An Electrical Frequency Analyzer[1]

By R. L. WEGEL and C. R. MOORE

SYNOPSIS: An apparatus has been developed by means of which it is possible to measure and obtain a permanent record of the frequency components of an electric current wave. The device has two frequency ranges: 20 to 1250 cycles and 80 to 5000 cycles; the amount of power required does not in general exceed 500 microwatts; and the time necessary for making a record is about 5 minutes. An attachment is provided which permits of the making of simultaneous harmonic analyses of two complex waves in the same length of time.

In principle, the process consists in feeding the complex wave to be analyzed into a selective network, the essential feature of which is a sharply tuned circuit whose frequency of tuning is controlled by varying the capacitance in small steps with a pneumatic apparatus similar to that in a player piano. A maximum of response of the circuit occurs at each frequency of tuning which coincides with a component of the complex wave. An automatic photographic recorder of the response to each frequency of tuning is provided by means of which the frequency and magnitude of each component of the complex wave may be obtained. For convenience of operation, an automatic control apparatus is provided, so that it is only necessary to connect the complex source or sources to be analyzed and press a starting button. The completed record of the analysis is delivered after the machine has passed through the entire range of frequencies.

The application has so far been principally to problems in the communication field such as the analysis of performance and distortion at audio frequencies of vacuum tube and mechanical oscillators and amplifiers, analysis of complex telephone waves and speech sounds, and the effect on a complex wave of transmission through electrical and acoustic apparatus. In the power field many applications are obvious, such as for example, quantitative comparison as to frequency content of the voltage and current supplied to and delivered by transformers, voltage and magnetic flux studies in generators and motors, commutation, and the effect of wave-shapes in power transmission line problems and control apparatus.

INTRODUCTION

THE harmonic analyzer described in this paper consists of a variable tuned circuit into which the complex current wave to be analyzed is introduced, and an automatic recording apparatus to register its response as the frequency of tuning is changed.

The first recorded use of a tuned circuit as an analyzer was by Pupin in 1894.[2] He analyzed power waves by measuring the response of circuits tuned to each of the harmonic frequencies. It has been the practise for a number of years to determine the frequency characteristics of currents and voltages on power circuits and noise on telephone lines by means of a variable resonant circuit which includes a telephone receiver for listening.

[1] Presented at the Midwinter Convention of the A. I. E. E., Philadelphia, Pa., February 4-8, 1924.

[2] Resonance Analysis of Alternating and Polyphase Currents, Trans. A. I. E. E., Vol. XI, p. 523.

During the recent war a rapid automatic method was developed for varying the tuning of a circuit in such an analyzer in connection with the analysis of sounds radiated by submarines. The analyzer described in this paper is in principle the same as this apparatus but includes such improvements as were found desirable by experience to increase the speed, dependability and convenience of use. The present apparatus is capable of recording the frequency and magnitude of each component in a complex wave between 20 and 1250

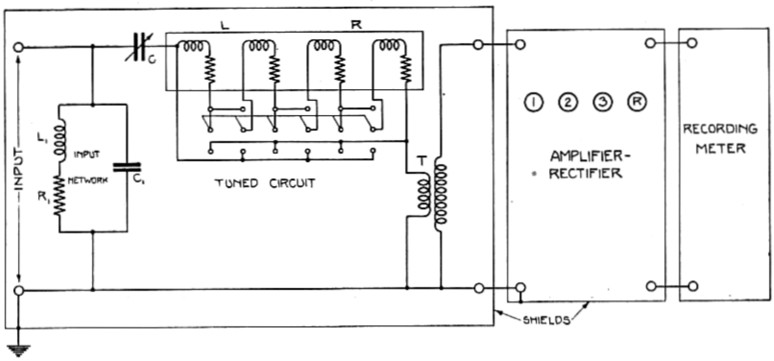

Fig. 1—Schematic Analyzer Circuit

cycles or 80 and 5000 cycles in about five minutes. This analyzer does not measure the phase of the various components but has the advantage that the frequencies need not be simple multiples of the fundamental as is the case with graphical analyzers. With this apparatus it is possible to measure quite accurately component frequencies as close together as about fifteen cycles at the lower end of the range and about 200 cycles at the upper end of the range, and to detect components as close together as three to five cycles at the lower end and fifty cycles at the upper end of the range.

