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ELECTRICAL COMMUNICATIONS TECHNIQUE AND ITS APPLICATIONS IN ALLIED FIELDS

THE MEASUREMENT OF A SMALL INDUCTANCE

IT has been known for some time that ordinary bridge measurements on the types of small inductance coils used in tuning radio-frequency receivers have been unreliable. At the same time, the commercial tolerances for these coils have been restricted, and it has become necessary to measure coils of this sort with an accuracy of considerably better than one microhenry.

A careful consideration of the bridge circuits used has revealed three sources of error—the sliding zero balance occurring when two fixed inductors having energy factors, $Q = \frac{X}{R}$, between 0.1 and 10 are compared; the variable inductance of any decade resistor added in series with either inductor; and the energy factor of the resistor in any bridge arm due to capacitance in parallel with it.

The bridge circuit shown in Figure 1 is used to measure an unknown inductor in terms of a standard inductor. Considering the quantities in the P arm as unknowns, their values are

$$\begin{aligned} L_P &= \frac{B}{A} L_N \\ P &= \frac{B}{A} N. \end{aligned} \qquad (1)$$

If both of the inductors are fixed, one of the ratio arms, preferably the B arm, must be variable. In addition, resistance must be added in series with that inductor having the larger energy factor Q in order to provide the resistance balance. Because the resistance A appears in both balance equations, the two balances for resistance and inductance are not independent. Successive balances of resistance A and the added resistance will differ progressively and approach the correct balance point for each. The final balance is not, however, unique. It can be recognized only as the best balance in a series of approximate balances on each side of it. The amount of uncertainty introduced by this type of sliding balance point depends upon the energy factor Q of the coil. For large values of Q, the inductance balance is definite, and a consid-

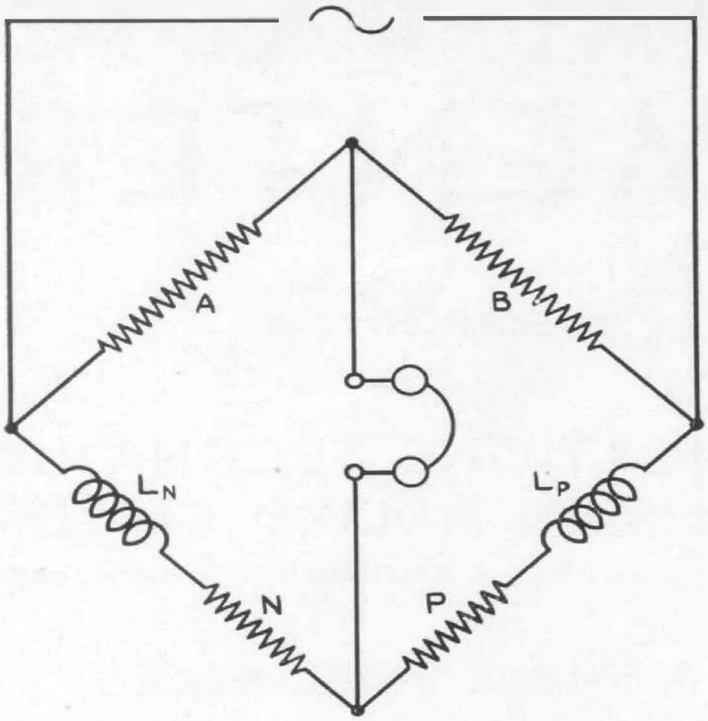


FIGURE 1. Basic bridge circuit for the measurement of inductance

erable error will appear in the resistance balance. Conversely, for values of Q less than unity, the greater uncertainty will appear in the inductance balance. Small inductors, which at radio frequencies may have energy factors approaching 100, have at a frequency of 1 kc values of Q between 0.1 and 1. Under these conditions it is quite possible for this uncertainty in the inductance balance to produce errors of a few per cent.

The two bridge balances may be made independent by the use of a small variable inductor placed in series with either inductance arm of the bridge. If the bridge is to be made direct-reading, it is preferable to place this small inductor in series with the unknown inductor. The inductance of an unknown inductor is

$$L_X = \frac{\Delta B}{A} L_N - \Delta L_P, \qquad (2)$$

where ΔB and ΔL_P represent the changes in ratio arm resistance B and inductance of the small variable inductor between the final balance of the bridge and the initial balance when the unknown terminals are shorted. By suitable calibration, the initial readings of both the variable inductor and the ratio arm B may be made zero so that the changes in their readings become their actual readings when the unknown inductor is connected in circuit.

This procedure will yield accurate results if no change in the inductance of the arm containing the added resistance occurs as the resistance is changed. In making precise measurements of inductances of less than 100 μh, however, the change in the inductance of a four-dial decade resistor can have an appreciable effect and must be taken into account.

The change in inductance of such a box from zero setting to full setting is of the order of 1 μh. The exact values for the TYPE 602 Decade-Resistance Boxes are given in the General Radio *Experimenter* for February, 1932. If this added resistance is placed in series with the small unknown inductor, the error introduced will be considerable. This error may be eliminated by the use of the TYPE 670 Compensated Decade Resistors. In these boxes, the total inductance is held at a fixed value by the use of compensating cards wound of copper wire having the same inductance as the corresponding resistance steps. Details of their construction are described in detail on page 6 of this issue. When this decade resistor is placed in the N arm, the standard in that arm may be adjusted to compensate for their inductance.

