, the control of these couplings is exercised for the purpose of attaining an accuracy of test that cannot be obtained so readily in other ways.

When we speak of electromagnetic and electrostatic coupling, it should be understood that these are simply component parts which together make up the total coupling which exists. They cannot be considered as existing independently of each other, and we cannot consider the shielding for one of these components without taking into consideration the effect on the other.

However, for the frequencies and impedances ordinarily used in communication work, at least, this interdependence is small enough to allow us to consider the shielding problem for each type by itself, without getting into practical difficulties due to this connection. As a result, two types of shielding which are known as electromagnetic, and electrostatic shielding have been developed.

It may be argued that by extensive separation of the physical parts of circuits and apparatus, any couplings can be decreased in value and in consequence errors caused by them can be reduced, thus eliminating any need for shielding. But there are obvious limits to the extent to which this method can be employed practically. In the case of electrostatic coupling to ground, it is scarcely of any value, and in any case excessive separation of the parts of a circuit introduces other errors due to the length of the wiring involved. Accordingly, it is usually necessary, where the maximum accuracy is desired, to have recourse to shielding.

[1] Presented before the A. I. E. E. Summer Convention, June 24–28, 1929.

The principles involved in the application of electromagnetic and of electrostatic shielding are quite different. In the case of electromagnetic shielding, the methods used have for their object the elimination of all couplings from the unit shielded to all other apparatus; thus, if perfect shielding were possible, the unit would have no coupling to any other parts of the circuit. It is never possible to accomplish this in the case of electrostatic shielding. Any electrical apparatus will have electrostatic coupling to any other apparatus in the vicinity and particularly to ground. The addition of shielding always introduces additional electrostatic coupling from the apparatus to the shield and the shield usually has more coupling to other equipment and to ground than the apparatus had before shielding it. Consequently, the principles of electrostatic shielding are mainly a matter of controlling this coupling in such a way that it has the least harmful effect in the circuit even at the expense of increasing its actual magnitude, rather than a matter of eliminating it entirely. For this reason electrostatic shielding requires much more extensive consideration and this paper is, therefore, devoted mainly to it, the principles of electromagnetic shielding being covered only briefly.

Principles of Electromagnetic Shielding

The necessity for electromagnetic shielding is limited practically to wound apparatus such as coils and transformers. It may be reduced to a minimum by using high permeability core material wherever possible in coils and transformers, and by using some form of closed core such as the toroidal type. By these means stray fields may be reduced to a relatively low figure. However, there are cases where the remaining coupling may be objectionable and it is then necessary to use shielding to reduce still further the amount of these stray fields.

Two types of shielding may be used. A high permeability material may be used for the purpose of short circuiting the stray field. The principles of this method of shielding are described fully in another paper and will not be considered further here.

In the case of air-core coils which are often of the solenoidal type, since the advantage of using the toroidal form is less in this case, and for coils used at very high frequency where heavy magnetic material is not so effective, shields of non-magnetic material may be used to confine the field by the effect of eddy currents. For these shields, a material of high conductivity is used, usually copper, and the principal consideration is the spacing of the shield from the coil rather than the thickness of the shield itself.

There is always a loss in efficiency due to the losses in the shield, and this loss is greater, the closer the shield is placed to the coil, that is, the stronger the field in which the shield is placed. However, even with solenoidal air-core coils very effective shielding may be attained by moderately thick copper shields spaced about the distance of a diameter from the coil.

PRINCIPLES OF ELECTROSTATIC SHIELDING

In both theory and practice all measurements assume that between different terminals or junction points of the system there are impedances having values known to a degree of definiteness consistent with the accuracies sought in the test. In an unshielded circuit it will generally be the case that the elements connected by the various terminals or junction points will not provide impedances so definitely known or in other words will not carry all of the current flowing between the points in question.

