THE General Radio EXPERIMENTER

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also IN THIS ISSUE

GENERAL RADIO OPENS CHICAGO OFFICE

● TO ASSIST USERS of General Radio equipment in the Chicago and middle western area, the General Radio Company is opening a Chicago engineering office on December 1, 1943. The new office is located at 920 South Michigan Avenue, Chicago 5, and the telephone number is Wabash 3820.

In charge of this office is Lucius E. Packard who for the past three years has been in charge of the New York engineering office. Mr. Packard is a graduate of the Massachusetts Institute of Technology, receiving his Bachelor of Science degree in 1935. Previous to his assignment to the New York office, he was a member of the factory engineering staff and was engaged in both development and commercial engineering work.

Customers in and around Chicago are urged to make use of the facilities of this new office and to get in touch with Mr. Packard on all matters regarding General Radio equipment design and procurement. His experience in the application of our instruments and his close contact with factory production schedules should materially increase the efficiency with which we can serve our midwestern customers.

NEW YORK OFFICE

Succeeding Mr. Packard at the New York office is Martin A. Gilman of the factory engineering staff, a graduate of Massachusetts Institute of Technology in 1937 with the degree of Master of Science. Like Mr. Packard, he has been engaged in both development and commercial engineering work at the factory and is already well known in the New York area. As a reminder, the New York office address is Room 1504, 90 West Street, New York City, and the telephone number is Cortlandt 7-0850.

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RESONANT VIBRATION IN LARGE ENGINE FOUNDATION

By G. M. DEXTER[1] and M. K. NEWMAN[2]

● **VIBRATION** in a large concrete foundation that was in near resonance with the gear mesh frequency of a pinion on a large Corliss engine was analysed recently with the aid of the vibration meter and sound analyser of the General Radio Company. The problem arose on mill engine No. 2 on the grinding tandem of the U. S. Sugar Corp., Clewiston, Florida. This grinding tandem consists of a set of revolving knives, a 2-roll crusher, and seven 3-roll, 78-inch mills. This tandem holds the world's record for its size in the amount of sugar cane crushed in 24 hours, namely about 7050 tons.

Engine No. 2 is a 36-inch by 60-inch Corliss engine that operates at 40 to 70 r.p.m., depending on the amount of sugar cane being crushed and its fiber content. Recent examination showed that its concrete foundation was vibrating badly and that the amount of vibration increased with the load on the grinding tandem and with the speed of the engine.

The engine is one of three on a large concrete foundation, about 145 ft. long, 40 ft. wide, and 11 ft. thick for over one-half its width. This engine drives three

