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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

THE BUTTERFLY CIRCUIT*

● **AT HIGH RADIO FREQUENCIES** transmission lines have been used for a long time to perform the functions of resonant circuits. In the region near resonance, the curve of line impedance as a function of frequency has the same shape as the resonance curve of a circuit with lumped constants. The equivalent Q depends upon the frequency, upon the configuration of the line, and upon the materials used. For a concentric line, for instance, with optimum ratio of outside to inside diameter of 3.6, with copper conductors and air dielectric, Q is approximately $0.1D\sqrt{f}$ where D is the inside diameter of the outer conductor in inches and f the frequency in cycles per second. Such a line has approximately 75 ohms characteristic impedance and, for an inside diameter of 1 inch, has a Q of 1000 at 100 Mc. Off resonance, transmission lines are reactances, but they change somewhat differently with frequency than do coils and condensers.

While transmission lines have been used at moderately high frequencies mainly to obtain superior performance as expressed by high values of Q, they have seemed to be the only practical means of tuning at still higher frequencies. It has been assumed that conventional tuning devices were of little use at frequencies over a few hundred megacycles, and so concentric lines have generally been adopted. Theoretically,

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*Patent applied for.

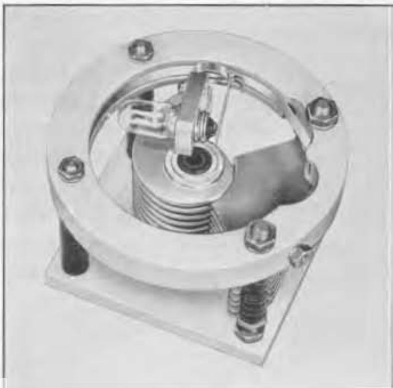


FIGURE 1. 55–400 Mc Wavemeter. Adaptation of conventional tuning condenser.

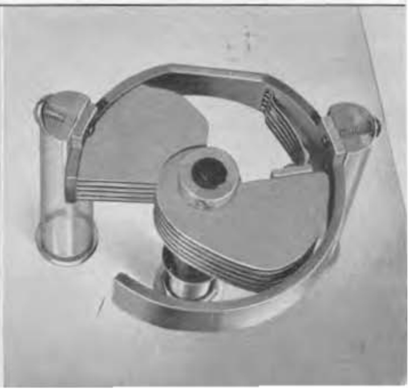


FIGURE 2. Contact type tuning unit for 60–660 Mc.

these lines are very suitable for the intended purpose, but in practice their performance has not been completely satisfactory. This is due entirely to mechanical difficulties, but thus far no simple solution to them has been found. The problem involved is merely that of changing the length of a line by accurately known amounts without introducing losses and erratic variations. In some applications the changes required are small, and actual contact with the line conductors can be avoided, but sliding contacts are required if the tuning range is large. In addition, the motion is ordinarily derived from a lead screw of considerable length, which is difficult to manufacture with sufficient accuracy.

It seemed desirable, therefore, to investigate again the possibility of circuits with lumped parameters, where tuning over wide frequency ranges could be achieved by rotating one member with respect to another and to see if sliding contacts could be eliminated.

Contact-Type Tuning Units

The first step of this development can be seen in the wavemeter shown in Figure 1. A conventional tuning condenser and a single-turn inductor consisting of a metal band fastened to a ceramic ring are mounted coaxially. The stator of the condenser is connected to one end of the metal band, and a metal brush on the condenser rotor shaft makes contact with the band. The band covers an arc of 270°, corresponding to the rotation of the condenser, and the length of the band between rotor and stator increases with increase of capacitance. The tuned circuit consists of a capacitance variable from 12 to 85 $\mu\mu$f and an inductance variable from 14 to 99 cm. It covers the range from 55 to 400 Mc. Resonance is indicated by an incandescent lamp or a small glow tube carried on the rotor arm. A transparent housing and a calibrated dial complete the wavemeter. The range could be extended to lower frequencies by adding tuning-condenser capacitance, but the top frequency is limited by the minimum capacitance of the condenser and by the relatively large inductance of the connections to the metal band.

To increase the top frequency obtainable in a circuit of this kind, the tuning condenser must be replaced by a more suitable structure, and the connections to the band must be shortened. The new circuit shown in Figure 2 has little resemblance to the wavemeter of Figure 1, but the basic structure is still the same. The capacitance of this unit, which has an inside band diameter of 2¾ inches, varies between 7.4 and 118 $\mu\mu$f and the inductance between 7.8 and 59 cm., giving a frequency range of 60 to 660 Mc. The law of inductance variation is determined by the design, but the frequency distribution can be chosen by shaping the condenser plates. The plates shown in Figure 2 give a straight-line logarithmic frequency scale, which is always desirable for an instrument covering a wide frequency range.