Principles of Operation of the Analyzer

Fig. 1 is a schematic diagram of the essential elements of the analyzer circuit. The wave to be analyzed is introduced at the input terminals from which it passes to an input equalizing network and to the variable tuned circuit. The tuned circuit consists of a variable condenser of capacitance C and a coil whose inductance is L and resistance R. The value of the capacitance C is varied in small steps by an automatic device to be described in the next section. The inductance L consists of four identical windings on a toroidal core which, by means of a switch, may be thrown in series or in parallel, thereby changing the value of the inductance in the ratio of 16 to 1. With the same range of capacitance values this change in inductance gives the two frequency ranges of tuning, 20-1250 cycles and 80-5000 cycles. By means of the high-ratio transformer T the response of this circuit is applied to a vacuum tube amplifier-rectifier and registered by means of the recording meter.

This circuit arrangement will analyze a complex wave by virtue of the selective shunting of current by the tuned circuit from the input network. The impedance of the source of the complex wave is in practise maintained high in value at all frequencies compared to that of the input network so that the input wave-shape is independent of the small changes in impedance of the analyzer due to the varying of condenser C. The current fed into the analyzer traverses two paths, the input network and the tuned circuit. The impedances of these paths are respectively,

$$Z_1 = \frac{(R_1 + j\omega L_1)/j\omega C_1}{R_1 + j\omega L_1 + 1/j\omega C_1}$$

and

$$Z = R + j\omega L + 1/j\omega C.$$

The transformer T introduces into the tuned circuit a small resistance and inductance, both of which are negligible. The input network impedance Z_1 varies gradually from 0.4 ohms for direct current to about 10 ohms at 5000 cycles. The values of the elements are: R_1 = 0.4 ohms, L_1 = 0.075 milhenries, C_1 = about 15 microfarads. Impedance Z of the tuned circuit depends on the setting of the variable condenser C. The resistance R of the iron-core coil, varies with frequency; its values for the parallel connection are 0.7 ohms for direct current, 1.5 ohms at 2500 cycles and 4.2 ohms at 5000 cycles The value of the inductance L for the parallel connection is 23.4 milhenries and is practically constant with change of frequency. For the series connection both R and L are sixteen times as great. The capacitance is varied from about 200 microfarads to about 0.05 microfarads. It will be seen that for each capacitance value there is a frequency, $f_r = 1/(2\pi\sqrt{LC})$, for which the tuned circuit impedance, Z, is R. For other frequencies Z is much greater due to the reactance. An incoming current of frequency f_r is, therefore, largely shunted through the tuned circuit while current of any other frequency passes through the input network. In this way if the capacitance C is varied gradually the tuned circuit will shunt selectively from the input network the successive components of the complex wave.