The third source of error is due to the inductance of the ratio arms and capacitance in parallel with the resistance in any arm of the bridge. Such extraneous reactances are called residuals and are shown diagrammatically in Figure 2. The terminal capacitances of the input transformer are placed across whichever pair of arms has its junction connected to ground, here the junction of the two inductance arms, because it will appear that in this position the smallest errors are introduced. The formulae applying to such a bridge are:

$$L_P = \frac{B}{A} L_N \left[1 - \frac{Q_A - Q_B + Q_{NC} - Q_{PC}}{Q_P} \right]$$

$$P = \frac{B}{A} N \left[1 + (Q_A - Q_B + Q_{NC} - Q_{PC}) Q_P \right],$$

where Q_A and Q_B are the energy factors of the A and B arms, respectively, and are of the form $Q = \frac{\omega \hat{L}}{R}$ in which $\hat{L} = L - R^2C$ as shown in Figure 3b. Q_{NC} and Q_{PC} are those parts of the energy factors of the resistances in the N and P arms due to the parallel capacitances and are of the form $Q = R\omega C$ as shown in Figure 3c. Q_N and Q_P are the energy factors of the known and unknown inductors increased by any added resistance and are of the form $Q = \frac{\omega L}{R}$ as shown in Figure 3a. The errors introduced by these residuals depend upon the same combination of Q_A, Q_B,

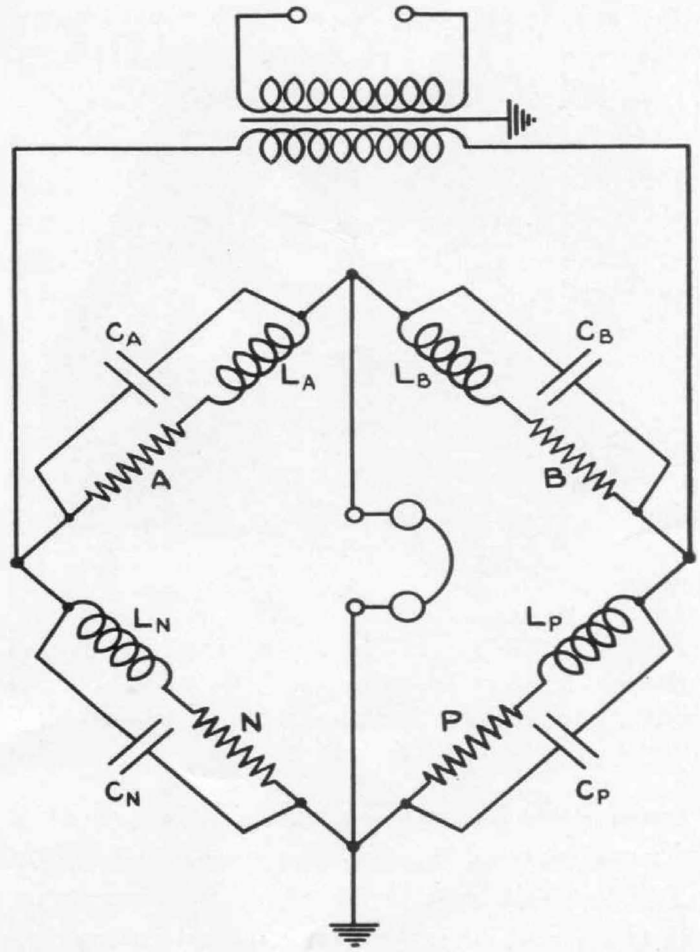


FIGURE 2. Inductance bridge circuit showing the presence of residuals

Q_{NC}, and Q_{PC} for both resistance and inductance except that, for inductance, this term is divided by the energy factor Q_P of the unknown inductor and for resistance it is multiplied by this same Q_P. An energy factor is of appreciable magnitude only when a high resistance is combined with a large parallel capacitance. For the case of 1 kΩ

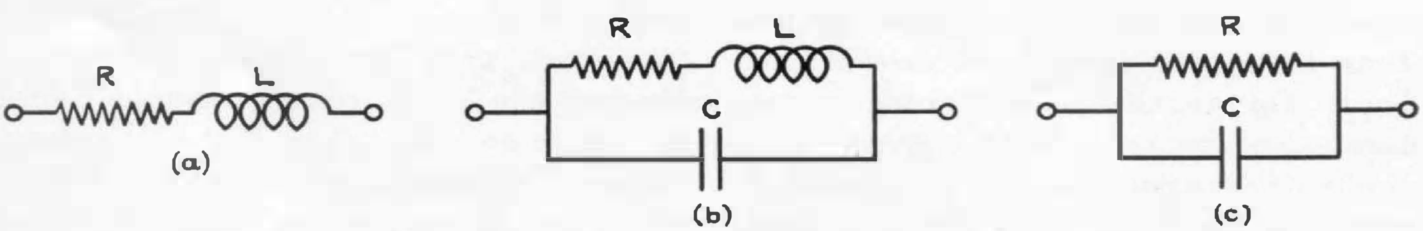


FIGURE 3. Equivalent circuits for three possible combinations of resistance, inductance, and capacitance. These relations are required for an understanding of the effect of the extraneous reactances shown in Figure 2