FIGURE 3. 400–1600 Mc. Wavemeter. End of stator band connected to rotor.

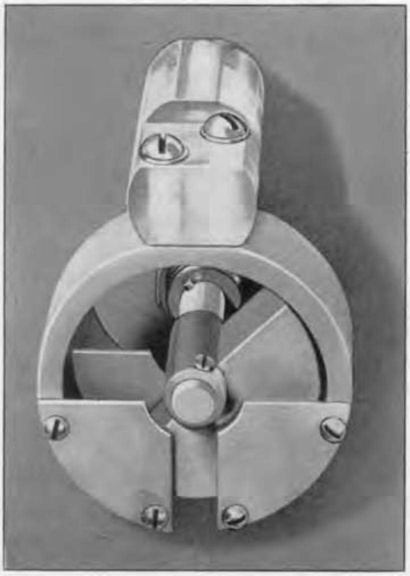


FIGURE 4. Tuning unit without contacts for 400–1200 Mc.

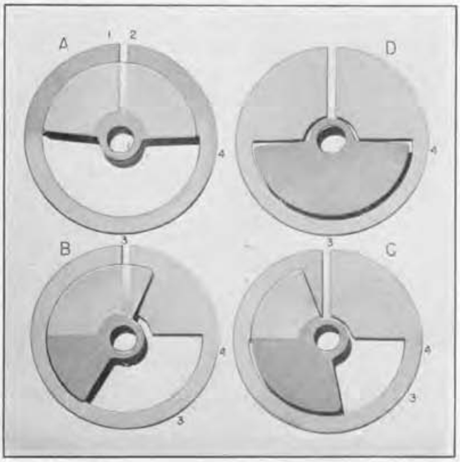
The unused part of the inductance band, projecting beyond the point of contact, is closely coupled to the tuned circuit and resonates at a high frequency. The end of the band is usually connected to the rotor to keep the resonant frequency outside the range of the tuned circuit. This connection can be seen in Figure 3 on a 400 to 1600 Mc wavemeter of somewhat different design, in which the capacitance is varied by an eccentric hub of the rotor.

These wide-range circuits are very useful for many purposes, but they still have sliding contacts which require a certain amount of care to insure low losses and trouble-free operation. To avoid these difficulties, the contact spring can be replaced by a capacitive contact member, but suppression of resonance effects by shorting the end of the band to the rotor is then no longer effective. Consequently, the top frequency of the circuit has to be lowered, and, since the bottom frequency is raised owing to the series capacitance of the contact, the tuning range is reduced considerably.

Tuning Units Without Contacts

A different approach to the problem is shown in Figure 4. In all the circuits discussed so far the highest resonance impedance was developed between a point on the rotor and a point on the stator. In the new circuit, the semi-butterfly circuit, so-called because of its relation to the butterfly circuit shown later in Figure 9, the highest impedance appears between two points on the stator. The plates of the semi-butterfly circuit are shown in four different positions in Figure 5. The stator consists of a semi-circular band connecting two pairs of sectorially shaped plates. To change from the lowest frequency position shown under *A* to the highest frequency position shown under *D*, the rotor is turned through 180°. In position *A* the capacitance between points 1 and 2 on the two stator plates is at maximum. In position *B* the capacitance is almost at minimum and changes only slightly until position *D* is reached. The inductance

FIGURE 5. Stator and rotor plates of semi-butterfly circuit. Capacitance and inductance between points 1 and 2 on the stator are at maximum in A and at minimum in D.



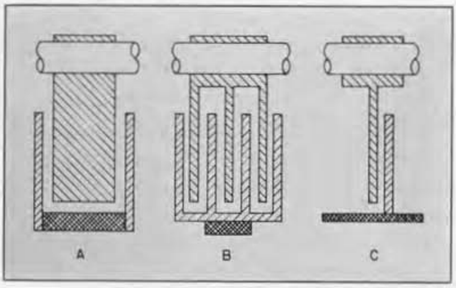


FIGURE 6. Cross section of butterfly circuit with different types of design. The double-cross-hatched section represents the inductance band.

between points 1 and 2 is likewise at maximum in position *A* and changes to minimum over position *B* and *C* to position *D*. The change in inductance of the semicircular band is brought about as the rotor gradually fills up the opening of the inductance loop. In the final position *D*, lines of magnetic flux are restricted to the small clearance between rotor and stator.

FIGURE 7. 100–500 Mc Oscillator. Inductive coupling to the load is varied by rotation of the coupling loop in lower part of the picture.

