An Analyzer for the Voice Frequency Range

By C. R. MOORE and A. S. CURTIS

[EDITORIAL NOTE: The frequency analyzers described in this paper and in the paper immediately following, demonstrate in an unusual manner how a single fundamental principle may be employed to accomplish quite dissimilar results. The analyzers described in both papers employ a resonating element of fixed frequency and translate the wave components under study to this frequency by heterodyning them with the output of variable frequency oscillators. In the analyzer described in the first paper, the wave components under study are translated to a higher frequency while in that described in the second paper the translation is downward to a lower frequency. In view of these differences in design it is desirable to call particular attention to the reasons which have led to the working out of the two designs.

The analyzer discussed by Moore and Curtis has been so designed as to sweep through the voice frequency range to as high as 5,000 cycles by the manipulation of a single control. To accomplish this end, it was found desirable to heterodyne upward by employing a variable frequency oscillator of considerably higher frequency than 5,000 cycles. The frequency of this oscillator can be varied continuously throughout the range from about 11,000 cycles to 16,000 cycles, and the fixed frequency resonating element is tuned to about 11,000 cycles. As translation of the wave under study to a higher frequency range reduces the percentage separation of the various components, it was necessary to choose a very sharply tuned resonating element. This takes the form of a steel rod which is loosely coupled magnetically to a driving circuit at one end and a registering circuit at the other. As the modulator used to accomplish the heterodyning process produces many frequencies other than the first of the "sum" and "difference" terms, it has been necessary to choose the frequency ranges such that all undesired frequencies which can not be made extremely small will be well removed from the single difference frequency under observation.

The analyzer described in the paper by Landeen is capable of working over the range from about 3,000 cycles to 100,000 cycles. A requirement of this design was that very high resolution be obtained. To assist in accomplishing this end, the frequencies under study are translated downward in the frequency scale to the resonating element which consists of a circuit tuned to 800 cycles. This downward translation increases the percentage difference of frequency separation of the components under study. Because of the great range of frequencies covered by the analyzer it is not possible to have sum and difference terms other than those of the second order fall outside of the range of sensitivity of the resonator. The modulator has therefore been so designed as to preclude formation in the higher order terms. To increase its discrimination, the analyzer makes use of two tuned circuits and amplifiers arranged in tandem and placed before the modulator. The frequency to which these circuits are tuned must of course be variable and is set to coincide with the component under study.]

THE present analyzer was designed to aid in the solution of certain problems arising in the study and development of commercial telephone transmitters. These problems require high discrimination and the accurate measurement of frequency components in the presence of much larger components.

The present analyzer differs fundamentally from that described by R. L. Wegel and one of the present authors about two years ago.[1]

[1] "An Electrical Frequency Analyzer," by C. R. Moore and R. L. Wegel, *A. I. E. E. Journal*, September 1924; *Bell System Technical Journal*, October 1924.

It is of the type employing a single resonating element of fixed frequency, the component waves under study being translated in frequency to it by heterodyning with the output of a variable frequency oscillator. It was deemed essential that the analyzer be so designed as to cover the entire voice range up to 5,000 cycles by the manipulation of a single control. In the presenta analyzer this control is the variable condenser of the heterodyning oscillator. Two of these analyzers have been built and are in use in the Bell Telephone Laboratories.

The development of this new form of analyzing device was undertaken only after a careful review of existing types. Such a study led to the conclusion that none of the available forms was applicable to the solution of our type of problem. This problem which had to do