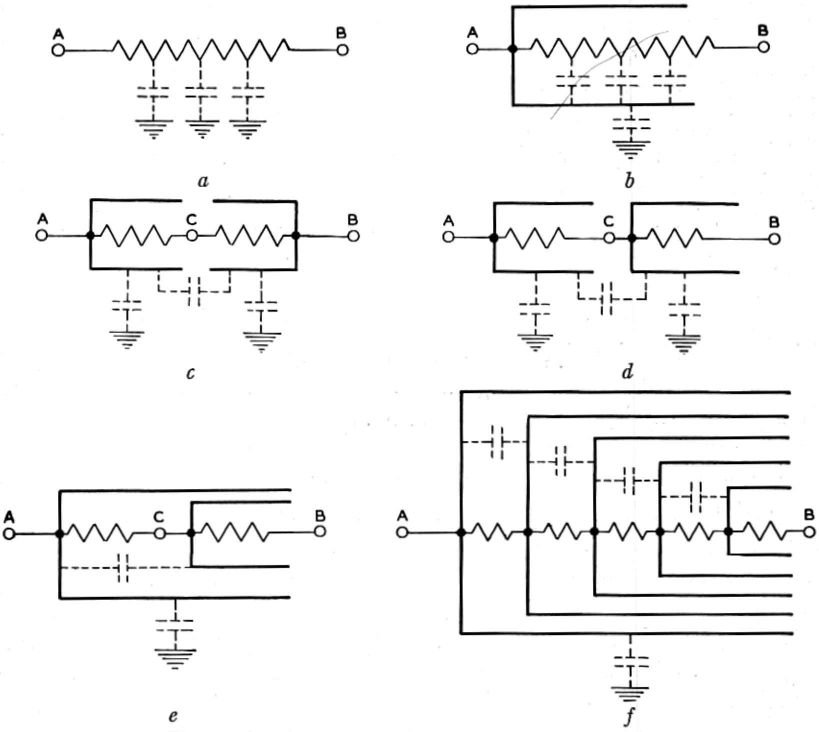

Fig. 1—Methods of Shielding Series Impedances.

Resistors

In the case of the simple resistor such as pictured schematically in Fig. 1*a* there are admittances from different parts of the conductor to other parts of the whole system and in particular to ground. These, of course, act to modify the effective impedance between the terminals and as they vary with the location of the resistor, the result is that its effective impedance is variable and known only for the location in which it has been calibrated. One of the first objects to be accomplished by shielding is to remedy this type of indefiniteness of value. This is done by mounting the elements within a shield of conducting material and in fixed space relation thereto, as shown in Fig. 1*b*. Thus, the circuit element has direct admittances only to the shield and as these are of fixed value the terminal to terminal impedance becomes independent of the location of the shielded element.

If, then, we connect the shield to any fixed point in the circuit element such as one terminal, all of the current transferred by the shield admittances passes to or from the circuit at this particular point. This concentration of admittance enables the ready evaluation of the effect produced by it when the element is used in conjunction with others in a complete measuring system. We may summarize all of this to form a fundamental rule of shielding, viz.: "the association of an element of a system with a shield so that all admittances from the element to other parts of the system or to ground are confined to one terminal."

If it is possible to connect such an element in a circuit so that the terminal to which the shield is connected is grounded, all variable admittances will be eliminated completely.

Series Impedances

In the case of two impedances in series as shown in Fig. 1*c*, shielding may be accomplished by connecting one shield to terminal A and the other shield to B. In addition to the effects described for a single impedance, there will then be admittance between the two shields which will depend on the position of the apparatus. This admittance is slightly more objectionable than admittance from shield to ground since, while we may ground either A or B, there will always be an admittance from one shield to ground which will be variable.

The shields may also be connected as shown in Fig. 1*d*, in which case the admittance between shields appears across the first impedance. Now if we extend the shield connected to A to include the other shield as shown in Fig. 1*e*, we have introduced a fixed admittance across AC and have variable admittances to ground from A. The admittance across AC is not objectionable in the case of a capacitor since it may be considered simply as an addition to it, but it has the effect of increasing the phase angle of a resistor and in the case of an inductor it increases the effective inductance and resistance variation with respect to frequency.

If this combination of impedances can be grounded at *A* we have a complete system having no variable admittances. The principle may be extended to include any number of series elements, the effect being to place admittances across all of the elements but one, and to enclose the whole system in one outer shield. Such a system for five elements in series is shown in Fig. 1*f*.