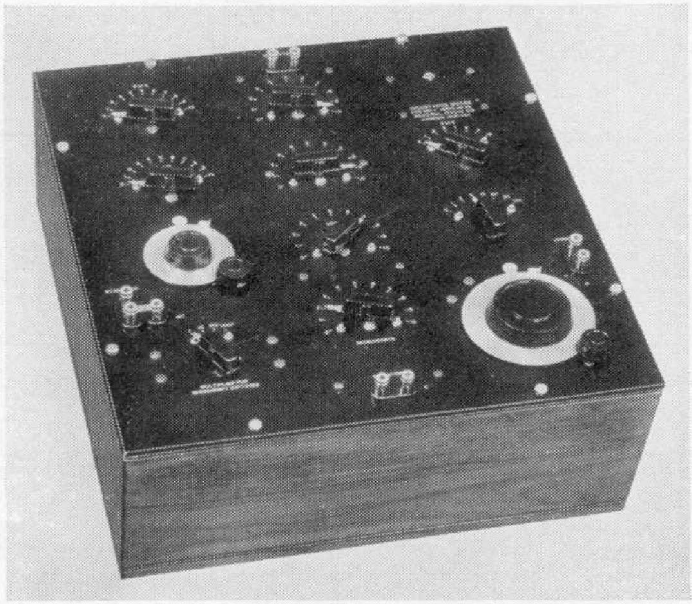


FIGURE 4. Inductance bridge making use of the principles described in this article. It is complete except for the generator and null detector

combined in parallel with 100 $\mu\mu$f at a frequency of 1 kc, the resulting Q is .0006. This would produce 0.06% error if Q_P were unity. For higher values of Q_P the error in inductance would be still smaller while the error in resistance would increase in proportion. For values of Q_P less than 1, it is the error in inductance which increases while the error in resistance remains negligible. Since it is quite possible to have a 100-μh inductor with a Q of only 0.1, errors of the order of 0.5% in inductance are possible for this case. Using a standard inductance L_N of 1 mh, resistance B is usually kept at 1 kΩ, while resistance A varies from 1 kΩ down to zero for unknown inductances of less than 1 mh. It is thus very desirable to keep the parallel capacitance across the ratio arms as small as possible. It is for this reason that the ground is placed at the junction of the two inductance arms. Terms involving the natural frequency of the inductances in the N and P arms determined by the parallel capacitances are omitted from the bridge equations because they are negligible for very small values of inductance at low frequencies. These terms become of importance only at high frequencies or in measurements of large inductances.

The three sources of error which have been previously considered—sliding zero balance, variable inductance of the added resistor, and energy factors of the bridge arms due to parallel capacitance—have been found to include all those responsible for inaccurate measurements of small inductances. When provision is made for eliminating them it should be possible to measure inductances up to 0.1 h to an accuracy of 0.1 μh or 0.1%, whichever is the larger. The upper limit of inductance, 0.1 h, is set by the use of a 1-mh standard inductor L_N, a limit of 1 kΩ for the resistances of the ratio arms, and by the fact that the accuracy of a 1-ohm decade is only 0.25%. By using larger inductance standards up to a value of 1 h, which in turn may be compared with the 1-mh standard, it should be possible to measure inductances up to 100 h to within 0.1%, and up to 1000 h to within 0.25%. If the resistance of either inductor exceeds a value of 1 kΩ the errors introduced by the parallel capacitances across the inductance arms must be considered.

When inductance measurements are made with the TYPE 193 Decade Bridge or the TYPE 293-A Universal Bridge, the TYPE 106-G Standard Inductance and the TYPE 670-FW Compensated Decade Resistor are placed in series in the standard arm and the TYPE 107-J Variable Inductor is placed in series with the unknown inductor in the X arm. The leads used in the standard arm should be twisted together loosely in order to minimize their inductance, while at the same time keeping their distributed capacitance small. The inductance of the Type 670-FW Compensated Decade Resistor is known and may be added to that of the standard inductor. The two inductors in the *X* arm should be spaced from each other and from the standard inductor so that no appreciable mutual inductance exists. Provision should be made for short-circuiting the unknown inductor without changing the position of its leads. The Type 514-A Amplifier and head telephones should be used as the null detector with its grounded terminal connected to that terminal which places the added resistance in series with the *X* arm. Any battery-operated generator such as a Type 213 Audio Oscillator or a Type 613-A Beat-Frequency Oscillator may be connected directly to the input terminals of the bridge. An a-c operated oscillator such as the Type 508-A Oscillator should be connected through a Type 293-P1 Transformer used step-down. This transformer should be used in any case if the leads from the oscillator are shielded and have large capacitance to ground. The Type 578 Shielded Transformer, having small terminal capacitances, is being developed for such use.

The greatest accuracy and ease of adjustment are usually attained with any bridge circuit when its component parts are built into a single compact instrument. A bridge embodying the features discussed above has been built on special order and is shown in Figures 4 and 5. — Robert F. Field

[A bridge of the type described is being built under Mr. Field's direction. — Editor]

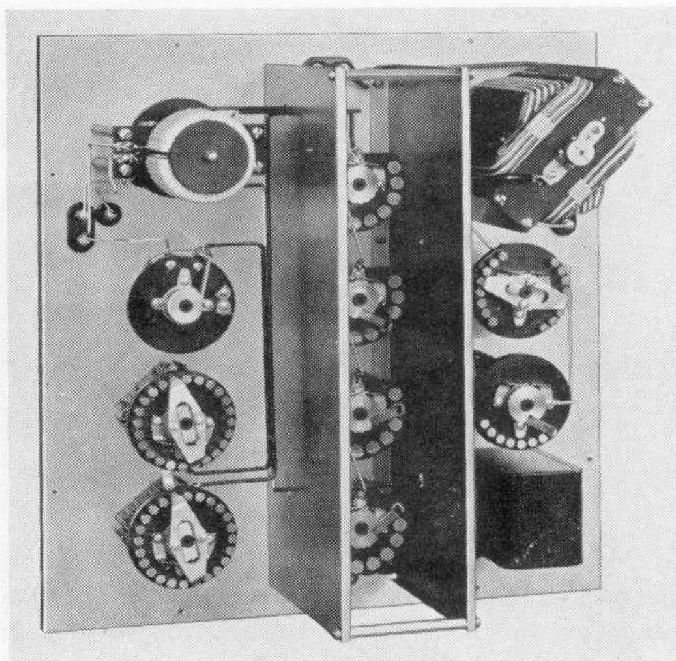


Figure 5. Behind the panel view of the inductance bridge shown in Figure 4. The arrangement of the various units is clearly shown