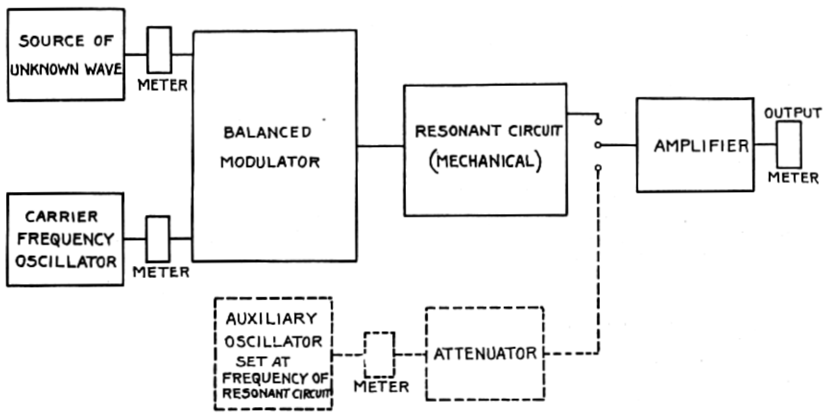

Fig. 1—Functional Diagram

with the study of commercial telephone transmitters did not require the analysis of a complex wave containing a fundamental frequency and its associated harmonics. What we were interested in was the measurement of the transmitter output at a particular frequency in the presence of a much greater output at other frequencies. For example, the measured component may be only one per cent of the magnitude of the disturbing component and separated from it by only 30 to 40 c.p.s. It is evident that if the frequency of the component which we wish to measure is close to that of one of the disturbing components and much smaller in magnitude a very high degree of frequency discrimination on the part of the analyzer is necessary.

A functional diagram of the analyzer is shown in Fig. 1. The wave to be analyzed is impressed at the "voice" input terminals of a balanced modulator. The variable carrier frequency is also supplied to the modulator and in conjunction with the wave to be analyzed produces the familiar upper and lower sideband frequencies in the modulator output.[2] The modulator output is connected to a resonant element, the natural frequency of which is left unchanged during the analysis, and the response of the resonant element is measured by a suitable amplifier and a meter. The tuned element of the analyzer makes use of longitudinal vibrations in a steel bar which in the apparatus herein described has a natural frequency of approximately 11,000 c.p.s. The frequency range of the carrier oscillator is from the natural frequency of the resonant element to 5,000 c.p.s. above. It will readily be seen that if, for instance, there is a 1,000 c.p.s component in the unknown wave and the carrier frequency oscillator is set at a frequency of 1,000 c.p.s. above the natural frequency of the resonant element, the lower sideband or difference component from the modulator will be at the frequency of this resonant element. The process of analysis is then to vary the frequency of the carrier oscillator gradually and to determine the output from the resonant element at each desired frequency. Inasmuch as the frequency range of the carrier oscillator is relatively small, the entire variation of frequency can be accomplished by a single air condenser. Therefore, the frequency setting of the analyzer may be varied continuously instead of in discrete steps. The frequency calibration chart of the carrier oscillator is arranged to show the input frequencies of the unknown wave to which a given frequency of this oscillator will correspond rather than to indicate the frequency of the oscillator itself.

It has been found convenient, for comparing the magnitudes of the various frequency components in the unknown wave, to use an auxiliary oscillator supplying current to a potential attenuator. The frequency of this oscillator is maintained at the frequency of the tuned element. The input terminals of the amplifier may be connected either to the output of the resonant circuit or to the output of the potential attenuator. The procedure is to note the deflection on the output meter of the amplifier produced by the resonant element and then switch the amplifier to the attenuator and to reproduce this deflection. The frequency components can readily be compared in this manner and their relative magnitudes determined directly in *TU* by reference to the attenuator dial setting.

In order to give a clearer idea of the operation of the analyzer the pertinent theory of the vacuum tube modulator will be discussed in the Appendix.

[2] *A. I. E. E. Journal,* April 1921—"Carrier Current Telephony and Telegraphy," by E. H. Colpitts and O. B. Blackwell.

The modulator used employs two vacuum tubes and its circuit is arranged to suppress the carrier frequency together with certain higher order modulation components in the modulator output. These together with other higher order modulation components which are not eliminated in this type of balanced modulator could produce false indications of frequency components in the wave to be analyzed, but it will be shown in the Appendix that these errors may be reduced to any desired extent by keeping the magnitude of the wave to be analyzed as low as is consistent with securing satisfactory meter readings.

The suppression of the carrier wave is desirable in that it makes it possible to carry the analysis to lower frequencies than could be done if the carrier frequence were present. When analyzing low frequencies, the frequencies of the carrier wave and the lower sideband approach each other and if the relatively large carrier were present in the output of the modulator it would tend to obscure the results.