In this design, wide tuning range with simultaneous change of lumped capacitance and inductance is obtained by rotation of a member that does not require any electrical connections. The rotor shaft can be made of insulating material, and the flow of radio frequency currents through the bearings of this shaft is easily avoided. A cross section of the unit of Figure 4 is shown schematically in Figure 6*A*. The rotor is a solid block. The stator carries a pair of plates on each end of a circular band. The cross section of the band corresponds to the cross-hatched area. The resonant frequency in closed position, corresponding to Figure 5*A*, is changed most effectively by a change in size. Capacitance and inductance increase, and frequency decreases, approximately with the square of the diameter. The resonant frequency in the open position, corresponding to Figure 5*D*, does not vary as rapidly, and the tuning range, therefore, increases almost proportionately to the diameter. At any given diameter the frequency range can be shifted by variations in design. Figure 6*B* shows a unit in which capacitance and inductance have been increased by the addition of plates and by reducing the width of the band. Figure 6*C* is the corresponding high-frequency unit with lowered capacitance and inductance.

The law of inductance variation again is determined by the geometry of the design. In general, the inductance variation will be considerably smaller than in the circuits with sliding contacts and will be further reduced if the rotor plates are shaped to provide a predetermined frequency distribution. The loss of tuning range, the price that has to be paid for a desirable frequency distribution, is, therefore, much higher in the butterfly circuit than in a conventional tuning condenser.

A further modification that yields a lower L/C ratio is used in the 100 to 500 Mc oscillator shown in Figure 7. This circuit uses 120° sections for the stator plates and a 240° section for the rotor. The rotor turns through 120°.

It is important to keep in mind that the tuning devices described so far are two-terminal impedances only. These two terminals are designated 1 and 2 in Figure 5. No point on any of the circuits maintains electrically its position relative to these terminals over the tuning range, in the sense, for instance, of a tap on a coil with respect to the ends of the winding. In Figure 5, the point 3, midway electrically between the terminals, is symmetrically located only in the two extreme positions *A* and *D* and shifts toward terminal 2 for intermediate settings. The potential of the rotor is midway between points 1 and 2 in position *A* and *D* but shifts toward terminal 1 for intermediate settings. This fact is an important consideration in all applications.

Any point of the circuit can be connected to ground, but it is convenient at times not to make any definite connections. This might be desirable in an oscillator circuit, for instance, where plate and grid of a tube are connected to the two terminals and where the cathode is grounded.

The optimum method of coupling a load to the circuit depends upon the ground arrangement. If one terminal is grounded, electrostatic coupling is most convenient. When the circuit is left floating, electromagnetic coupling is more desirable. The only point where effective magnetic coupling over the entire tuning range can be obtained is shown as point 4 in Figure 5. The oscillator shown in Figure 7 uses this type of coupling. By rotating the coupling loop, the amount of coupling can be varied without disturbing the "floating ground" condition of the oscillator.

The Butterfly Circuit

A certain amount of electrical symmetry can be obtained by a modification suggested by Dr. A. P. G. Peterson, whereby two circuits are opened up and connected in parallel. The result is the butterfly circuit shown in Figure 8, which received its name from the shape of the rotor.

Figure 8*A*, *B*, *C*, and *D* correspond to the positions shown in Figure 5. Points 3 and 3′ are the electrical midpoints between terminals 1 and 2, and points 4 and 4′ are the locations for magnetic coupling.

Electrically the rotor of a butterfly circuit is always the midpoint between terminals 1 and 2, and the rotation between extreme positions is 90°. With

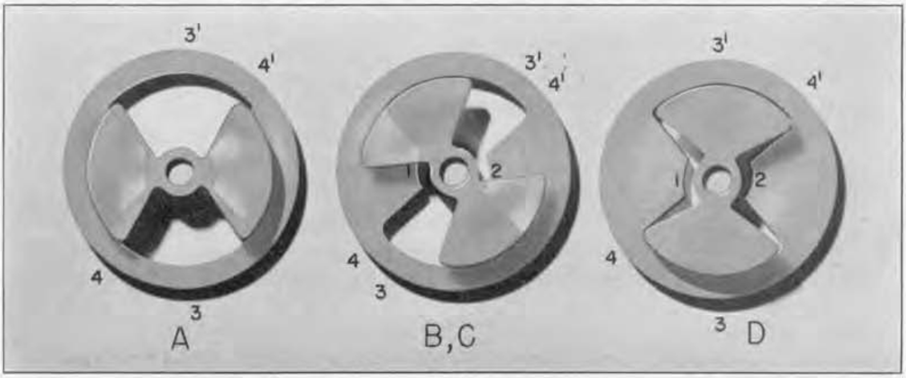


FIGURE 8. Stator and rotor plates of butterfly circuit. Capacitance and inductance between points 1 and 2 on the stator are at maximum in A and at minimum in D.

