The Calibration of Wave-Meters for Radio-Telegraphy

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1911 Proc. Phys. Soc. London 24 251

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XXXVIII. *The Calibration of Wave-Meters for Radio-Telegraphy.* By Prof. G. W. O. HOWE.

READ MAY 31, 1912.

THE most common form of wave-meter or frequency meter for use in radio-telegraphy is a simple oscillatory circuit consisting of a variable air-condenser connected across the terminals of an inductive coil. The latter is loosely coupled with the aerial or other circuit under examination, and the capacity of the variable condenser is altered until resonance is obtained, *i.e.*, until the natural frequency of the wave-meter corresponds to the frequency of the oscillatory current in the aerial. The attainment of resonance is indicated either by an ammeter in series with the wave-meter or by a vacuum tube placed across the condenser terminals; the vacuum tube can sometimes be advantageously replaced by a low-reading electrostatic voltmeter. From the calibration curve of the variable condenser and the known inductance of the wave-meter coil the approximate frequency can be easily calculated. To cover a large range of wave-lengths a set of coils will be necessary, the

FIG. 1.

number depending on the range and on the ratio of the maximum capacity of the variable condenser.

The dielectric being air, the capacity is the same for high-frequency alternating as for static pressures. If fine wire or specially stranded wire be employed in winding the coil the inductance will also be independent of frequency. The main source of error or uncertainty in the calculation of the frequency is the capacity between neighbouring portions of the coil. Even when the variable condenser is removed the coil itself has a definite natural frequency, the ends acting as the plates of a condenser and the central portion as an inductance, the two functions being distributed, however, over the whole coil and gradually merging into one another. The distribution of potential P and the current i throughout the coil will be

somewhat as shown in Fig. 1, the width of the diagrams representing the amplitude at each point. When a condenser is connected across the coil as shown in Fig. 2 the distribution of the potential will be modified, owing to the smaller variation of the current amplitude throughout the coil.

The natural frequency of a cylindrical single-layer coil oscillating freely can be calculated by means of empirical formulæ and curves established by Drude from a large number of experiments.* It can, of course, be determined experimentally by bringing the coil near a circuit in which high-

FIG. 2.

frequency currents are maintained, the frequency of which can be adjusted until a vacuum tube near the coil indicates that resonance is produced. The frequency of the oscillatory current can then be found by means of a calibrated wave-meter. This was essentially the method employed by Drude.

Fig. 3 represents an imaginary oscillatory circuit of the same frequency as the coil, but with concentrated capacity and

FIG. 3

inductance. The current would have the same amplitude at the ends as at the middle. An infinite number of such imaginary circuits could be made with different values of K and L , but with the same product KL and, therefore, of the same frequency. Can anyone of these imaginary circuits, as represented in Fig. 3, be said to represent or be equivalent to the actual freely oscillating coil? If so, we should be justified in calling

* Annalen der Physik, 1902. Vol. 1X., p. 322.

the value of the inductance in Fig. 3 the effective inductance of the actual coil, and the capacity between the rings in Fig. 3, the effective or self-capacity of the actual coil. Drude* implies the existence of such an equivalent arrangement, and, because of the current distribution shown in Fig. 1, assumes that the effective inductance may be taken as $\frac{2}{\pi}$ of the total

inductance of the actual coil. Knowing the effective inductance and the natural frequency, the effective or self-capacity of the coil is easily calculated. When a coil is used in conjunction with a variable condenser to form a wave-meter the question which arises is: How must the calculation of frequency be modified in order to allow for the effect of this self-capacity of the coil? No attempt is here made to give a rigorous answer to this question, but it is shown that for practical purposes the effective inductance of the imaginary circuit in Fig. 3 can be taken as equal to the total inductance of the coil, and that if the self-capacity, calculated from the natural frequency on this assumption, be added to the capacity of the variable condenser when calculating the frequency the error in the resulting calibration curve will be very small.

Experiments were made on a coil of 169 turns on a glass cylinder 14.5 cms. diameter and 21.3 cms. long. Its inductance was 2.16 millihenries and its natural wave-length when freely oscillating in space was 185.5 metres. Its terminal capacity was increased by small amounts by means of brass spheres various distances apart, and the resonant frequency was determined in each case. Whether we plot the wave-length against the root of the added capacity as in Fig. 4, or the square of the wave-length against the added capacity, as in Fig. 5, the dotted straight line through the origin would be obtained were it not for the self-capacity of the coil. The experimental results are plotted as crosses in Figs. 4 and 5. The latter figure shows clearly that for practical purposes the effect of the self-capacity of the coil is to add a constant capacity of 4.5 micro-microfarads to that of the variable condenser. This 4.5 is the self-capacity obtained from the natural frequency of the coil on the assumption that the full inductance is effective.