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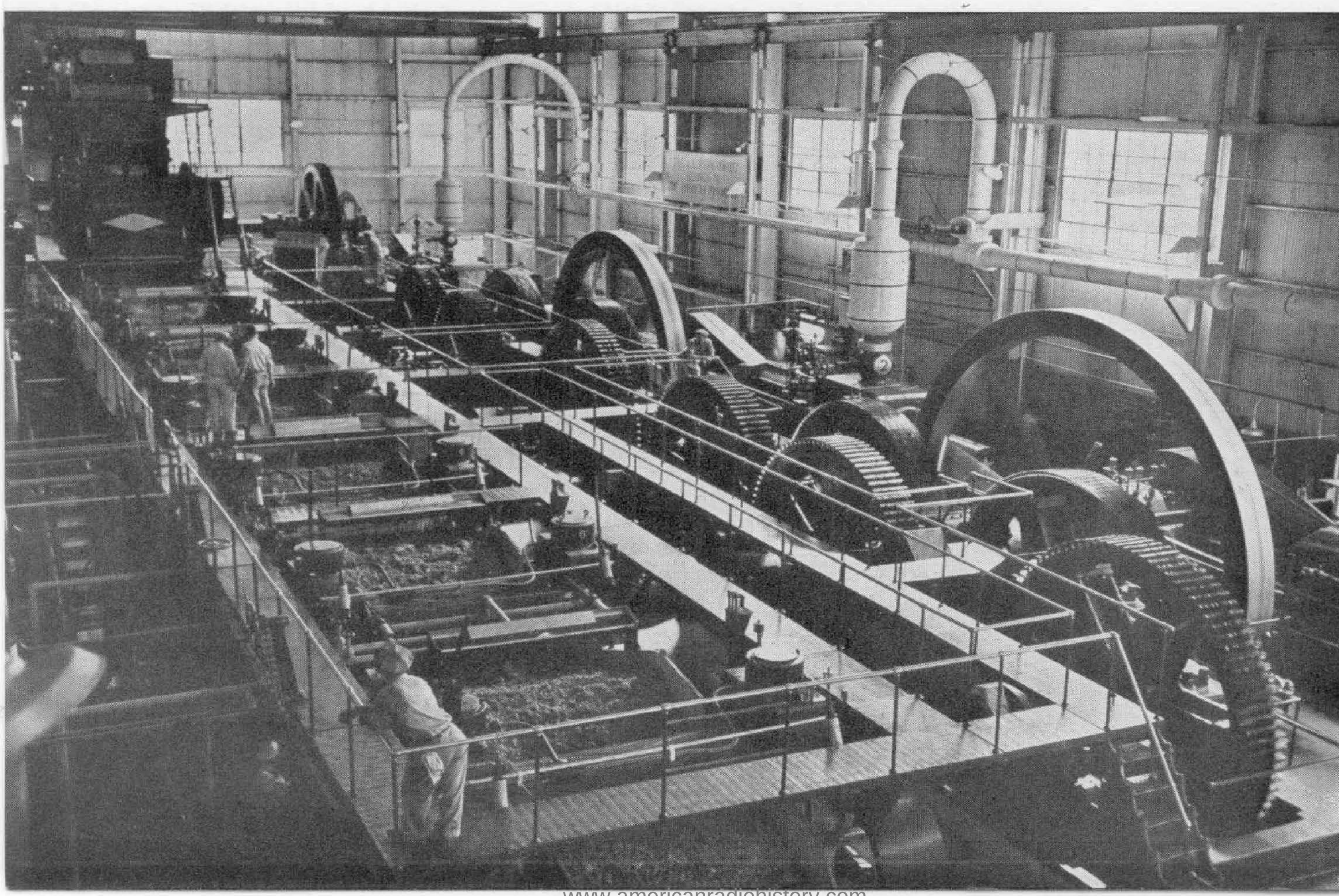
FIGURE 1. The grinding tandem of the U. S. Sugar Corporation at Clewiston, Florida. Mill engine No. 2 is the center unit.