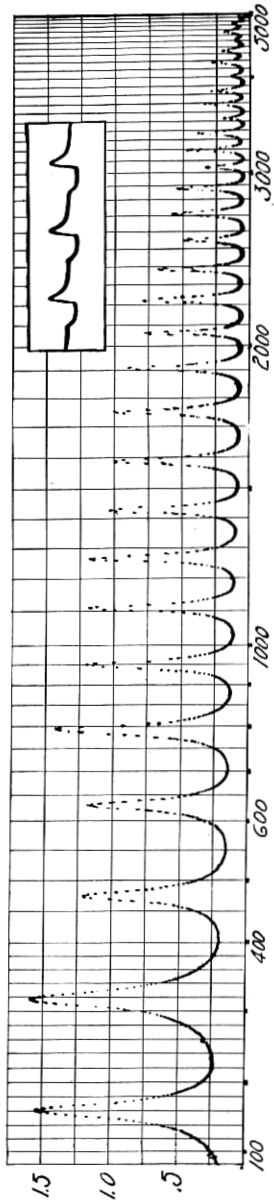

Fig. 2—Record of 160-cycle Buzzer Output

The special features of design of this analyzer circuit can be better explained by reference to a typical record made by the apparatus. Fig. 2 is the record of analysis of the current from a buzzer which vibrates with a frequency slightly under 160 per second and gives an irregularly shaped wave which is shown in the accompanying oscillogram. In taking this record the windings of the tuning inductance were in parallel so as to give the frequency range 80-5000 cycles. The vertical scale gives approximately the r. m. s. current in milliamperes at each frequency (as read on the horizontal scale) at which a peak occurs. It will be seen that a peak occurs at each multiple of the frequency of the buzzer. The r. m. s. values of input current at the corresponding frequencies as read from the peaks on the record are: 160, 1.6 milliamperes; 320, 1.6 milliamperes; 480, 1.25 milliamperes; 640, 1.2 milliamperes; 800, 1.45 milliamperes; 960, 1.25 milliamperes; 1120, 1.2 milliamperes; 1280, 1.1 milliamperes; 1440, 1.05 milliamperes; 1600, 1.0 milliamperes; 1760, 1.0 milliamperes; etc. The root square sum of all components shows that 4.7 milliamperes was the effective value of the complex current fed into the analyzer.

The fact that the 80-5000 cycle records read directly the current at each frequency component is due to the special design of the input network. A small correction is still necessary but can be neglected except where maximum obtainable accuracy is desired. If the input network were a pure resistance the higher frequency components would produce relatively lower peaks because of the falling off of efficiency with frequency of the amplifier-rectifier circuit and the increase in resistance of the tuning coil. The input network was designed empirically so that with constant input current the voltage drop across the input terminals increases with frequency in such a way as to compensate for these high-frequency losses. The tests to determine this were made by taking records of single frequencies of known amounts.

It will be seen that the frequency scale is gradually contracted as the upper end of the record is approached. Owing to the increase in resistance of the coil with frequency, the sharpness of tuning of the analyzing circuit decreases with frequency. Each peak on the record corresponding to a single frequency is a plot of the resonance curve of the variable tuned circuit. The sizes of the capacitance steps are so adjusted that a sufficient number of points, necessary to trace a resonance peak at all frequencies, is recorded. The length of the record and the time required for an analysis are determined by the number of points needed.

When peaks on the record are so close together as to overlap greatly, the reading on the scale is untrustworthy. If, instead of a rectifier and direct-current meter, an alternating-current meter giving deflections proportional to total r. m. s. values, were used, it would be theoretically possible to determine the component frequencies and amplitudes making up any composite peak, provided the number of frequencies could be determined. This procedure, however, would be impracticable. An examination of the theory of the rectifier shows that the problem of separation of the components of a composite peak is in general indeterminate. The rectifier however resolves adjacent peaks somewhat better than an alternating-current meter.

The analyzer has been most used in the analysis of audio-frequency currents for which the higher frequency range, 80-5000 cycles, is more useful. For the investigation of power problems the lower range would ordinarily be more suitable. In order to simplify the change from one frequency range to the other the tuning inductance only, is changed, leaving the mechanism for varying the capacitance in steps the same for both ranges. Since the inductance change in going from the high to the low-frequency range is in the ratio 1:16 and the change in the frequency range 4:1, the abscissas on the low-frequency records have one-fourth the value of those on the high-frequency records.