When the wave-meter has a set of coils, the ranges of which slightly overlap, another method can be used to determine experimentally the self-capacity of the coils. This may be

* *Loc. cit.*

illustrated by means of an actual example. The wave-meter consisted of an air-condenser in a glass vessel lined with tin-foil, the latter being connected to one terminal and preferably

FIG. 4.

earthed, and a set of four coils of silk-covered copper wire on wooden drums. From the calibration curve, Fig. 6, it will be seen

FIG. 5.

that the condenser has a minimum capacity of 76 and a maximum capacity of 1,042 micro-microfarads. The inductances

FIG. 6.—CALIBRATION CURVE OF VARIABLE AIR CONDENSER.

FIG. 7.

of the four coils, as determined at low frequencies were as follows :— $L_1=23.7$; $L_2=51.9$; $L_3=194.9$; and $L_4=1,673$ microhenries. The wave-meter was loosely coupled with an oscillatory circuit containing a spark-gap. The frequency of the oscillatory currents could be varied by cutting out the inductance one turn at a time. The variable condenser of the wave-meter was always adjusted until the helium tube placed across its terminals indicated resonance. Over certain ranges it was possible to obtain readings with two different coils, and this was always done when possible. The results are plotted

FIG. 8.

$\frac{1}{3}$ means that the ordinates are the readings obtained with Coil No. 1, and the abscissae those obtained with Coil No. 3 for the same frequency.

in Fig. 7, as A_1 , A_2 , &c., the numbers referring to the coils used. A, B and C refer to different series of readings, using different capacities in the spark-gap circuit, and are therefore not comparable, but all curves with the same letter are comparable. Thus with 10 turns cut out of the primary circuit $A_3=12$ and $A_2=67$, that is, for the same frequency, the wave-meter condenser reads 12 when using coil No. 3, and 67 when using coil No. 2. The results are plotted in another way in Fig. 8, where each curve shows the corresponding readings obtained for the same frequency on the two wave-meter coils. Each curve

in Fig. 8 contains points taken promiscuously from series A, B and C and their close agreement shows the accuracy of the wave-meter setting. It is seen that for a reading near the zero end of the condenser, where a knowledge of the self-capacity of the coil is essential, there is always a corresponding reading, obtained with a smaller inductance, with the variable condenser at the other end of the scale, where the effect of the self-capacity of the coil is almost negligible. From two such readings the self-capacity in the first case can be determined with sufficient accuracy for all practical purposes, as a large error in its assumed value when its effect is small causes a small error in the calculated value when its effect is large. This can best be shown by an actual example: Let K_a be the added capacity as read off the calibration curve of the variable condenser, K_s the self-capacity of the coil, and K_e the total effective capacity $K_a + K_s$.

All capacities are in micro-microfarads.

Now from Fig. 8, a wave-length which gave a reading 0 with L_4 , gave a reading of 72.5 with L_3 . Calling the capacities of the condenser for these readings K_{a4} and K_{a3} , we see from Fig. 6 that $K_{a4} = 76$ and $K_{a3} = 810$. It is known that the self-capacity of coil No. 3 is about 15, but let us assume firstly that it is 10, and secondly that it is 20, and see how this affects the calculated value of K_{e4} , the self capacity of coil No. 4.

We have

$$\frac{K_{e3}}{K_{e4}} = \frac{L_4}{L_3} = \frac{1,673}{194.9}.$$

(a) If $K_{s3} = 10$, $K_{e3} = 810 + 10 = 820$, $K_{e4} = 95.5$ and $K_{s4} = K_{e4} - K_{a4} = 95.5 - 76 = 19.5$.

(b) If $K_{s3} = 20$, $K_{e3} = 810 + 20 = 830$, $K_{e4} = 96.6$ and $K_{s4} = K_{e4} - K_{a4} = 96.6 - 76 = 20.6$.

Hence it may be safely assumed that the self-capacity of coil No. 4 is about 20. Similarly it was found that K_{s3} was 14 and K_{s2} about 18 micro-microfarads.

The natural frequency of coil No. 4 when oscillating freely, but with the earthed terminal still connected to the condenser, was found to be 347 metres. Taking the whole inductance of the coil, viz., 1,673 microhenries, this gives a self-capacity of 20.3 micro-microfarads, which agrees substantially with the value found above.