Parallel Impedances

The shielding of parallel impedances is comparatively simple since any number may be shielded individually and the shielding all connected to the same point. In reducing the shielding of multiple impedances to the simplest form the question arises whether it is sufficient to include them in a single shield or whether in addition they should be shielded from one another. If they are not shielded from one another, there will be distributed admittances between them which may cause errors. Preferably each should be shielded individually. Fig. 2 shows such a shielding system for capacitors in parallel.

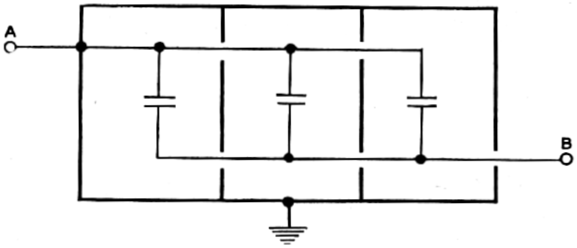

Fig. 2—Method of Shielding Parallel Impedances.

By following the procedure outlined above it is comparatively simple to apply shielding to any combination of impedances in series or in parallel in such a way that we will have all admittances to external conductors from the shielded elements concentrated at terminals or junction points of the system.

Circuit Shielding

In many cases it is impossible to connect the above combinations in a given circuit so that the outer shield is grounded. In such cases it is necessary to determine from the position of the network in the system the effect of admittances from the shield to other shields and to ground. To illustrate let us take the simple bridge circuit shown in Fig. 3. Each of the four impedances constituting the arms may be considered as any combination of individual impedances. With the shields connected as shown, the total admittances are reduced to three; namely, between B and D and from B and D to ground. These admittances do not affect the bridge balance and, therefore, are not objectionable. However, if we add input and output circuits and follow the same system of shielding, we get the result shown in Fig. 4. In this case it is impossible to concentrate all of the admittances at B and D. Neglecting for the present the ground at D, we have added variable admittances from A to B, to D and to ground. The only way of overcoming this difficulty is to use double shielding as shown, adding an outer shield to the impedance across AC and connecting it to D. This puts a fixed admittance across AD, but as we have not made any distinction between the four arms of the bridge, this admittance may generally be placed across an arm where it can be taken care of satisfactorily. If in addition we ground D, the admittances reduce to a single one from B to ground.

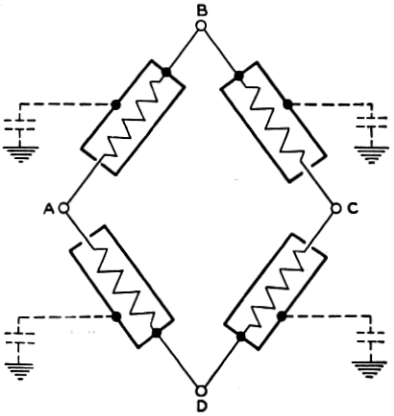

Fig. 3—Bridge Network Using Shielded Impedances.

Admittance to Ground of Unknown Impedance

From the above it would appear that the general bridge circuit is susceptible of a simple complete solution, since the shielding shown in Fig. 4 is equally applicable to all cases. This would be true if the unknown impedance to be measured in the circuit had no admittance to ground. This is usually not the case. We generally have an additional requirement that the potential condition with respect to ground of the impedance during the measurement be defined in some way.

If the impedance can be connected across one arm of the bridge and its value is desired with one terminal grounded, the circuit shown is satisfactory. However, these are special conditions, and where the impedance to be measured forms only part of the total series impedance of an arm, or where the potential requirements are different, such as the requirement that the coil be measured with its terminals at equal potential to ground, the bridge shielding becomes a more serious problem.

In general, the question of selecting the most suitable system of electrostatic shielding for a specific test circuit, resolves itself into a determination of the most advantageous location of the admittances which, as described above, have been arranged to terminate at certain terminals or junction points. The facts which need to be taken into consideration are usually so varied that no general rules can be established. A few typical examples in which shielding is applied with considerable success will, therefore, be taken and the selection of suitable shielding for these circuits discussed.