It will readily be seen that since the resonant frequency of the tuned circuit is 11,000 c.p.s. and since the frequency discrimination at low frequencies depends upon the sharpness of resonance of this circuit, extremely sharp tuning is necessary. The considerations here differ somewhat from the ordinary considerations in tuned circuits where the effect of the resonance depends upon a percentage departure from the resonant frequency. The reactance-resistance ratio, Q, which is in common use in the treatment of electrical circuits, gives a measure of what we may call the percentage sharpness of tuning of a circuit, that is, with a given value of Q, a given percentage departure from the resonant frequency will cause the same loss independent of the resonant frequency. While it is possible at frequencies from 10,000 to 20,000 c.p.s. to obtain higher values of Q than at frequencies from 100 to 1,000 c.p.s., it is not feasible to secure the same loss with a given departure in cycles from the resonant frequency at high frequencies as it is at low frequencies. It is evident that in this method of analysis we are not concerned with a percentage departure in frequency from the resonant frequency of the tuned circuit but are concerned with the loss in transmission through this circuit per cycle departure from the resonant frequency. Therefore, inasmuch as we would desire to have good discrimination between a frequency of 100 c.p.s. and one of 110 c.p.s., the requirements of the 11,000 c.p.s. resonant circuit are extremely rigid.

Some consideration was first given to the design of an electrical network which would give sufficiently sharp tuning. At best, such a network required a considerable number of coils and condensers and these coils would require higher values of Q than could be obtained economically. Moreover, inasmuch as this selective circuit would consist of a number of highly resonant elements, it would be rather questionable whether these elements would all be affected alike by ordinary variations in room temperature. Some experiments were then made using mechanical resonance and these have given a very satisfactory solution of the problem.

The resonant element now in use consists of a steel rod clamped at the center having the magnetic element of a telephone receiver at each end with its poles separated a few mils from the end of the rod as shown in Fig. 2. One of the receiver units is connected to the output of the modulator and is used for driving the bar while the other receiver unit

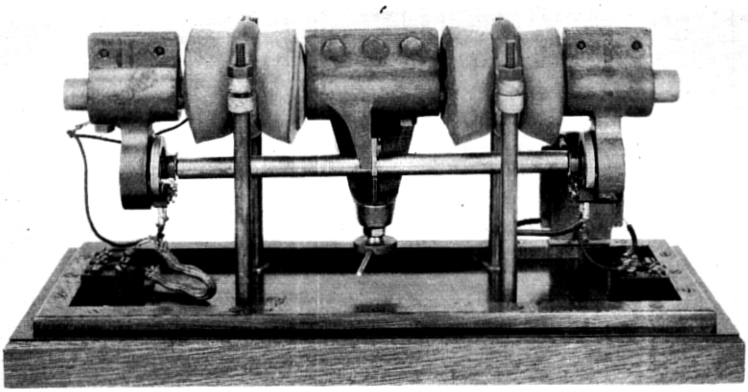

Fig. 2—Mechanical resonant circuit

is connected across the input of a suitable amplifier having a thermocouple and meter at its output. In order to minimize the effect of other extraneous frequency components the amplifier is tuned to have its maximum efficiency at the resonant frequency of the bar. The bar is approximately 9 inches long and resonates to longitudinal vibrations at 11,350 c.p.s. A frequency response curve of the bar, showing variation of the output of the driven receiver with frequency, is shown in Fig. 3. It will be seen that a departure of 10 c.p.s. from the resonant frequency gives a loss of over 25 *TU* corresponding to a voltage ratio of approximately one to twenty. Therefore, even when frequencies in the unknown wave are as low as 50–100 c.p.s. the frequency discrimination is quite satisfactory. It may be of interest to note that the value of the reactance-resistance ratio Q, calculated from the curve, is about 15,000 whereas the construction of an electrical inductance to operate at this frequency having a value of Q over 200 would be difficult and expensive.