Since the smallest frequency divisions at the lower end of the high-frequency records are 20 cycles, these divisions on the low-frequency records are 5 cycles. There are, therefore, four times as many steps of tuning in the same frequency interval on the low as on the high-frequency record. The low-frequency record is therefore not of minimum practicable length. Since the same input network is used with the 20-1250 range as with the 80-5000 range, the low-frequency records are not direct reading in input current, but must be used with a calibration. Our use of the low-frequency range, however, has been so limited as not to justify the preparation of additional equipment for this use of the analyzer.

The apparatus is equipped with a device which permits of making simultaneous analyses of two complex waves. The principal reason for making such double records is to reduce errors in comparing two sources which may vary with time. The device may also be used simply to save time. It operates by connecting alternately to the analyzer the two complex waves in such a way that the record for each wave is traced by points representing alternate tuning condenser settings.

Description

The mechanism of the analyzer is so designed that to take a record it is only necessary, after starting the amplifier and connecting to a 110-volt power source, to attach the leads from the source or sources to be analyzed and press a starting button. The completed record is then automatically delivered in about 5 minutes after which the apparatus returns to the starting condition ready to repeat the

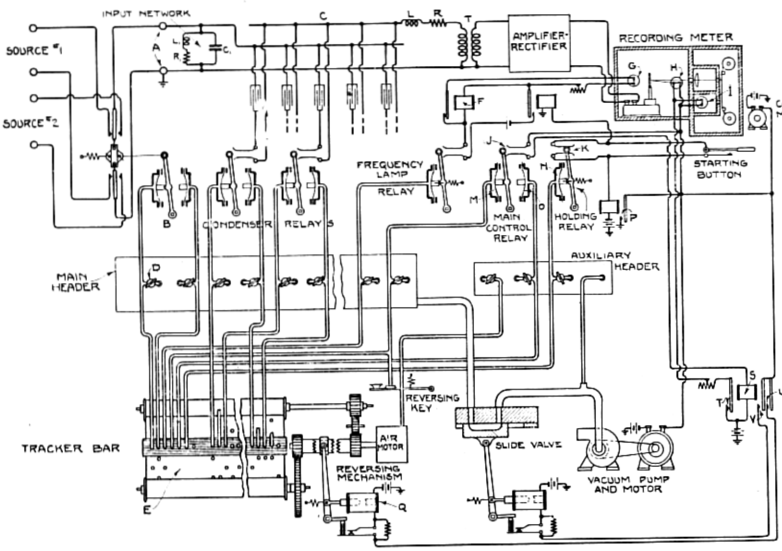

Fig. 3—Arrangement of Pneumatic and Electrical Apparatus

operation. This is accomplished by means of pneumatic apparatus operating in conjunction with a photographic recording device.

The pneumatic arrangement is a modification of a piano player mechanism in which a paper roll of standard dimensions is used. By proper perforation of the roll special pneumatic relays are operated in proper sequence to switch the condensers of the tuned circuit, flash frequency lines on the record, stop the mechanism after a record has been completed, rewind the piano roll, and perform other functions necessary to leave the analyzer in the starting condition. Electrical relays for switching the tuning condensers were not found practicable on account of the disturbances induced into the analyzer circuit.

The photographic recording apparatus consists of the camera motor for moving the sensitized record paper at a constant rate proper arrangement of lenses and lamps for illuminating the mirror galvanometer and tracing the scale and frequency lines, and suitable baths for developing and fixing the record. The record is drawn through the mechanism by means of two motor-driven rubber rollers, which also serve to remove excess solution.

The development of the pneumatic switching apparatus was carried out with a view to making use of as many standard piano player parts as possible. However, it was found necessary to make some