CONSTANT-INDUCTANCE RESISTORS

ALTHOUGH the residual inductance of the TYPE 510 Decade-Resistance Units has been reduced to a very small value by the choice of a suitable type of winding, it is still large enough to produce appreciable errors in the measurement of capacitance at radio frequencies and of a small inductance at audio frequencies. The former use was discussed in the General Radio *Experimenter* for December, 1933, in a description of the TYPE 516-C Radio-Frequency Bridge. The latter application is described on page 1 of this issue in connection with the design of a bridge for measuring small inductances.

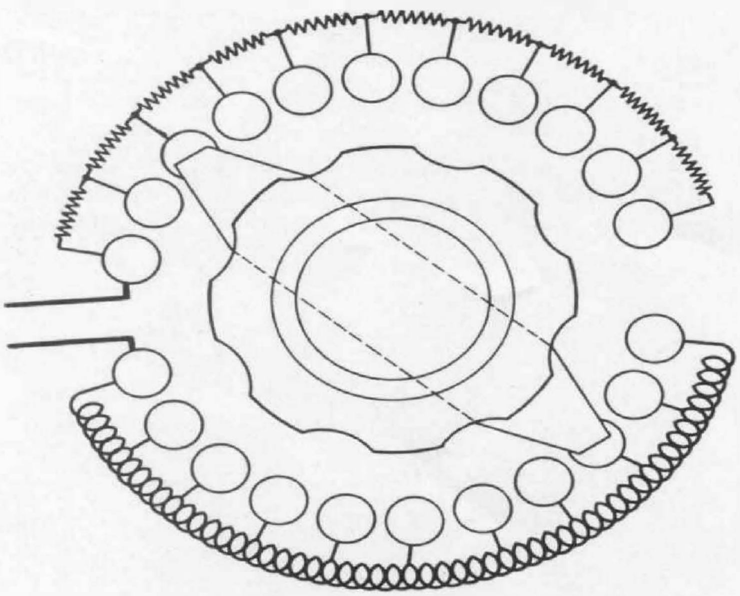


FIGURE 1. Schematic diagram of the inductance compensated decade resistors shown in Figures 3 and 4

Since the ideal of an inductance-free resistor is unattainable, the next best choice for a variable resistor is one in which the inductance is kept constant. This may be accomplished either by so designing the separate resistors that they all have the same inductance or by compensating for their variable inductance by introducing, at each step, sufficient inductance to keep the total inductance constant. The latter method has been adopted because it is very desirable, in switching from one value of resistance to another, that no new values be introduced during the transition.

The TYPE 668 Compensated Decade-Resistance Units make use of a double switch as shown in Figure 1, which connects between the decade resistors and a compensating winding of copper wire. This winding has the same inductance as the resistors but arranged in the opposite sense. In this way, as resistance is increased by a clockwise motion of the switch, the inductance of the compensating winding is reduced so that the total inductance remains constant. This method of compensation can be applied only to the smaller resistance decades because of the effect of the parallel capacitance introduced by the switch mechanism and by the windings themselves.

Any resistor may be represented by the series-parallel combination shown in Figure 2. The equivalent

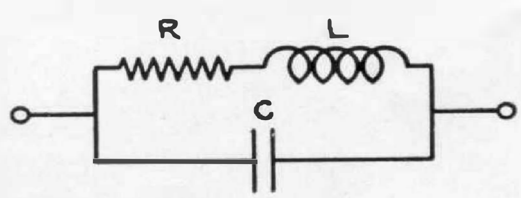


FIGURE 2. The behavior of any resistor can be predicted from a study of its series-parallel equivalent circuit