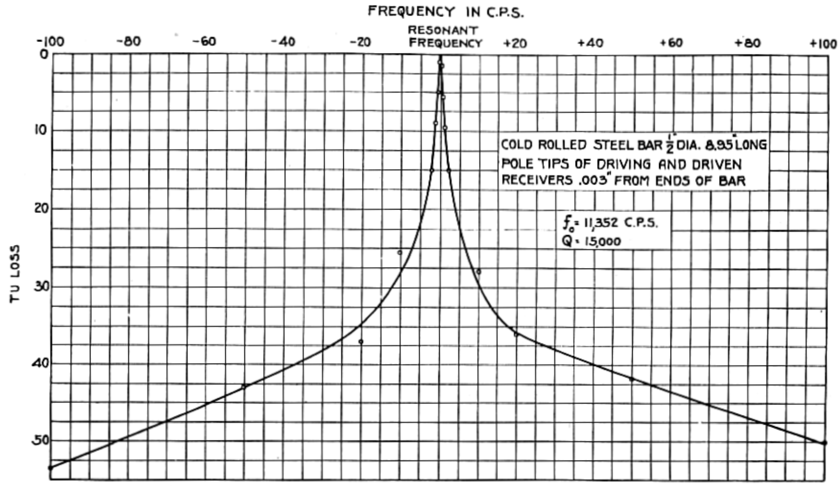

Fig. 3—Response-frequency characteristics of resonant bar

One of the two heterodyne frequency analyzers is built as a self-contained unit mounted on wheels and contains its own "A" and "B" batteries for the vacuum tubes. Fig. 4 shows the top view of the panel where the necessary controls and meters are situated and Fig. 5 shows the complete assembly with some of the compartments open. A schematic diagram of the complete circuit is shown in Fig. 6.

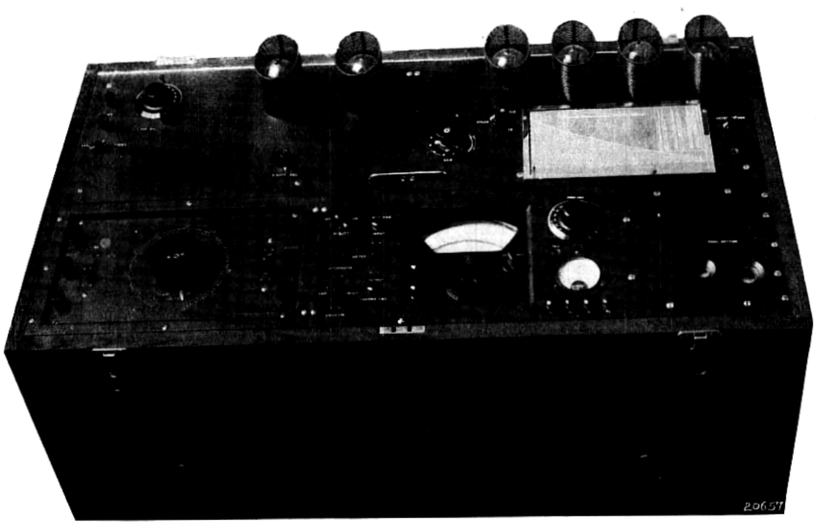

Fig. 4—Top view of panel

In addition to its use for determining the relative magnitudes of the components in an electrical wave, the analyzer is also useful in making acoustic measurements. It was primarily developed for the study of what we may term the frequency distortion of transmitters; it may also be used in the measurements of non linear distortion. As may be