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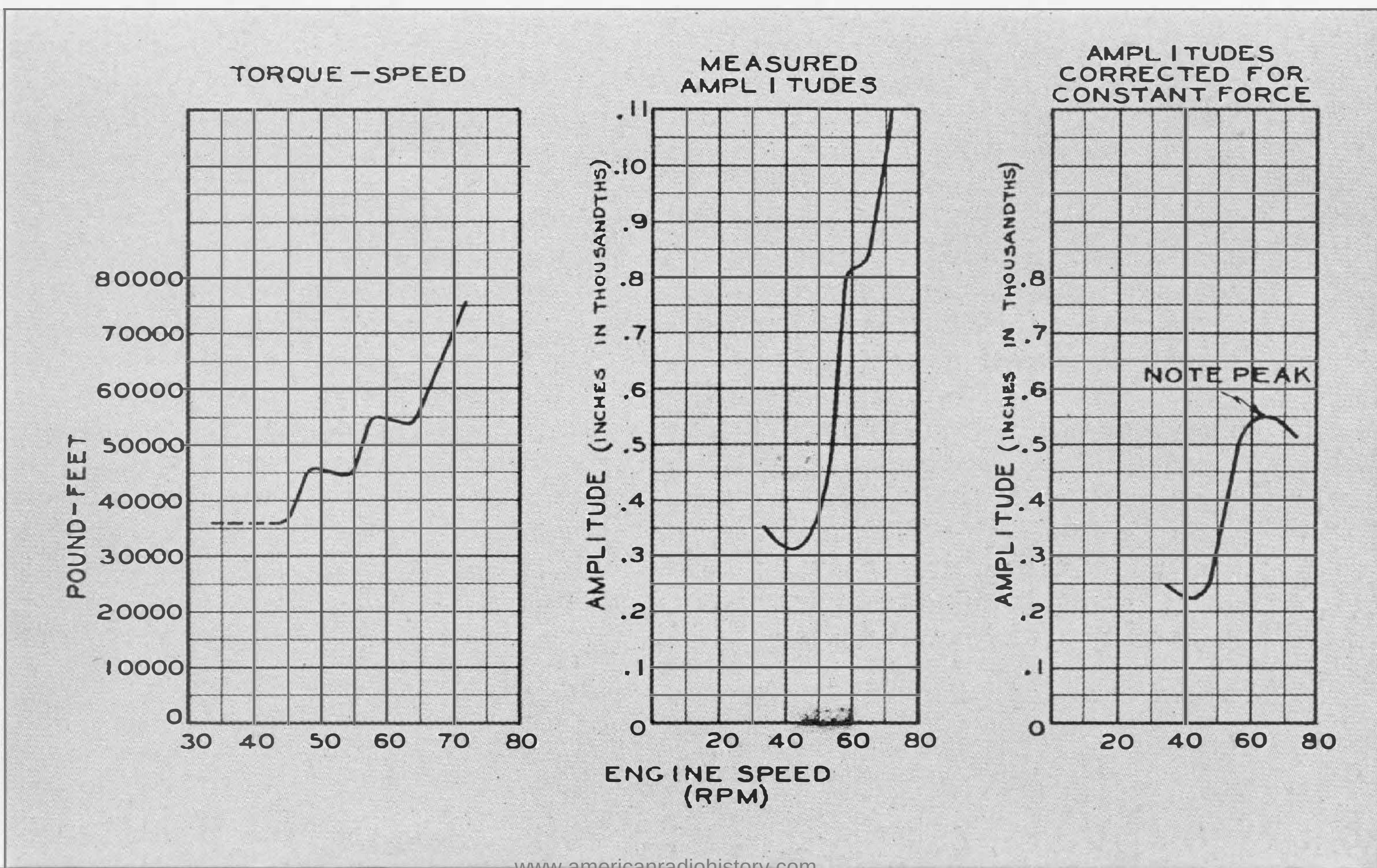
mills of the grinding tandem through a set of five large gears and three pinions. The foundation is on the typical muck on sand on porous rock of the Everglades where the water level is about three feet below the surface. The unusual nature of the soil made the problem more difficult. Although there is a definite friction against lateral movement of water, an irregular lateral movement does take place in the soil.

The first reaction to the vibration problem was that the concrete foundation by settling unequally was causing misalignment of gears that produced vibration. Four deep wells nearby were a part of the problem as they drew about 550 gallons per minute and caused a cone of depression in the ground water level that extended under the concrete foundation. Weekly level readings on various control points on the concrete foundation and ground water level were started to determine whether any settlement was actually taking place. An analysis of the load on the soil from the foundation and its machinery showed that the load was fairly well distributed and was about 0.8 tons per square foot. This amount is well within the limit that experience has shown to be safe for Everglades conditions where drainage ditches are in use.

While the preceding work was under way, a vibration meter and a sound or wave analyser of the General Radio Company were brought into use by Mr. M. K. Newman. He found that the vibration of the mill engine foundation could be broken down with the sound analyser into several frequencies, one of which was identical with the frequency of the gear mesh of the main pinion on engine No. 2, the others being multiples of this frequency. All

FIGURE 2. Compound amplitudes at engine No. 2 as measured on concrete foundation with TYPE 761-A Vibration Meter.



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frequencies in the foundation varied with the speed of engine No. 2. The vibration meter permitted the determination of amplitudes of vibration, velocities, and accelerations due to each frequency. The frequency spectrum of the amplitudes showed that the most important effect was that due to the single-mesh frequency of the main pinion on engine No. 2. This vibration was found to exist throughout the foundation. A complete response characteristic of the foundation was taken up to the highest engine speeds used and a definite resonance peak was found for a constant vibrating force at a frequency corresponding to an engine speed of about 68 r.p.m.