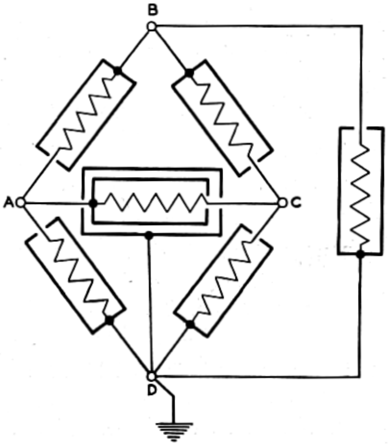

Fig. 4—Completely Shielded Bridge Network.

EXAMPLES OF ELECTROSTATIC SHIELDING

Adjustable Resistor

An adjustable resistor usually takes the form of a dial box in which there are from one to six dials arranged in series in decade formation. Each decade considered by itself is no more difficult to shield than a single resistor. The admittance of the shield, however, has a different effect at each step, which means that the phase angle varies with the setting of the dial. If the admittance to the shield is small, this effect will not be very great and in any case it is always the same for a given setting and hence may be included in a calibration.

In shielding several decades in series, admittances between decades are introduced. Effects due to these admittances can be taken care of completely by the use of nested shields as already shown in Fig. 1*f*. For a resistance box of five or six dials, this type of shielding becomes prohibitive from a size and cost standpoint and in consequence such shielding is usually not attempted. The use of a single shield for all decades of a resistor means that the impedance of two or more dial settings is not exactly equal to the sum of the impedances of each setting by itself. If the difference is appreciable the only alternative to the expensive type of shielding mentioned above is the use of a calibrated value for every combination of dial settings. This error in additions is smaller the lower the resistance, and usually may be neglected for values below 100 ohms.

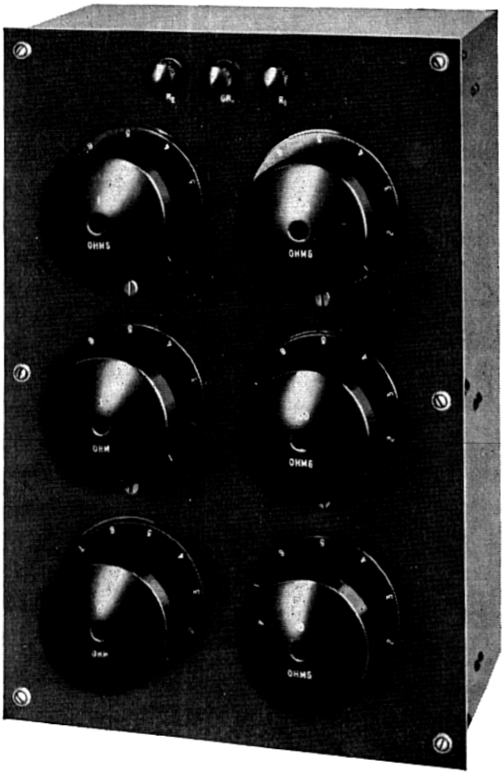

Fig. 5—Six-Dial Shielded Adjustable Resistor.

The decades are ordinarily connected in series in ascending order of magnitude. The shield should always be connected to the low end, that is, to the terminal to which the decade of smallest value is connected. The reason for this may be explained as follows: the admittance from any decade to the shield is a function of the dimensions of the dial switch rather than of the resistance value. Consequently, all dials have approximately equal admittance to ground. It is desirable that the total admittance to ground be a minimum across the higher resistance settings. This requires that the low resistance dials be connected between the high dials and the shield, that is, the shield should be connected to the low end of the box.

In the actual constructon of such a resistor it is essential that the shielding be complete, particularly at the dials. Since the effect of the hands in operating the dials is more variable than any other coupling, it is of very little value to place an unshielded dial box in a metal shield which allows admittance from the hand of the operator to the circuit.

An example of a six-dial resistor in a complete single shield is shown in Fig. 5. The box itself and the panel are of metal, and the construction of the dials is such that there is a continuous metal shield between each dial head and the switch proper which it controls.