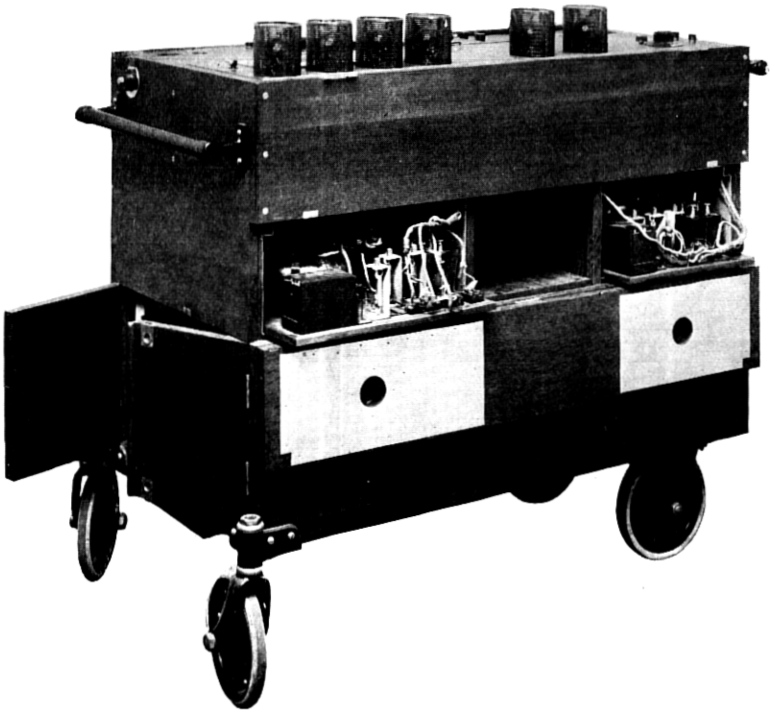

Fig. 5—Portable analyzer unit

inferred, frequency distortion is a departure of the wave form of the electrical output from that of the acoustic input due to the fact that the transmitter does not respond equally to acoustic forces of the same magnitude over the frequency range under consideration. Non-linear distortion is the distortion produced by the fact that the voltage across the transmitter at any particular frequency is not a linear function of the magnitude of the impressed acoustic force. This type of distortion usually manifests itself by the production of frequency components in the electrical output which are not present in the acoustic input. The analyzer may be used for quantitative determinations of this non-linear distortion and in such measurements high frequency discrimination and ability to measure frequency components of widely different magnitudes are very valuable.