The preceding fact immediately suggested that the pinion might be at fault. Measurements were taken that showed the pinion was in poor alignment with the two large gears it drove. Plaster of Paris casts of the teeth of the pinion and the two gears it drove showed they were worn.

A calculation of the foundation modulus by means of a method developed by M. A. Biot for an infinite beam on an elastic foundation (Journal of Applied Mechanics, May, 1937) and the use of methods outlined by S. Timoshenko in "Vibration Problems in Engineering" showed that the mill-engine foundation had several natural frequencies that were very close to frequency of the gear mesh of the main pinion on engine No. 2. The forced vibration problem was solved for a beam on an elastic foundation. The nine lowest modes of vibration were found to contribute appreciably to the resulting vibration, with the second harmonic in bending predominant because in near resonance. The resulting distribution of amplitude of vibration showed the same typical form that was obtained with a Davey Vibrometer. These data supported the conclusion reached with the instruments of the General Radio Company that the mill-engine foundation was in near resonance with the gear-mesh frequency of that pinion. In other words, the amplitudes of the vibration of the concrete foundation were greatly magnified.

The level readings also showed that two or three points near engine No. 2 on the foundation settled at high speeds of that engine but did not at low speeds. This fact is confirmation of the conclusion that settlement is due to vibration. Amplitude of vibration was a little more than 0.001 inches at a frequency of about 30 cycles per second.

In addition to the preceding, numerous other studies were made such as possible wabble of the flywheel of engine No. 2, possible loose foundation bolts in the base plate of the engine, stresses in gear teeth due to the heavy load on the grinding tandem, etc. A detailed discussion of all that was done is out of place here.

The meters of the General Radio Company were selected only after a definite search had been made for meters that could be used to analyse vibrations encountered in part from an unusual soil condition. Their successful application to this problem opens up a new field of investigation on the behaviour of concrete foundations under vibrating loads. This account is probably the first description of the application of the meters of the General Radio Company to a problem in the resonant vibration of a concrete foundation. With those meters, it was possible to analyse the problem so definitely that the cause and cure of the vibration could be given with considerable certainty.

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MEASUREMENTS OF THE CHARACTERISTICS OF TRANSMISSION LINES

● **THE PROBLEM** of measuring the characteristics of transmission lines is frequently encountered both in the laboratory and in production testing. These measurements can be made conveniently on standard impedance-measuring equipment.

The methods in common use depend upon (a) the measurement of input impedance for various conditions of line termination or (b) the observation of voltage (or current) amplitude at input and output.

Input Impedance Methods

In terms of the so-called "telegraphist's equations" the behavior of a transmission line is defined by the characteristic impedance (usually designated as Z_O) and the complex propagation constant ($\gamma = \alpha + j\beta$). These two parameters of the line can be specified completely by two impedance measurements at the input to the line, one with the far end short-circuited, the other with the far end open-circuited. Designating these two impedances as Z_{SC} and Z_{OC}, respectively, we can write

$$Z_O = \sqrt{Z_{SC} Z_{OC}} \quad (1)$$

$$\gamma l = \tanh^{-1} \sqrt{\frac{Z_{SC}}{Z_{OC}}} \quad (2)$$

where l is the length of the line, in any convenient units.

A consideration of the variation of input impedance as the line length (or the frequency) is varied reveals that Z_O and γl can be obtained from certain specific (electrical) lengths. These lengths are the quarter wavelength (or its odd multiples) from measurements on which the attenuation constant (α) is readily deduced, and the eighth wavelength (or its odd multiples), from which the characteristic impedance is most accurately determined.

If both the frequency of measurement and the length of the sample are specified, the short- and open-circuit calculations involved, particularly for γl, are somewhat awkward. Measurements at specific lengths are more convenient and should be used if either the length or the frequency can be adjusted.