As stated earlier, the effect of the shield on the performance of the resistor is to increase the phase angle of the higher resistance values. In the case shown the admittance introduced by the shielding is of about the same value as the total admittance distributed in the coils themselves and from the coils to the switch parts.

Adjustable Inductor

The same considerations apply to an inductor as to a resistor except that on account of the larger physical size of the former, larger admittances are associated with it and for that reason it is usually necessary to use nested shields. Fig. 6 shows a standard inductor consisting of three decades and an inductometer using four shields. The three top panels have been removed showing the method of nesting the shields, and the construction used to bring the dial controls through the shields. The shielding of this unit is not complete in that the fourth shield (the outer one) does not extend over the top. This is allowable as the admittance from the third shield to ground is across the inductometer and any variation in it has little effect, particularly as the final balance is obtained with the inductometer, thus eliminating variations due to the hands of the operator, which occur in operating the other dials.

The admittance between shields is considerable but due to the method of construction the largest admittance is across the smallest inductance and there is no intershield admittance added across the highest decade. Accordingly, the effect is not as serious as might be thought at first glance.

In the case shown, the inductometer and the lowest decade are generally used only in combination with the higher dials and under these conditions they are not used at sufficiently high frequencies for the admittance shunting them to have much effect. The greatest effect of the admittance introduced by the shielding usually occurs when the second highest dial is used at a high frequency with the high dial set on zero. However, the admittance introduced across this decade is not appreciably larger than the distributed admittance across the coils. The shielding, therefore, does not limit the range of these inductance standards to any great extent.

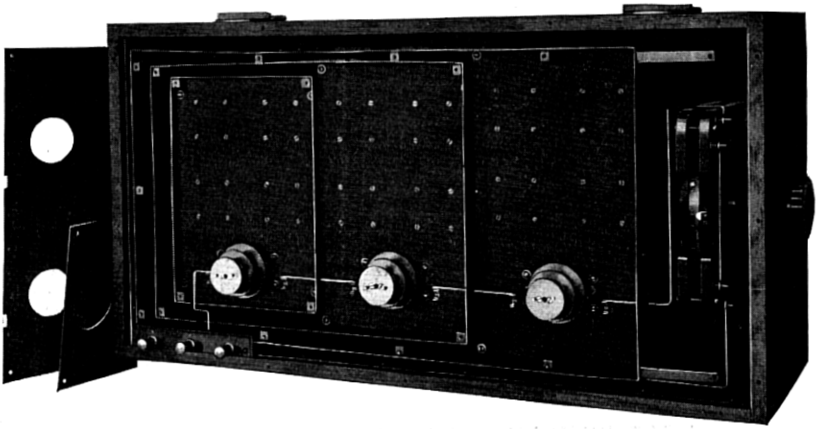

Fig. 6—Three-Dial Shielded Adjustable Inductor.

Adjustable Capacitor

The units of an adjustable capacitor are practically always connected in parallel and the problem of shielding them is that of shielding a single capacitor. It is desirable to shield the decades from each other if the capacitances are small as this facilitates calibration and is easily effected. Where the capacitance is large, say over 10,000 $\mu\mu$f., this precaution is unnecessary. The capacitance introduced from the shield to the units has the effect of increasing slightly the value of each dial setting. The form of construction of the shielding is similar to that of the resistor shown in Fig. 5.

Bridge Circuits

The general principles of bridge shielding have been discussed by Campbell[2] and the equal ratio-arm comparison bridge has been discussed in detail by Shackelton.[3] The mechanical construction of the bridge itself exclusive of standards is simplified by the fact that there are comparatively few dials to be brought through the shielding.

This bridge with the standards described above may be used for a wide variety of measurements. A rather simple modification is the so-called resonance bridge, in which the bridge unit is an equal ratio-arm comparison type, and a resistance is balanced in one impedance arm against a capacitance and an inductance connected in series in the other impedance arm. The balance is usually effected by adjusting the resistance and capacitance.