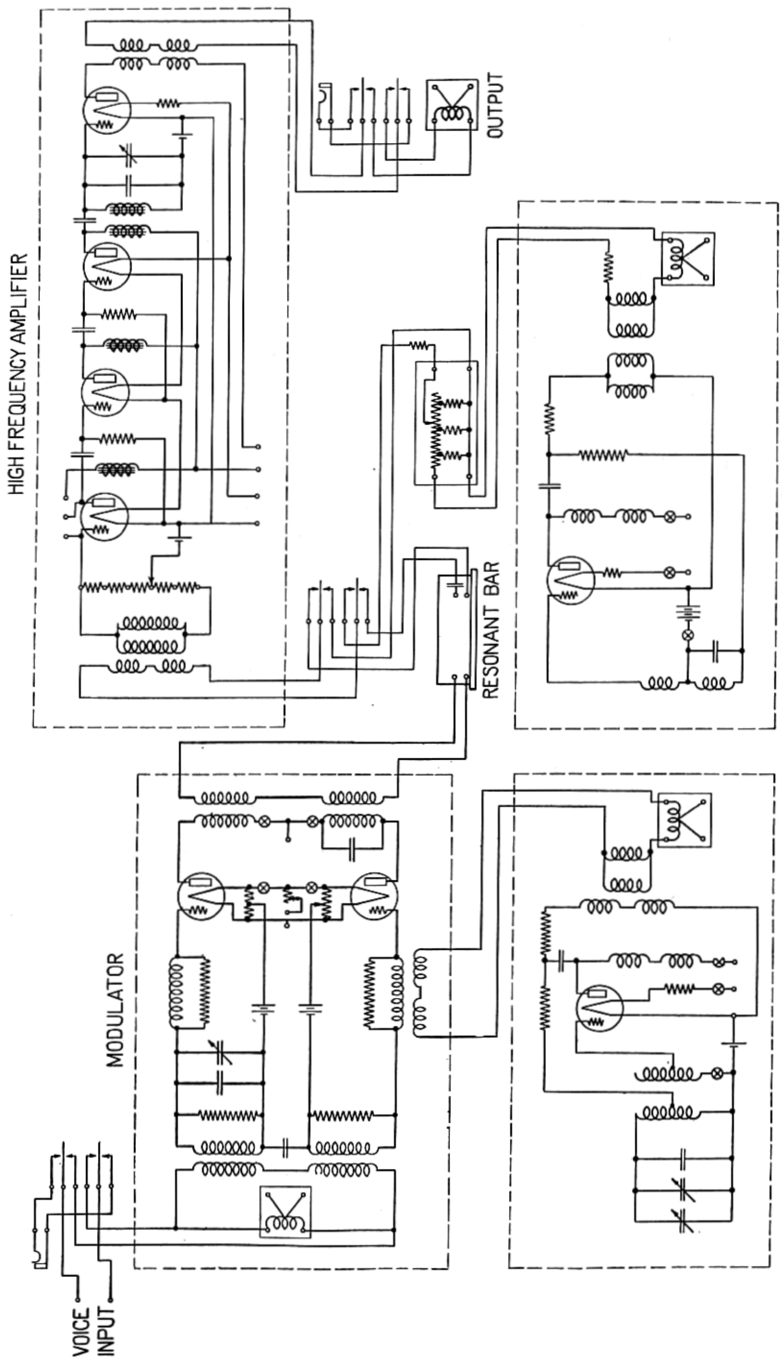

Fig. 6—Schematic diagram of analyzer circuit

A number of other uses of the analyzer in acoustic measurements might be cited; for instance, the output of a transmitter at one particular frequency may be measured in the presence of room noises or other disturbing sounds. In general its high selectivity, convenience of operation and portability make the analyzer an extremely valuable instrument in a wide variety of acoustic and electrical measurements.

Appendix

Inasmuch as the incorrect operation of the modulator could give false indications of frequency components in the wave to be analyzed, it may be of interest to take up some of the more important aspects of the theory of the vacuum tube plate current modulator as applied to this analyzer.[3] In general, the output of a vacuum tube is of the form

$$I_1 = A_0 + A_1E + A_2E^2 + A_3E^3 + A_4E^4 + \text{etc.}, \tag{1}$$

where E is the voltage applied between the cathode and grid of the tube and the coefficients A_0, A_1, A_2, A_3, etc., depend upon the average potential of the grid, the constants of the tube itself and the total impedance of the output circuit to the various frequency components appearing in the output. If we apply two voltages of the form $P \cos (pt - \theta)$ and $Q \cos (qt - \phi)$ simultaneously to the input of a vacuum tube, the above general expression will have the form

$$\begin{aligned} I_1 = A_0 &+ A_1[P \cos (pt - \theta) + Q \cos (qt - \phi)] \\ &+ A_2[P \cos (pt - \theta) + Q \cos (qt - \phi)]^2 \\ &+ A_3[P \cos (pt - \theta) + Q \cos (qt - \phi)]^3 \\ &+ A_4[P \cos (pt - \theta) + Q \cos (qt - \phi)]^4, \text{ etc.} \end{aligned} \tag{2}$$

For simplicity let $a = P \cos (pt - \theta)$ and $b = Q \cos (qt - \phi)$ and then expanding algebraically we obtain

$$\begin{aligned} I_1 = A_0 + A_1(a+b) + A_2(a^2+2ab+b^2) + A_3(a^3+3a^2b+3ab^2+b^3) \\ + A_4(a^4+4a^3b+6a^2b^2+4ab^3+b^4) + \text{ etc.} \end{aligned} \tag{3}$$

Now substituting $P \cos (pt - \theta)$ and $Q \cos (qt - \phi)$ for a and b respectively and simplifying trigonometrically, the frequencies appearing in the output of the tube are shown in Table 1.

If we employ a balanced modulator of the type shown in Fig. 7, certain frequency components shown in the table are eliminated. In this modulator the voice input transformer is so connected as to

[3] For a more complete discussion of the vacuum tube modulator see *Proceedings I. R. E.*, April 1919; "A Theoretical Study of the Three Element Vacuum Tube," by J. R. Carson.