Attenuation Measurement at Quarter Wavelength

The input impedance of a line terminated in an impedance Z_T is given by

$$Z_{in} = Z_O \frac{Z_T \cosh \gamma l + Z_O \sinh \gamma l}{Z_T \sinh \gamma l + Z_O \cosh \gamma l} \quad (3)$$

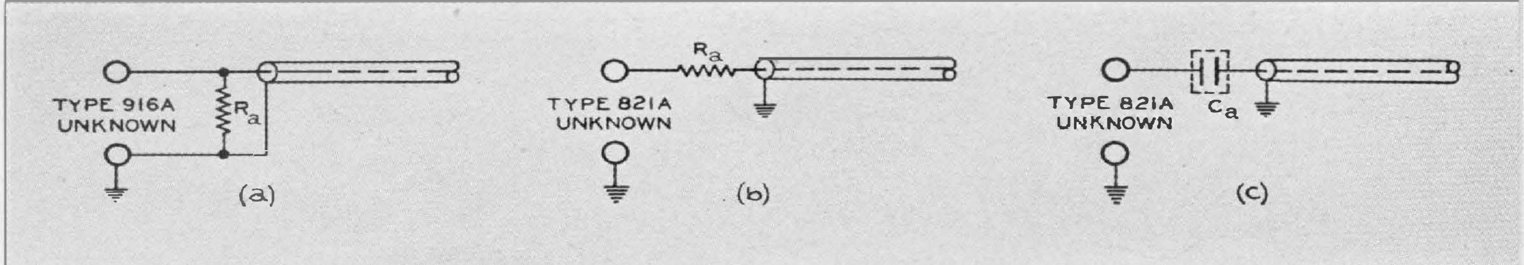
For a line one-quarter-wave long short-circuited at the receiving end ($\beta l = \frac{\pi}{2}$, $Z_T = O$) the input impedance is

$$Z_{SC} = Z_O \coth \alpha l \quad (4)$$

For the same length of line with the end open-circuited, the input impedance is

$$Z_{OC} = Z_O \tanh \alpha l \quad (5)$$

FIGURE 1. In (a) and (b) are shown the methods of using an auxiliary resistor to assist in locating the frequency of quarter-wave resonance, when the real component of the input impedance is outside the direct-reading range of the TYPES 916-A and 821-A, respectively; (c) shows the conventional series capacitor method for accurate measurement with the TYPE 821-A.



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If $\alpha l \ll 1$, the input impedances can be written in the approximate form

$$Z_{SC} = \frac{Z_O}{\alpha l} \qquad (6)$$
$$Z_{OC} = Z_O \alpha l$$

The input impedances represented by (6) will have slight reactive components from the reactive component of $Z_O = R_O - jX_O$. Consequently, it is difficult to locate experimentally the true quarter-wave condition. Practically, however, no significant error will be introduced if either the condition of zero reactance or the condition of maximum input resistance is determined. The most convenient method to use will depend, to a certain extent, on the magnitude of the input resistance and upon the instrument used for measurement. Neglecting the effects of the reactive component, X_O, Equation (6) can be rewritten as

$$\alpha l = \frac{R_O}{R_{SC}} \qquad (7)$$
$$\alpha l = \frac{R_{OC}}{R_O}$$

Equation (7) yields accurate results for attenuation constant, as the quantities involved can be determined within a few per cent, and the formulae are valid to about the same accuracy for values of αl and $\frac{X_O}{R_O}$ small compared to unity.

Example of Attenuation Measurement

A length of concentric cable (General Radio Type 774), about 117 feet long, was found to have its quarter-wave resonance at a frequency in the vicinity of 1.25 megacycles. The input conductance for the shorted condition was found to be outside the direct-reading range of the Type 821-A Twin-T Impedance Measuring Circuit, and was measured by the methods indicated in Figure 1b. Although best accuracy is obtained by the use of an auxiliary series capacitor, as indicated in Figure 1c, the use of a series resistor simplifies the process of finding the resistance maximum.

The resistance maximum (conductance minimum) was located at 1.26 mc and found to be approximately 1325 ohms from the series resistance method. A more nearly accurate measurement using the series capacitor method[1] gave an input resistance of 1370 ohms.