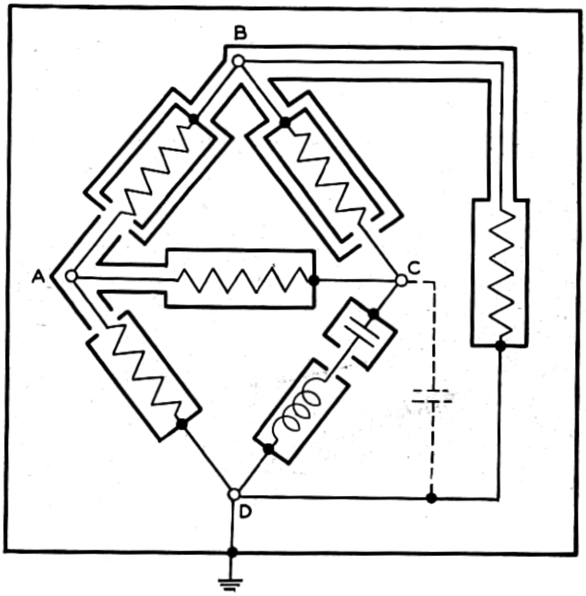

Fig. 7—Shielded Resonance Bridge Network.

The shielded circuit of such a bridge is shown in Fig. 7. The capacitance from C to D introduced by the shielding may be compensated for in the usual way by the addition of an equal capacitance across AD. In this circuit the coil is usually measured under the

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[2] G. A. Campbell, "The Shielded Balance," *Electrical World and Engineer*, April 2, 1904, p. 647.

[3] W. J. Shackelton, "A Shielded A-C. Inductance Bridge," *A. I. E. E. Journal*, Feb., 1927.

condition of one terminal at ground potential. Thus D is shown trapped to the ground shield. For this case, the shielding may be simplified considerably. Fig. 8 shows the mechanical construction of the combined resistance and capacitance standard used with the bridge unit for these measurements. The unit is shown with the top of the outer shield removed. The capacitance, in accordance with the shielding diagram, is double shielded, while the resistance requires only a ground shield.

Another bridge of the comparison type but using capacitance ratio arms is described by Kupfmuller [4] with a complete description of the shielding involved.

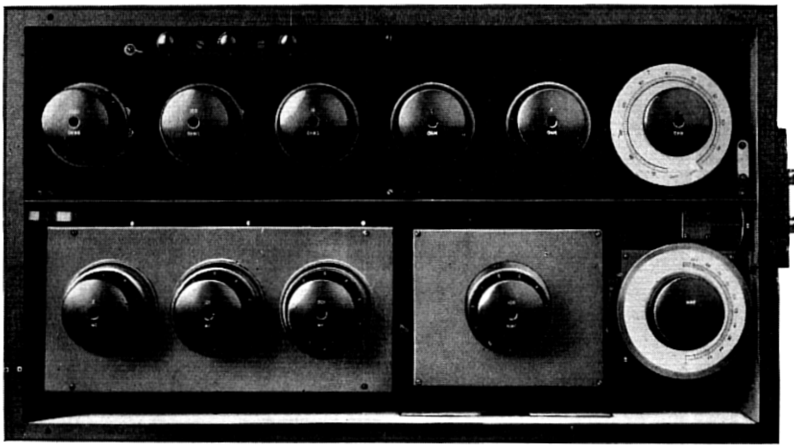

Fig. 8—Shielded Resonance Unit, Top Panel Removed.

A bridge of the general comparison type having self-contained standards of resistance and capacitance is shown with top panel removed in Fig. 9. It may be used for a wide variety of measurements such as series or shunt resonance, and direct comparison, by using the switches controlled by the small dials on the extreme left and right to throw the standards into various combinations.

Another bridge circuit which is interesting from the shielding point of view is the Owen bridge.[5] This is a skew bridge in which the ratio arms are 90° out of phase instead of being equal. For this reason any admittance introduced in one arm by the shielding cannot be compensated for by any equal admittance in another arm. Two

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[4] Von K. Kupfmuller, "Über eine Technische Hochfrequenz Messbrucke," *Elek. Nach. Tech.*, September, 1925, pp. 263–270.