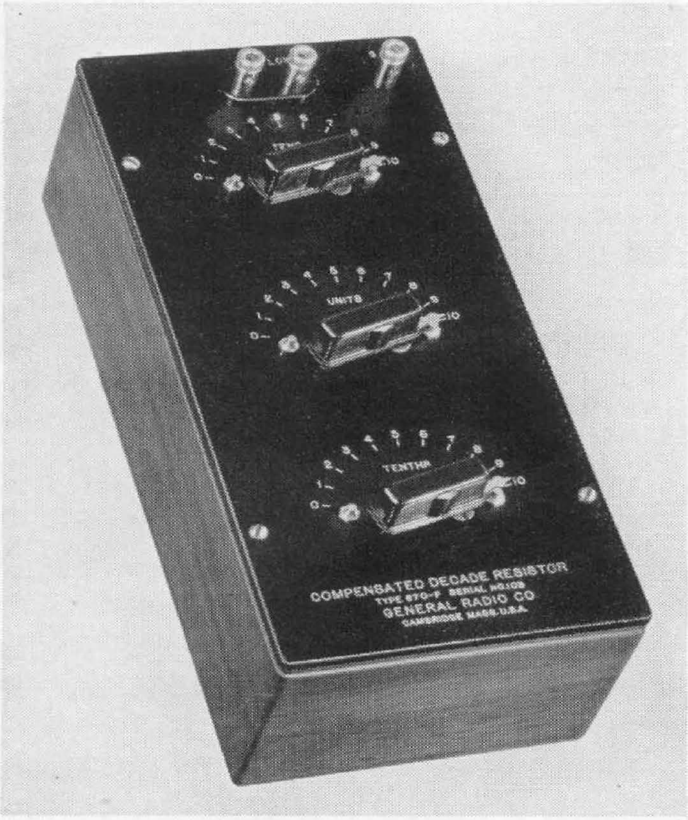


Figure 3. The Type 670-F Compensated Decade Resistor. An assembly of three Type 668 Decade-Resistance Units

inductance of this circuit is

$$\hat{L} = L - R^2C \qquad (1)$$

at all frequencies low compared with the natural frequency determined by the inductance and capacitance. It was shown in the General Radio *Experimenter* for February, 1932, that for the Type 510 Decade-Resistance Units the inductance L is proportional to resistance R and that the parallel capacitance C is approximately constant. The value of this capacitance is 6 $\mu\mu$f for a single decade, and it may be increased in a Type 602 Decade-Resistance Box by the multiple switches and shielding to a possible maximum of 60 $\mu\mu$f.

The form of equation (1) indicates that the equivalent inductance $\hat{L}$ will cease to increase at a certain value of resistance, will become zero when $L = R^2C$, and, for larger values of resistance, will become negative, that is, capacitive. The maximum value of inductance occurs at a resistance of about 100 ohms and reverses its sign at about the middle of the 100-ohm decade. Since it is possible to compensate for inductance variations by the method shown in Figure 1 only for an equivalent inductance increasing with resistance, this method is applicable only to the 10-ohm decade and lower.

The appearance of these compensated decades is shown in Figure 3.

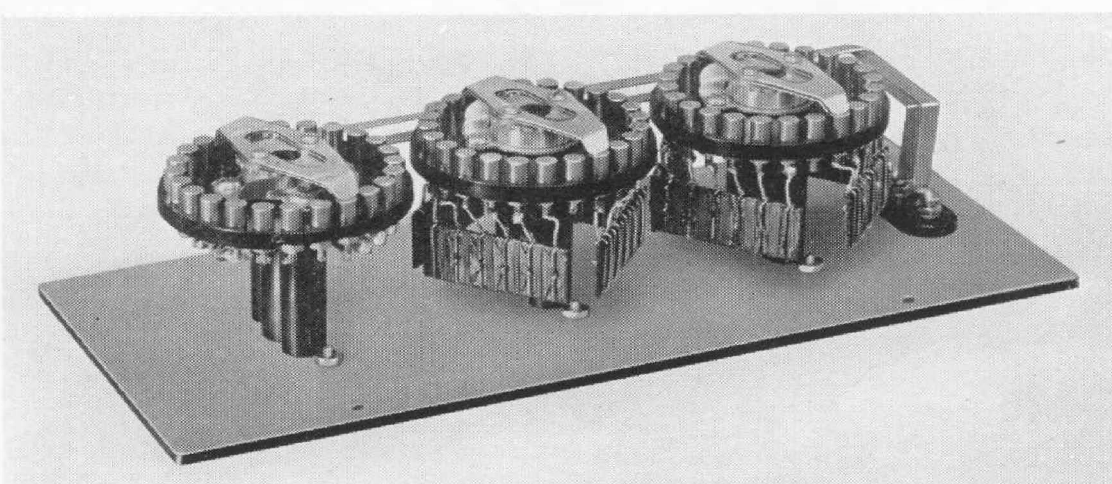


Figure 4. An interior view of the compensated decade resistor shown in Figure 3. In Figure 1 is shown the method by which the inductance is maintained constant for all settings of each switch

TABLE I

DATA SUMMARY FOR
TYPE 668 Compensated Decade-Resistance Units
and for TYPE 669 Compensated Slide-Wire Resistors

Type	*668-A*	*668-B*	*668-C*	*669-A*	*669-R*
Decade	0.1 ohm	1 ohm	10 ohms	....	....
Maximum Resistance	1 ohm	10 ohms	100 ohms	1 ohm	0.1 ohm
Time Constant	0.15 μ sec	0.03 μ sec	0.005 μ sec	0.15 μ sec	1.5 μ sec
Total Inductance	0.15 μh	0.3 μh	0.5 μh	0.15 μh	0.15 μh
Inductance Change	0.05 μh	0.05 μh	0.05 μh	0.005 μh	0.005 μh
Zero Resistance	0.005 ohm	0.020 ohm	0.015 ohm	0.045 ohm	0.020 ohm
Current for 40°C. Rise	1.6 a	0.5 a	0.16 a	1.6 a	5 a
Error	1%	0.25%	0.1%	1%	5%

The individual resistors of the tenth-ohm decade are similar to those used in the TYPE 510-A Decade-Resistance Unit. The cards used in the units and tens decades are smaller and thinner than those used in the TYPE 510-B and TYPE 510-C Decade-Resistance Units and were developed for use at high frequencies in the TYPE 516-C Radio-Frequency Bridge. Their power rating is 0.25 watt for a temperature rise of 40°C. and their inductance is considerably less than that of the corresponding TYPE 510 Decade-Resistance Units. The values of their time constants and total inductance at maximum setting are given in Table I. There is also given in this table the maximum change in inductance with setting due to imperfect compensation, their zero resistance, the current necessary to produce a temperature rise of 40°C., and the accuracy of adjustment. It will be noted that the total change in inductance is only 0.05 μh. Their zero resistances are larger than the switch resistances of the TYPE 510 Decade-Resistance Units, due to the resistance of the compensating winding. Since it is expected that the greatest use for these decades is in substitution methods, this relatively large zero resistance is not objectionable. The accuracy of adjustment given applies to the change in resistance from its zero value.