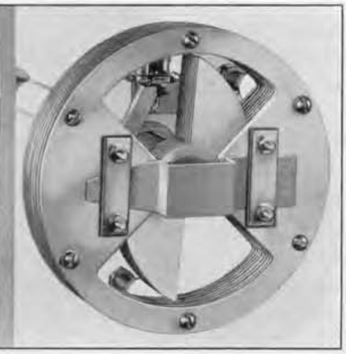


Fig. 9. (Left) 220–1100 Mc butterfly circuit with terminals for Type 703-A door knob type tube.

Fig. 10. (Right) 100–200 Mc butterfly circuit of heterodyne frequency meter.

these exceptions, the discussion in the preceding paragraphs can be directly applied to the butterfly circuit.

Figure 9 shows a 220 to 1100 Mc oscillator unit intended for use with a Type 703-A door-knob type tube. Grid and plate terminals of this tube fit into the spring clips provided on the two stator sections. Figure 10 is the close-up view of the 100 to 200 Mc oscillator of a heterodyne frequency meter. The rotor plates are shaped and provide a logarithmic frequency distribution. The 958 acorn-type oscillator tube can be seen in the rear. Grid and plate are connected to extensions of the two stator sections and the cathode is connected directly to the housing. Figure 11 shows the smallest butterfly circuit built so far, together with an acorn tube and a Type 1N22 Detector. This circuit has a tuning range of 900 to 3000 Mc.

Design of Butterfly Circuits

It was mentioned in the introduction that the equivalent Q of a resonant transmission line is of the order of $0.1D\sqrt{f}$. A quarter wave line covering the range from 220 to 1100 Mc would be about 13½ inches long and might have a diameter of 2 inches. The theoretical Q would be 3000 at 220 Mc and 6700 at 1100 Mc. To cover this frequency range, the length of the line would have to be varied by over 10 inches. The circuit shown in Figure 9 with 2½ inches outside diameter covers exactly this range with a Q of 650 at 220 Mc and of 300 at 1000 Mc.

While the losses in butterfly circuits cannot be made as low as in concentric lines, values of Q can be obtained that are sufficient for many applications. The characteristics of the butterfly circuit shown in Figure 9 are given in Table I, together with the variation in these characteristics that can generally be obtained by varying design factors. In the third column, n is a factor between 1.5 and 3.5, depending on design and size, with the lower values applying for smaller units.

TABLE I

	Circuit of Figure 9	*In General*
	Low High	Low High
Frequency	220 – 1100 Mc	$1 - n^2$
Inductance	0.011 – 0.0041 μh	$1 - n^{-1}$
Capacitance	48 – 5 μμf	$1 - n^{-3}$
Q	650 – 300	$1 - n^{-1}$
$R = \frac{\omega L}{Q}$	0.023 – 0.095 Ω	$1 - n^2$
$\sqrt{L/C}$	15.2 – 28.6 Ω	$1 - n$
$Z = Q\sqrt{L/C}$	9800 – 8600 Ω	Constant

The maximum inductance of butterfly circuits in the closed position can be computed by any of the standard inductance formulas by taking ⅛ of the inductance of the full ring and multiplying by a factor of 1.35 to allow for the contribution of the stator and rotor plates. For instance,

$$L = 1.35 \times \tfrac{1}{8} \times 0.01257r \left(\ln \frac{36r}{t + w} - 2\right) 10^{-6} \text{ henrys}$$

or

$$L = 2.12r \left(\ln \frac{36r}{t + w} - 2\right) \text{centimeters}$$

Another formula suggested by Dr. A. P. G. Peterson that gives fairly accurate results is

$$L = \frac{\pi^2}{6} (r^2 - r_1^2) \times \left[\frac{1}{t + w} + \frac{1}{\sqrt{r^2 - r_1^2}}\right] \text{centimeters}$$