[5] D. Owen, "A Bridge for the Measurement of Self Inductance," *Proc. Phys. Soc. London*, October, 1914.

methods of taking care of this admittance may be used. It may be concentrated in the arm consisting of a capacitance and considered part of it, or an admittance across one impedance arm may be compensated for by a resistance across the other impedance arm. Both methods have been used in the construction of these bridges. A more detailed discussion of the shielding involved in this type of bridge is contained in a previous paper by the present author.[6]

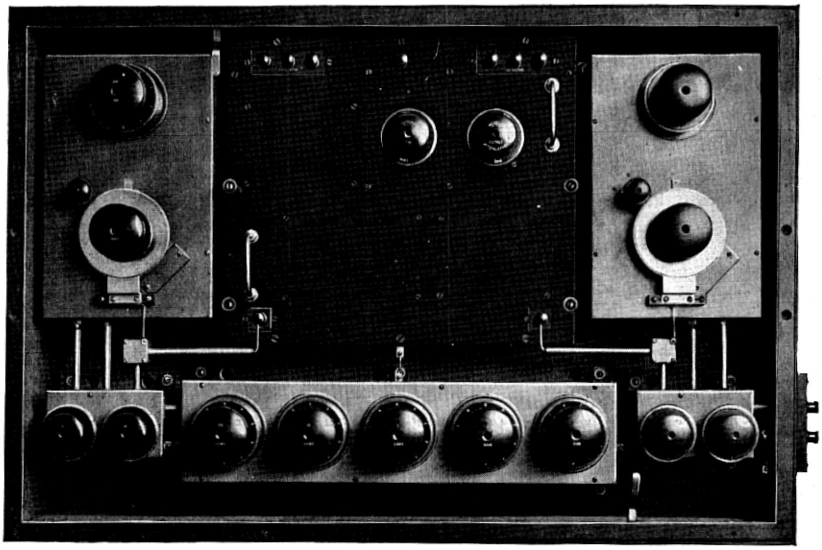

Fig. 9—Shielded Comparison Type Bridge, Top Panel Removed.

Details of Construction

We have discussed so far the admittance introduced by the shielding without going into details as to the form which this admittance takes although it has been broadly assumed that it is principally due to capacitance. Since it generally forms an integral part of the measuring circuit, it is obvious that as much consideration should be given to it as to the rest of the circuit. While the admittance is due essentially to capacitance, the necessary supports introduce a certain amount of conductance which causes some difficulty in obtaining compensation.

For instance, in the typical equal ratio-arm bridge circuit where the admittance across one arm requires compensation in the other arm, it is a simple matter to use an adjustable condenser for the compensation of capacitance. However, if the conductance is left un-

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[6] J. G. Ferguson, "Measurement of Inductance by the Shielded Owen Bridge," *Bell System Technical Journal*, July, 1927, pp. 375–386.

compensated for it may cause considerable error, particularly in the measurement of high impedances at high frequencies. For this reason it is desirable that all shields be supported by insulating material of the highest quality such as hard rubber, glass or quartz and that only the minimum amount necessary for satisfactory mechanical support be used.

The wiring it will be noticed in Fig. 9 is shielded by brass tubing. This shielding is insulated from the conductor by means of bushings, only enough being used to insure that the conductor and shield do not change their relative positions with respect to each other. The insulating bushings used most generally are either hard rubber or glass beads.

Even after taking these precautions it has been found necessary for the highest precision work at the highest frequencies, to introduce a conductance compensator in the form of a small adjustable condenser in which the dielectric is an insulating material such as phenol fiber. By this means the amount of conductance in one arm may be varied to obtain correct compensation. The balance, once obtained, does not vary appreciably with frequency. Such an adjustment is used with the bridge shown in Fig. 9.

In bridge input and output transformers, which must generally be double-shielded, the shielding is rendered more difficult due to the requirement of a low conductance between shields. This demands a much more expensive construction than the simple requirement of complete electrostatic shielding.