The characteristic resistance, R_O, as determined from measurements described later, is about 72.5 ohms. Then, from Equation (7) we have

$$\alpha l = \frac{72.5}{1370} \text{ nepers}$$
$$= 0.0528 \text{ nepers}$$

The attenuation constant at this frequency is, therefore, 0.211 nepers (1.83 db) per wavelength.[2]

The same cable was measured on the Type 916-A Radio-Frequency Bridge for the short-circuit condition. A substitution method[3] as indicated in Figure 1a was used. The data observed were:
R_1 = 580 ohms (connection as shown)
R_2 = 998 ohms (cable disconnected)

$$R_{in} = \frac{580 \times 998}{995 - 580}$$
$$= 1380 \text{ ohms}$$

A measurement was also made for the open-circuit condition on the same length of cable, using the Type 916-A. This measurement is particularly convenient, as the input resistance is within

[1]Described in detail in instruction book for Type 821.

[2]One neper = 8.686 decibels.

[3]The use of a parallel capacitor is normally recommended. The parallel resistor method, however, is somewhat more convenient in use, and for this particular measurement leads to about the same final accuracy.

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the direct-reading range of the bridge. The observed input resistance was 3.68 ohms[4], from which

$$\alpha l = \frac{3.68}{72.5} = 0.0507 \text{ nepers}$$

The check between the two values of αl obtained by different methods of measurement is seen to be within ±2%.

Comparing the two instruments, the Type 916-A is found to have a definite advantage over the Type 821-A for the following reasons.

(a) The initial balance is virtually independent of frequency, and the frequency of maximum (or minimum) resistance can be located more readily.

(b) The resistance dial calibration is independent of frequency, somewhat simplifying the computations.

Characteristic Impedance Measurement by Open- and Short-Circuit Measurements

The optimum length of line on which to make open- and short-circuit impedance measurements is an eighth wavelength. At this length the magnitudes of the two impedances are approximately equal, with reactive components of opposite sign. Also, the resistive component is small, and very little error is introduced by considering only the reactive component. As an example, the following observations were made on the piece of cable previously discussed, at a frequency of 0.63 megacycles.

$$Z_{SC} = 7 + j\,73.0 \text{ ohms}$$
$$Z_{OC} = 2.5 - j\,71.4 \text{ ohms}$$
$$Z_0 = \sqrt{Z_{SC}Z_{OC}}$$
$$= \sqrt{(7 + j\,73.0)(2.5 - j\,71.4)}$$
$$= \sqrt{5238 - j\,318}$$
$$= \sqrt{5238}\sqrt{1 - j\,0.061}$$
$$= 72.3 - j\,2.1 \text{ ohms}$$

If the reactance components only of Z_{SC} and Z_{OC} were taken, the *magnitude* of the characteristic impedance so calculated would differ by only a few tenths ohm from the correct value.

The Type 916-A is particularly convenient for the eighth wavelength measurement, inasmuch as both components fall within the direct-reading range of the bridge, for either condition of termination.

The short- and open-circuit impedance measurements can equally well be made on the Type 821-A, with the advantage that the reactance component is determined from the readings of a precision condenser which has an accuracy of ±0.1%. The Type 821-A, however, has the disadvantage that the input reactance cannot be measured directly at lower frequencies, and an external series capacitor must be used.

The effective input capacitance of the eighth-wave line depends, of course, upon the frequency. The approximate

[4]The absolute accuracy limitation of the Type 916-A has been set as 0.1 ohm. The value of 3.68 is therefore subject to an uncertainty of the order of 3%.