TABLE 1

TERMS IN THE FIRST FOUR ORDERS OF MODULATION

$P \cos (pt - \theta)$ AND $Q \cos (qt - \phi)$

General Expression for Current Output

$I_1 = A_0 + A_1 E + A_2 E^2 + A_3 E^3 + \text{etc.}$

Frequency $\omega = 2\pi f$	Coefficients			
	A_1	A_2	A_3	A_4
0		$1/2\ P^2$, $1/2\ Q^2$		$3/8\ P^4$, $3/2\ P^2Q^2$, $3/8\ Q^4$
$(pt - \theta)$	P		$3/4\ P^3$, $3/2\ PQ^2$	
$(Qt - \phi)$	Q		$3/4\ Q^3$, $3/2\ P^2Q$	
$(2pt - 2\theta)$		$1/2\ P^2$		$1/2\ P^4$, $3/2\ P^2Q^2$
$(2qt - 2\phi)$		$1/2\ Q^2$		$1/2\ Q^4$, $3/2\ P^2Q^2$
$(pt - \theta) \pm (qt - \phi)$		PQ		$3/2\ P^3Q$, $3/2\ PQ^3$
$(3pt - 3\theta)$			$1/4\ P^3$	
$(3qt - 3\phi)$			$1/4\ Q^3$	
$(2pt - 2\theta) \pm (qt - \phi)$			$3/4\ P^2Q$	
$(pt - \theta) \pm (2qt - 2\phi)$			$3/4\ PQ^2$	
$(4pt - 4\theta)$				$1/8\ P^4$
$(4qt - 4\phi)$				$1/8\ Q^4$
$(3pt - 3\theta) \pm (qt - \phi)$				$1/2\ P^3Q$
$(2pt - 2\theta) \pm (2qt - 2\phi)$				$3/4\ P^2Q^2$
$(pt - \theta) \pm (3qt - 3\phi)$				$1/2\ PQ^3$

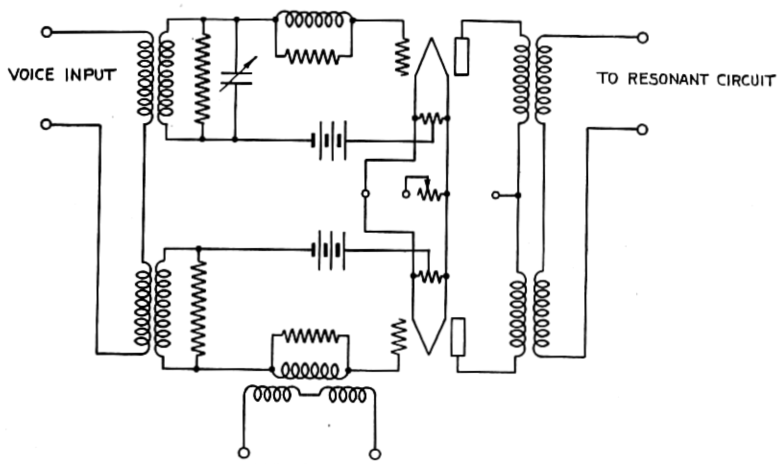

Fig. 7—Schematic diagram of modulator

impress instantaneous voltages of opposite signs on the two tubes, while the carrier windings impress instantaneous voltages of the same sign on the tubes. The output transformer is connected so that the algebraic difference of the two plate currents appears in the output of the modulator. Equation (3) shows the output of one of the tubes, but the output for the other tube in which the voice input is reversed will be

$$I_2 = A_0 + A_1(a-b) + A_2(a^2 - 2ab + b^2) + A_3(a^3 - 3a^2b + 3ab^2 - b^3) + A_4(a^4 - 4a^3b + 6a^2b^2 - 4ab^3 + b^4) + \text{ etc.} \tag{4}$$

If the circuits of the two tubes are exactly balanced, then since the output of the modulator is so connected that only the algebraic difference of the two plate currents will appear, all of the frequencies arising from the terms of like sign in equations (3) and (4) will be suppressed or, subtracting equation (4) from equation (3), the resultant current will be

$$I_1 - I_2 = +2A_1b + A_2(+4ab) + A_3(+6a^2b + 2b^3) + A_4(+8a^3b + 8ab^3). \tag{5}$$

The frequency components arising from the various terms of equation (5) are shown in Table 2.

TABLE 2

FREQUENCY COMPONENTS ARISING FROM ALGEBRAIC DIFFERENCE OF $I_1 - I_2$

$2\ A_1Q \cos\ (qt - \phi)$
$2\ A_2PQ \cos\ [(pt - \theta) \pm (qt - \phi)]$
$3\ A_3P^2Q \cos\ (qt - \phi)$
$3/2\ A_3P^2Q \cos\ [(2pt - 2\theta) \pm (qt - \phi)]$
$1/2\ A_3Q^3 \cos\ [3qt - 3\phi]$
$3/2\ A_3Q^3 \cos\ (qt - \phi)$
$A_4P^3Q \cos\ [(3pt - 3\theta) \pm (qt - \phi)]$
$3\ A_4P^3Q \cos\ [(pt - \theta) \pm (qt - \phi)]$
$3\ A_4PQ^3 \cos\ [(pt - \theta) \pm (qt - \phi)]$
$A_4PQ^3 \cos\ [(pt - \theta) \pm (3qt - 3\phi)]$