Limitations of Shielding

Having discussed the uses and advantages of shielding, it may not be amiss to discuss briefly some of the limitations. As already brought out, the introduction of shielding always brings with it some additional admittance. Since this admittance is a function of frequency it is natural that shielding should introduce more trouble, the higher the frequency. However, it is also equally true that the stray admittances due to lack of shielding introduce more trouble, as the frequency is increased.

In general, it may be said that if shielding a circuit is found to have a definite advantage at moderately high frequencies, it will have an advantage up to the maximum frequency at which the circuit is used. The principles outlined already apply over the whole range of communication frequencies. Where shielding is found to result in frequency limitations, it is due to the added admittance introduced with it and not due to inherent defects in the principles involved.

The shielding may, in special cases, limit the maximum frequency at which the circuit will operate; but in such cases it can usually be taken for granted that even if the circuit would operate at higher frequencies without shielding, the accuracy of the results would be highly questionable. Examples of limitations of shielding may be given using the apparatus already described. Take the case of the resistor shown in Fig. 5. The admittance across the resistances results in objectionably high phase angles and an effective change in the resistances at very high frequencies. While this effect would be present even though no shielding were used, the shielding increases it and therefore limits the maximum frequency at which the apparatus can be used from the standpoint of this type of error. The same limitation occurs in the case of the inductance standards only it is more serious due to the large physical size of these standards. The exact type of limitation here is that the individual units increase in inductance due to the admittance across them to such an extent that the difference between them cannot be bridged by the next lower decade, thus rendering it impossible to obtain certain values of inductance by any dial combination.

In the case of a symmetrical bridge the principal limitation is the shunting effect of the admittance introduced across the impedance arms. This becomes so large that, at frequencies in the order of 100 kilocycles, difficulties are encountered in measuring the current through the unknown impedances by the method of measuring the total current input to the bridge. If the meter question is eliminated, the actual loss in sensitivity, which is the only other objectionable feature of this admittance, may be made of no serious consequence up to frequencies as high as 2,000 kilocycles. In all other respects, the shielding functions as satisfactorily at this frequency as at the ower frequencies.

Auxiliary Equipment

While auxiliary apparatus such as oscillators and detectors is not strictly speaking measuring apparatus, its operation is essential to the satisfactory operation of the measuring circuit and so a few words may be added regarding the shielding of this apparatus.

Provided they are separated sufficiently from the measuring circuit and from each other, there is no need to shield the oscillator or detector from the standpoint of operation of the measuring circuit. However, for maximum flexibility it is desirable that they be so constructed that no special precautions are necessary in placing them relative to the measuring circuit. If, as is usually done, the individual apparatus included in these circuits is adequately shielded it is only necessary to place the completed equipment in an electrostatic shield to avoid all coupling to the measuring circuit or from one to the other. This is usually done by mounting the apparatus on a metal panel and placing it in a wood box with a sheet metal lining. By this means it is possible to place the auxiliary apparatus as close to the measuring circuit as desired, without introducing errors.

As far as the internal shielding of the auxiliary apparatus is concerned, the same rules hold as for other apparatus described. However, in the case of vacuum tube equipment, wherever any gain is introduced, coupling between parts of the circuit must be reduced in proportion to the gain introduced between these parts. This is usually accomplished quite readily by suitable mechanical design and may be insured by placing each stage in a separate grounded shield, although this is seldom necessary.

CONCLUSION

It has been impossible to go into very great detail in this brief paper on the subject of shielding. The attempt has been made, therefore, to outline a few general rules and to give representative examples of typical measuring circuits. It will be noted that the examples have been limited largely to the bridge circuit. This is because our experience has shown that this circuit is the most flexible and accurate over the whole of the frequency range over which precise impedance measurements have been made, and because the problems of shielding it are sufficiently difficult and varied to give satisfactory examples of the solution of rather complicated problems. The principles of shielding given have been found to apply equally well at all frequencies and it has been found that up to the maximum frequency at which precision measurements have been made, the shielding methods developed for use with moderate frequencies require practically no modification as the frequency is increased. Experience with measurements and measuring circuits up to 2,000 kilocycles makes it appear probable that when precision measurements are made at still higher frequencies, the shielded bridge circuit will continue to remain the most satisfactory measuring circuit.