In the case here considered the error introduced by neglecting the effect of self-capacity reaches about 12 per cent.; by allow-

ing for the self-capacity of the coil in the way indicated the error can easily be reduced to less than 1 per cent.

By suitably designing the coils of wave-meters the effect of self-capacity may be greatly minimised. It will have been noticed that whereas coil No. 4, with an inductance of 1.673 millihenries, has a self-capacity of 20 micro-microfarads, the coil on the glass cylinder, with an inductance of 2.16 millihenries has a self-capacity of only 4.5 micro-microfarads. This difference is due to the fact that coil No. 4 has a diameter 7.6 times its axial length, whereas the diameter of the other coil is only 0.7 of its axial length.

As an example of the effect of shape on the self-capacity, in the following table are given four different designs for a coil of 2 millihenries, wound with wire of such a diameter that there are 20 turns per centimetre. The inductances are calculated from the formulæ of Rayleigh and Niven, and Lorenz, and the natural frequencies from Drude's curves for single-layer coils on ebonite tubes.

Diameter	Axial length.	Natural wave-length.	Self-capacity in micro-microfarads
5 cms.	22.5 cms.	102 metres	1.46
10 "	8.0 "	148 "	3.08
15 "	5.15 "	194 "	5.3
20 "	3.8 "	229 "	7.38

The effect of the self-capacity of the coils being to reduce the range of wave-length covered by each coil, it is necessary when calculating the inductances required for the various coils of a set, to allow considerable overlap, if self-capacity be neglected in the preliminary calculations, as otherwise there may be gaps between the ranges of the various coils when actually tested.

ABSTRACT.

Wave-meters consisting of a variable air-condenser and a set of coils can be calibrated approximately by calculation from the known capacity of the condenser and the inductance of the coils. The most probable source of error is that due to the capacity from turn to turn of the coil. This can be allowed for, with sufficient accuracy for all practical purposes, by finding the natural frequency of the coil alone and calculating its effective or self-capacity on the assumption that the whole steady current inductance of the coil is effective even when it is oscillating freely. This capacity is then added to the capacity

of the air-condenser. Another method of finding the required correction by comparison of the results obtained on the overlapping portion of the ranges of two coils is also described.

The correction can be made small by suitably designing the coils.

DISCUSSION.

Dr. W. E. SUMPNER remarked that it could not be considered satisfactory to find the self-capacity of a coil from its free period, taking the whole of its self-induction as effective, until this had been shown to give the same result as that deduced experimentally with a large number of different coils.

Mr. W. DUDELL remarked that Prof. Howe's experiment showed that for practical purposes the self-capacity of a coil could be considered quite constant, for he had used much smaller external capacities than usual, and still could detect no difference. It was very important for a wave-meter to have a very definite free period of its own, and therefore L/R must be large. Its coefficient of damping should be less than that of the antenna circuit, as the usual method of finding this latter really gives the sum of the two. It was thus more important to keep the high frequency resistance of a coil small than its self-capacity. Dielectric losses were an important item in the high-frequency resistance, hence the voltage from one turn to the next should be kept down.

Prof. T. MATHER pointed out, with reference to a table Prof. Howe had put on the board, giving dimensions of different coils having the same self-induction but different self-capacities, that the length of wire necessary was almost the same in each case.

Dr. W. H. ECCLES pointed out that theoretically the self-capacity could not be constant when the external capacity was small, and cited the somewhat analogous case of a weight vibrating from a heavy spring when one-third of the weight of the spring was added to the weight provided the weight was relatively large. There might be some compensating influence at work such as the variation of the self-induction with frequency.

Mr. A. CAMPBELL stated that the method of obtaining the working value of a wave-meter coil by finding the frequency giving resonance on open circuit was used by Dieselhorst some years ago. At the National Physical Laboratory it is customary to plot λ^2 against the condenser capacity; over the working range the line obtained is straight, and from its slope the high frequency value of the inductance of the coil can be immediately deduced by dividing by $4\pi^2$. It was interesting to learn that Prof. Howe found by experiment that such a line passes through the point given by Dieselhorst's method. The capacity of a coil could be diminished by winding it in slices like the secondary of an induction coil.

Dr. ERSKINE-MURRAY pointed out that at high frequencies the current would go straight up through the coil, and not round it, if it were wound as Mr. Campbell suggests.

The AUTHOR, in reply to Dr. Sumpner, stated that he had only experimented on three or four coils, but he had purposely used specially small added capacities in order to detect any variation of the self-capacity, so for practical purposes it could well be assumed to be constant.