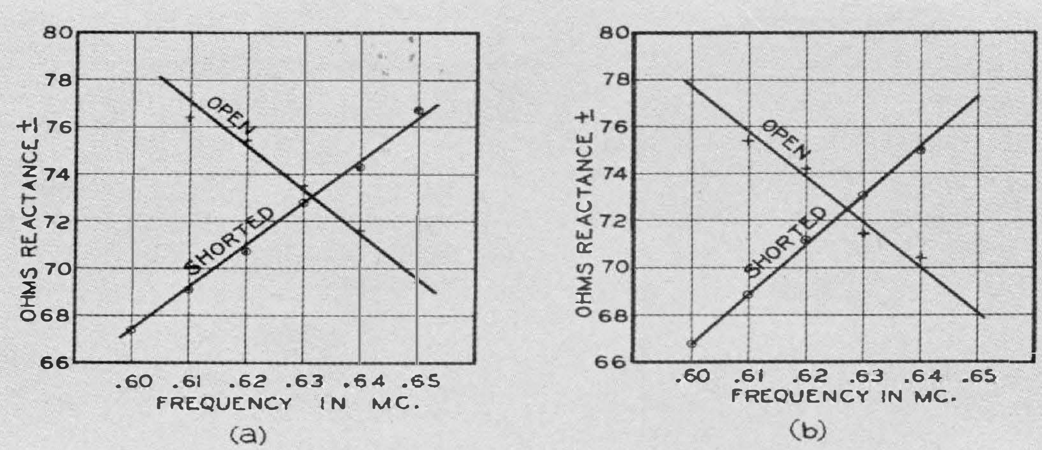

Figure 2. Plots showing the variation of input reactance in the vicinity of the eighth wavelength as observed with (a) the Type 916-A and (b) the Type 821-A. The intersection gives accurately the real component of the characteristic impedance, provided $(\alpha l)^2 << 1$.

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value of the effective input capacitance at any frequency can readily be estimated, as the order of magnitude of the characteristic impedance is usually known. We may write

$$X_{in} \approx \pm Z_O = \frac{1}{\omega \hat{C}} \qquad (8)$$

where $\hat{C}$ is the effective input capacitance and may be positive or negative.[5] If the typical value of 70 ohms is taken for Z_O, the effective capacitance becomes approximately

$$\hat{C} \approx \frac{2300}{f}$$

where $\hat{C}$ is in μμf and f in megacycles.

For any frequency lower than about two megacycles, this capacitance is outside the direct range of the 821 (1000 μμf) and a substitution method must be resorted to using a series capacitor. The method is illustrated in Figure 1c, and the input reactance can be expressed directly in terms of observed data as[6]

$$X = \pm \frac{159{,}200}{fCC_a}(C_a - C) \qquad (9)$$

In this expression C is the observed capacitance with the connection as shown in Figure 1c, C_a the value obtained when the cable input is shorted, and f the frequency in megacycles.

Examples of Measurement

The eighth-wavelength frequency for the section of cable already discussed is about 0.63 megacycle. At this frequency the input capacitance of the open-ended line is about 3500 μμf, from Equation (8). An auxiliary series capacitor of about 700 μμf was used, and the following data obtained

$$f = 0.63 \text{ mc}$$
$$C = 588.5 \ \mu\mu f$$
$$C_a = 709.7 \ \mu\mu f$$
$$X_{in} = \frac{(159{,}200)(709.7 - 588.5)}{(0.63)(588.5)(709.7)} = 73.3 \text{ ohms}$$

For the short-circuit condition, at the same frequency, the data were

$$C = 372.8 \ \mu\mu f$$
$$C_a = 336.6 \ \mu\mu f$$
$$X_{in} = 72.8 \text{ ohms}$$

In Figure 2 is shown a plot of the observed input reactance for both short- and open-circuit conditions over a narrow range of frequency in the neighborhood of the $\frac{\lambda}{8}$ frequency.

The equations and computations just presented have neglected the real components of the input impedances. Taking them into account (following the method of computation outlined in the instruction book for the TYPE 821-A) the results were

$$Z_{SC} = 7.0 + j\,72.8$$
$$Z_{OC} = 2.8 - j\,73.2$$

As with the data cited for the TYPE 916, the neglect of the resistive component affects the magnitude of the calculated Z_O by a negligible amount.

— IVAN G. EASTON

(To be continued)

[5] It is convenient to refer to negative input capacitance as the measuring circuits use capacitance standards.

[6] This expression is valid only if the resistive component of the input impedance is small compared to the reactive component. This condition is satisfied at the eighth wavelength.

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