There are many uses for a variable resistor in which it is necessary to adjust its resistance value closer than 0.1 ohm and at the same time to keep its inductance constant. This may be accomplished by a slide wire compensated for inductance as shown in Figure 5. This is a developed view of a circular slide wire in which a short-circuiting arm connects from the top resistance wire to the bottom copper wire so that the inductance of the combination is independent of the position of the short-circuiting bridge. The copper wire return is placed symmetrically with respect to the two outer wires. This construction is adopted in the TYPE 669 Compensated Slide-

TABLE II

DATA SUMMARY FOR TYPE 670
Compensated Decade Resistors

Type	*670-F*	*670-FW*	*670-BW*
Zero Inductance	1.05 μh	1.05 μh	0.70 μh
Zero Resistance	0.045	0.085	0.050

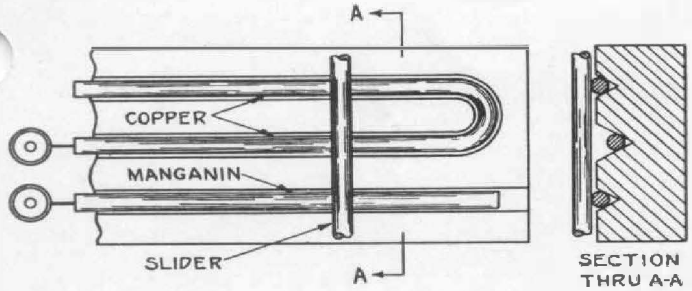


FIGURE 5. Inductance compensation as applied to slide-wire resistance units is shown schematically in this figure. The slider does not make contact with the center inductor

Wire Resistors as shown in Figure 6. There are two sizes with total resistances of 1 ohm and 0.1 ohm. In the latter, all the wires are of the same diameter. In the former, the copper wires are made of larger diameter than the manganin resistance wire in order to provide a greater wearing surface on the copper. In this case, the central copper return wire is unsymmetrically placed with respect to the two outside wires so that its inductance, with respect to them, is the same.

The various characteristics of these slide wires are given in Table I. Their constancy of inductance is such that they may be used as standards by which the inductance of other variable resistors may be measured.

The three TYPE 668 Compensated Resistance Units and the two TYPE 669 Compensated Slide-Wire Resistors are combined in three ways to form the TYPE 670 Compensated Decade Resistors. The TYPE 670-F Compensated Decade Resistor contains all three of the compensated decade resistors. The other two resistance boxes, TYPE 670-FW and TYPE 670-BW each combine one of the TYPE 669 Compensated Slide-Wire Resistors together with the next two higher compensated decades. The zero inductance and resistance of these three boxes are given in Table II.

—ROBERT F. FIELD

[Mr. Field is the designer of these new resistors.—Editor]

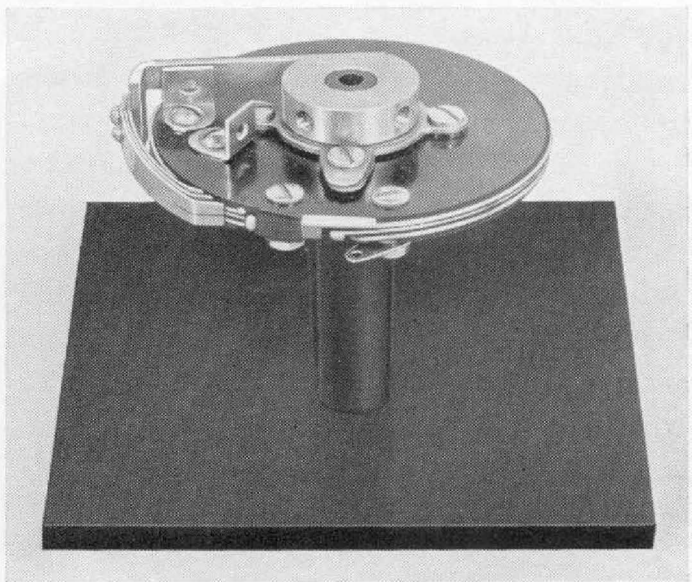


FIGURE 6. The TYPE 669 Compensated Slide-Wire Resistor. Its construction is indicated schematically in Figure 5

See Page 12 for Specifications

TAKING SLOW-MOTION MOVIES WITH AN ORDINARY MOTION-PICTURE CAMERA

ALL stroboscope-minded engineers are familiar with slow-motion movies in which a high-speed shutterless camera is used in conjunction with stroboscopic light, but it is not so generally known that similar pictures can be taken at normal speeds with the conventional movie camera.