In the analyzer the only useful order of modulation is the second, that is, the frequencies arising from the A_2 term of equation (1). The component of interest here is the term $2A_2PQ \cos\ [(pt - \theta) - (qt - \phi)]$. As can be seen, this frequency component is proportional to both P and Q and for a given value of P is proportional to Q. In other words the input into the tuned circuit is a linear function of the magnitude of the particular frequency component under consideration in the wave to be analyzed. As will be seen from Table 2, there are a number of other frequency components due to the various orders of modulation in the modulator output. A little consideration, however, will show that a number of these components cannot appear in the output of a resonant circuit tuned to approximately 11,000 c.p.s. where the upper frequency limit of the voice input is 5,000 c.p.s. and the range of the carrier oscillator is limited from the resonant frequency of the tuned circuit to 5,000 c.p.s. above. The only components of Table 2 which can be passed by the tuned circuit are:

$$2A_2PQ \cos [(pt - \theta) - (qt - \varphi)],$$
$$3A_4P^3Q \cos [(pt - \theta) - (qt - \varphi)],$$
$$3A_4PQ^3 \cos [(pt - \theta) - (qt - \varphi)],$$
$$1/2\, A_3Q^3 \cos (3qt - 3\varphi),$$
$$A_4PQ^3 \cos [(pt - \theta) - (3qt - 3\varphi)].$$

In addition to the desired term in the second order modulation of frequency $(pt - qt)/2\pi$ there are two other terms of the same frequency in the fourth order modulation. These have respectively the coefficients $3A_4P^3Q$ and $3A_4PQ^3$. With a given value of carrier input P, the first of these is proportional to Q and it will add to the second order term but will cause no serious trouble. The second term, however, is proportional to Q^3 and, therefore, would cause the input to the tuned circuit to depart from the desired linear relationship with respect to Q. However, the ratio of the cofficient of this fourth order term to that of the second order term is $3A_4Q^2/2A_2$ which is proportional to Q^2 and, therefore, the effect of the fourth order term will fall off rapidly as Q is reduced. In the third order modulation, there is a component of frequency $3qt/2\pi$ which would be passed by the tuned circuit if there were a component of 1/3 the resonant frequency of this circuit in the wave to be analyzed. Considering the extreme sharpness of the tuned circuit, it is rather improbable that such a condition will occur. Moreover, this component is proportional to Q^3 and, therefore, will fall off rapidly as Q is reduced. In the fourth order modulation, there is also a component $A_4PQ^3 \cos [(pt-\theta) - (3qt-3\phi)]$ of frequency $(pt-3qt)/2\pi$. This component would indicate a third harmonic in the unknown wave although it actually contained no other frequency than that of $qt/2\pi$. However, the ratio of its coefficient to the desired second order term is $A_4Q^2/3A_2$ and, therefore, the false indications of a third harmonic can be reduced to any desired extent by reducing Q.

It is evident, therefore, that in an analyzer of this type it is desirable to keep the magnitude of the input of the unknown wave as low as is consistent with obtaining satisfactory meter readings. In the two analyzers now in operation, false indications by the introduction of extraneous frequency components due to the third, fourth and higher orders of modulation are negligibly small. Measurements on an essentially pure frequency within the frequency limits of the apparatus show harmonics less than 0.1 per cent of the fundamental. With an indicated harmonic of not more than this magnitude, it is difficult to tell whether such a harmonic is actually present in the wave or a false indication. At any rate, the harmonic is small enough as to be of no significance. It is, of course, difficult to build the modulator so that it will be exactly balanced over the frequency range covered by the carrier oscillator and, therefore, frequency components such as $(pt-2qt)/2\pi$ appearing in the third order modulation as shown in Table 1 are not totally eliminated. However, the effect of unbalance is of no serious consequence in the practical operation of the analyzer. There is, of course, a possibility of false indications due to higher orders of modulation than the fourth, but the coefficients A_3, A_4, etc., are usually small in comparison with A_2 and in general become successively smaller. Moreover, it will be evident that these false indications may be reduced to any desired extent by reducing the magnitude of the unknown wave.