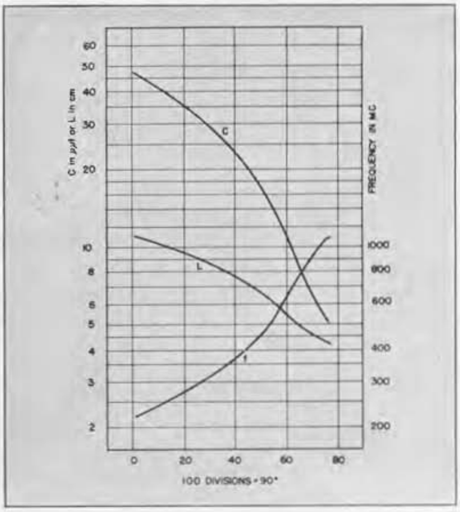
where r is the inside radius of the band, r_1 is the outside radius of the rotor hub, and t and w the thickness and width of the band, all in centimeters. The minimum inductance depends to a great degree on the clearance between stator and rotor along the circumference of the band and the clearance between the radial plate edges. This latter clearance cannot be reduced very far without adding capacitance and lowering the top frequency. In general, the ratio of maximum to minimum effective inductance will be between 1.5 and 3.5. The highest ratio actually obtained has been 4.6. This circuit had a band diameter of 5¼ inches and 1/16 inch clearance to the rotor. In this particular case the capacitance ratio of the 14-plate unit was 22 — the frequency range 47–470 Mc.

Maximum and minimum capacitance of a butterfly circuit can be computed as in a variable air condenser, but, owing to the butterfly shape, capacitance ratios are considerably less than in well-designed conventional tuning condensers. Figure 12 shows inductance, capacitance, and frequency plotted against dial rotation for the 220 to 1100 Mc butterfly circuit of Figure 9.

FIGURE 11. 900–3000 Mc butterfly circuit. Acorn tube and 1N22 detector are shown for size.

One effect of changing the number of plates deserves special mention, although it has not been fully explored. As expected, the ratio of maximum to minimum capacitance increases with the addition of plates and the inductance of the stator decreases due to its increased width (designs where the band differs in width from the stator, as shown in Figure 6*B* and Figure 6*C* have only rarely been used in practice). For very low numbers of plates, the inductance can decrease more rapidly than the minimum capacitance increases, and a butterfly circuit with four plates, for instance, may have a lower low- and a

FIGURE 12. L, C and f variation of unit shown in Figure 9.



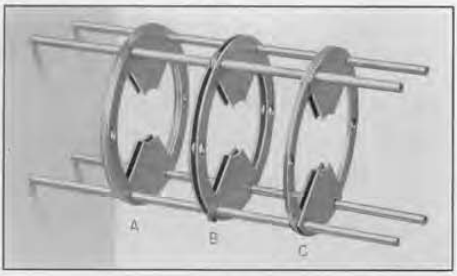


FIGURE 13. Assembly of butterfly stators.

higher high-frequency limit than with two plates. As further plates are added, the range is shifted to lower frequencies and the span slightly increased, but soon odd modes of resonance appear that were not previously observed. These modes are not always noticed in oscillator circuits where a single dominant frequency is produced, but they are easily found by other methods. It appears that these modes can be suppressed or at least can be shifted by additional shorting connections between the individual plates of the four groups of plates. Two connections can be applied at the inside of the stator and two at the outside of the rotor on the radial edges of the plates where they do not interfere with the rotation of the rotor. In practice, shorting of the plates can be avoided by using a larger unit with fewer plates instead of a small unit that requires too many plates to cover the desired frequency range.

The equivalent series resistance of a butterfly circuit increases linearly with frequency and reduces *Q* at the high-frequency end, where the *Q* of a transmission line is increased. This increase in equivalent resistance is due to the fact that the change of inductance in the butterfly circuit is brought about by eddy currents in the rotor and not by a reduction of conductor length. Additional losses originate at the junction of the inductive and capacitative parts of the circuit where currents pass from one plate to another in a direction perpendicular to the plates. Three methods of stator construction with individual plates and spacers are shown in Figure 13. From an electrical point of view, Method A appears to be the best. Method B has the advantage that the rotor can be observed through the slots in the stator and can be centered after assembly. Method C may be desirable in experimental work since it uses parts that can be obtained more easily without special tools. For lowest losses stator and rotor should be soldered after assembly and plated with a material of high conductivity. Dielectric losses can be almost completely avoided in butterfly circuits, if two supports are used, placed at the two points of equal potential corresponding to 3 and 3′ in Figure 8*A*. In practice, however, the supports are often placed at other points, more desirable for mechanical reasons, and on large units three supports may be required. It is interesting to note that, in the circuit shown in Figure 9, about ¼ of the 0.023 Ω equivalent series resistance, measured at 220 Mc, is accounted for by the metallic losses in the silver-plated inductance band.

The resonant impedance of butterfly circuits is well within the range of plate resistance of vacuum tubes and changes very little from the low to the high frequency end. This makes it possible to produce uniform oscillations over the tuning range.

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