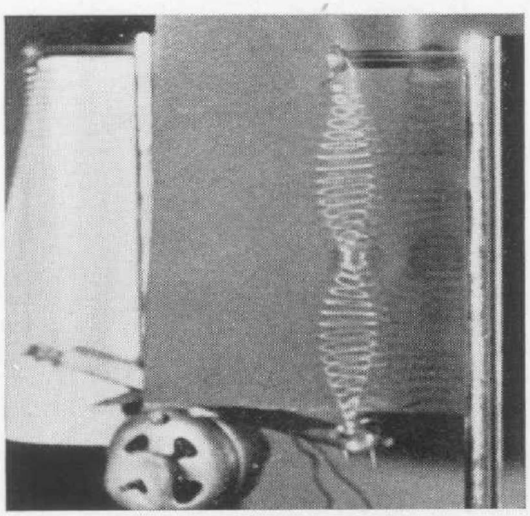
It is an almost axiomatic principle in motion-picture photography that you can photograph anything that you can see, provided, of course, that certain restrictions as to brilliancy of illumination are met. So, in theory at least, one should be able to photograph oscillatory phenomena in "slow motion" just as he views them with a stroboscope.

The hitch is, of course, that the camera shutter is closed for an appreciable part of the time, so that occasionally no flashes occur while the shutter is open. The result is a blank frame which, on projection, causes annoying flicker.

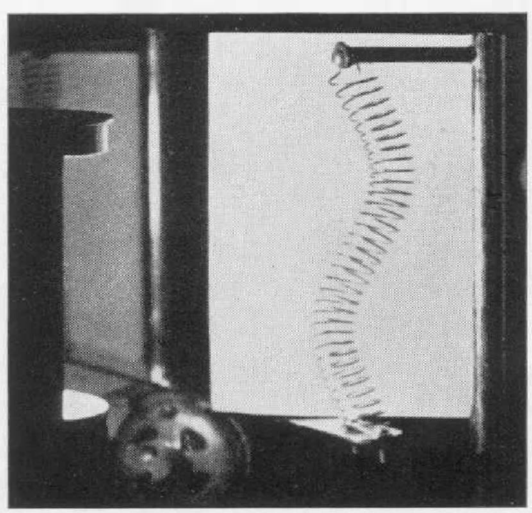
This difficulty is successfully overcome by so choosing the flashing speed of the stroboscopic light that there are at least two flashes for every frame, but, since there are 16 frames per second, this would seem to limit the application of this method to rotational speeds of 2 x 16 x 60 = 1900 revolutions per minute. Slower rotational speeds can, however, be photographed by reducing the speed of the camera sufficiently to retain the two-flashes-per-frame relationship. This is easy to do, and if, in addition, the *differential* flashing rate which determines the rapidity of the "slow motion" is reduced in proportion, the movies, when projected, will show the motion at the normal slow-motion rate.

Although this method is necessarily limited to recurrent (as distinguished from transient) phenomena, it is an excellent means of preparing pictures for demonstration purposes or for recording experimental results for future study and measurement.

—JOHN D. CRAWFORD

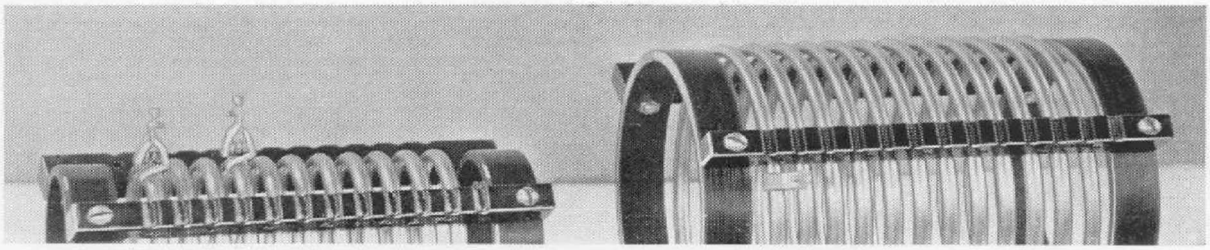


WITH ORDINARY LIGHT

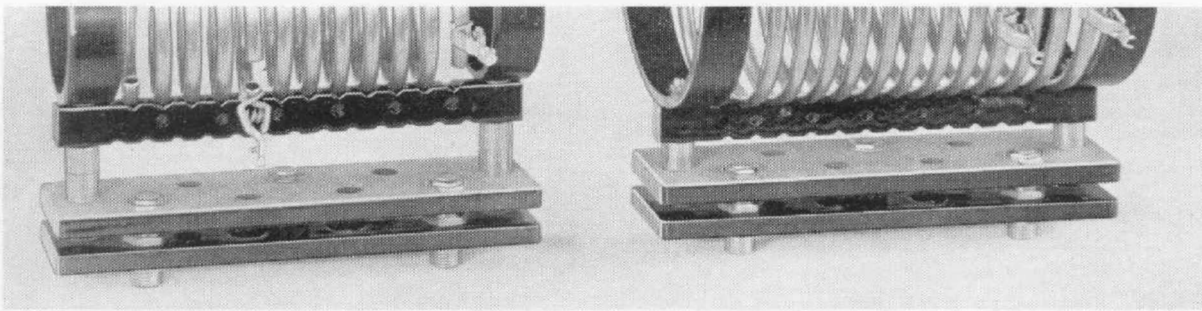


WITH STROBOSCOPIC LIGHT

One frame from a stroboscopic slow-motion movie made by the method described in the foregoing article compared with another taken with ordinary light. The TYPE 548-A Edgerton Stroboscope supplied plenty of illumination. (The photographs are unretouched and were taken with an ordinary 35-mm camera on super-speed panchromatic film with an *f*3.5 lens)



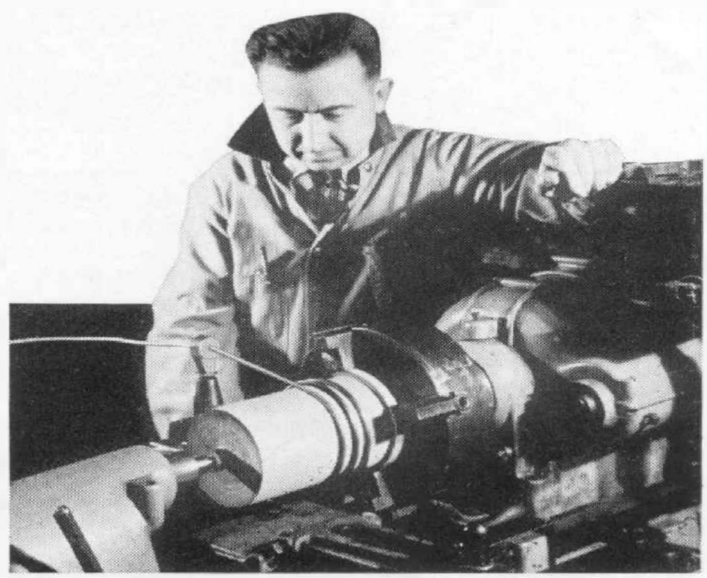
NEW INDUCTORS FOR THE POWER OSCILLATOR



ONE of the toughest mechanical jobs that the amateur or experimental laboratory constructor has is the winding of high-frequency coils for power amplifiers and oscillators. Copper tubing is the best material for such service, is extremely difficult to wind without flattening or breaking, even when the method of doing it has been carefully explained.* With care, the inexperienced mechanic can do it, but it's a long, hard job, and after he has tried it once, the amateur constructor, unless he has the patience of Job, will certainly try to buy his inductors ready-made.

The two new inductor units shown at the top of the page (at the right, TYPE 679-A; at the left TYPE 679-B) are recent additions to the General Radio line. The tubing is space-wound on a form by the method shown at right and then fitted into the ribbed porcelain supports which are held in place at both ends by bakelite rings. Each unit has a jack base fitted with three of the large-size General Radio plugs and there are holes for four more, if at some later time it is desired to add them.

It should be noted that the outer edges of the porcelain supports are also notched, so that extra coupling windings can, if desired, be added. Connections are made by copper clips, the jaws of which have been formed



This is how General Radio winds copper tubing in the manufacture of a TYPE 679-A Inductor

*See, for example, *The Radio Amateur's Handbook*, Tenth Edition, p. 88.

to fit the copper tubing. The tubing is nickel plated to eliminate the oxidation that always ruins the appearance of bare, unprotected copper. The added resistance of the nickel plating is entirely negligible, superstition to the contrary notwithstanding (in fact, it is a toss-up as to whether the nickel-plated or the oxidized-copper surface shows the greater resistance).

The essential details are given in the accompanying specifications. Both inductors were designed by J. M. Clayton in collaboration with Melville Eastham.

SPECIFICATIONS

Tubing: ¼-inch copper, nickel plated to prevent tarnish.

	Type 679-A	Type 679-B
Turns	12	7 and 4
Number of sections	1	2
Inductance (approximate)	10 μh	2 μh, 1.5 μh
Clips supplied	3	4
Type 674-P Plugs supplied	3	3
Outside diameter of coil	5¾ in.	3¼ in.
Length, over-all	7¼ in.	7¼ in.
Height, over-all	8½ in.	6¾ in.
Depth, over-all	6½ in.	4½ in.
Net weight	3⅛ lbs.	2⅜ lbs.

Mounting: The terminal plate of each inductor is fitted with three Type 674-P Plugs so that the whole unit may be plugged into a Type 680-J Jack Base. Four additional plugs may be added to terminal plate of inductor if desired. (See illustration.)

Jack Base: This base (not included in the price of either inductor) is the counterpart of the plug base on the inductor unit. It is fitted with three Type 674-J Jacks, and four more may be added, if desired.

Prices: Type 679-A Inductor, $7.50; Type 679-B Inductor, $6.50; Type 680-A Jack Base, $1.25.

SPECIFICATIONS (Continued from page 9)

TYPE 668 COMPENSATED DECADE-RESISTANCE UNIT

Type	*Resistance*	*Code Word*	*Price*
668-A	1 ohm, total, in steps of 0.1 ohm	GABLE	$15.00
668-B	10 ohms, total, in steps of 1 ohm	GAILY	15.00
668-C	100 ohms, total, in steps of 10 ohms	GALOP	15.00

TYPE 669 COMPENSATED SLIDE-WIRE RESISTOR

Type	*Resistance*	*Code Word*	*Price*
669-A	0 to 1 ohm, continuously adjustable	GAMIN	$25.00
669-R	0 to 0.1 ohm, continuously adjustable	GAZEL	25.00

TYPE 670 COMPENSATED DECADE RESISTOR

Type	*Resistance*	*Dials* *Decades*	*Dials* *Slide Wire*	*Code Word*	*Price*
*670-BW	0 to 11 ohms, total (slide wire)	2	1	ABRID	$80.00
670-F	0 to 111 ohms, total, in steps of 0.1 ohm	3	. . .	ABYSS	65.00
*670-FW	0 to 111 ohms, total (slide wire)	2	1	ADOWN	75.00

*Built to order only and not carried in stock. Normal delivery, two weeks.

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