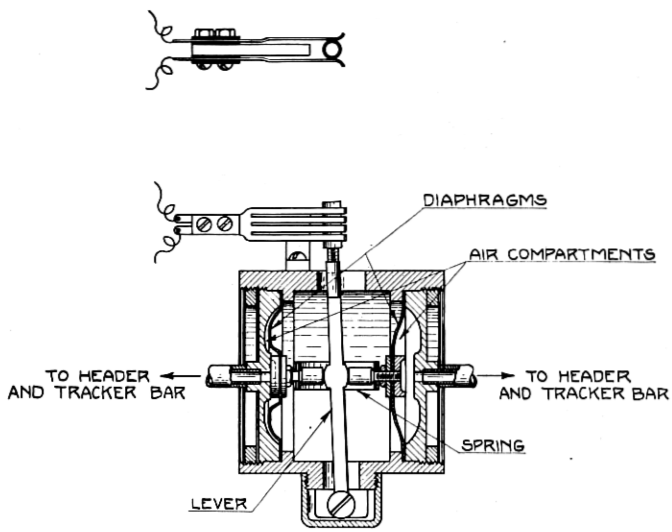

Fig. 4—Pneumatic Relay

modifications in method and apparatus; in particular a new pneumatic motor element (air relay) for switching the condensers at the requisite speed had to be developed.

Fig. 3 is a schematic drawing showing the principal features of the analyzer. In this drawing the vacuum pump is shown driven by an electric motor, and connected by means of pipes to the auxiliary and main headers and relays. This pump maintains in the headers an absolute pressure of about 4 or 5 lb. per square inch. The player piano roll E operates the entire mechanism by passing over the tracker bar in the usual manner. The air motor and tracker bar equipment are substantially as supplied by the manufacturers except that the reversing mechanism is arranged to be operated electrically instead of by hand.

The essential features of the air relay which was developed for this analyzer may be better understood by reference to Fig. 4. A cylindrical casting is arranged to mount two flexible diaphragms and two end plates in such a way as to form at each end of the cylinder, compartments, one side of each of which is a diaphragm. When assembled the two diaphragms face each other and are connected together by a circular spring made of steel strip. In use the two end compartments are partially evacuated thus causing the diaphragms to pull apart, straining the spring. When distended the diaphragms lie against the inner faces of the end plates which are shaped as shown. Obviously if air be allowed to enter either of the compartments the diaphragm belonging thereto will be pulled toward the other diaphragm by the spring. Passing through the circular spring is a lever pivoted at one end and carrying on the other end an insulated metallic sleeve. This lever is not attached in any way to either diaphragm and will of itself remain in position where last placed. Switch points are mounted in such a way that the sleeve may be forced in or out between them by the action of the diaphragms. This relay has proved very satisfactory in service and is particularly fast in its operation.

Connections between the tracker bar, main header, and the pneumatic relays are made by means of rubber tubing. As shown in Fig. 3 each of these relays requires two rubber tubes leading to the main header and two from the header to the tracker bar. These tubes are connected to the header by means of stop cocks *D* so connected that the direct passage of air from tracker bar to relay is practically unobstructed but the passage leading from the junction to the header may be made as small as desired by turning the finger valve. As adjusted, the opening to the header is small compared to the size of the tubes so that if air be permitted to enter one of the tube lines (as at the tracker bar), the diaphragm of the relay associated therewith is immediately released. When the tube is closed again, the entrapped air is soon removed through the small opening leading to the header thus restoring the diaphragm to its original position. The relay lever, however, does not follow the diaphragm.

This arrangement possesses the advantage that small openings only are necessary in the player piano roll, and that the opening which connects a condenser into the circuit is not in line on the roll with the opening which disconnects this condenser. Also at the beginning of an analysis by suitable perforations in the roll all air relays can be set simultaneously in the off position (condensers disconnected), thus making sure of the initial conditions. The apparatus is so designed that all the openings causing condenser circuits to close are on one side of the roll and those causing them to open are on the other side.

As before mentioned the tuned circuit is made up of inductance L, having some resistance R, and a bank of condensers designated by C. The function of the "Condenser Relays" is to connect into the tuned circuit any one or any combination of the 25 fixed condensers, thus tuning the circuit in small steps over a wide range of frequencies. The input is fed into this circuit as shown at A, and the degree of resonance, that is the response of the circuit at any

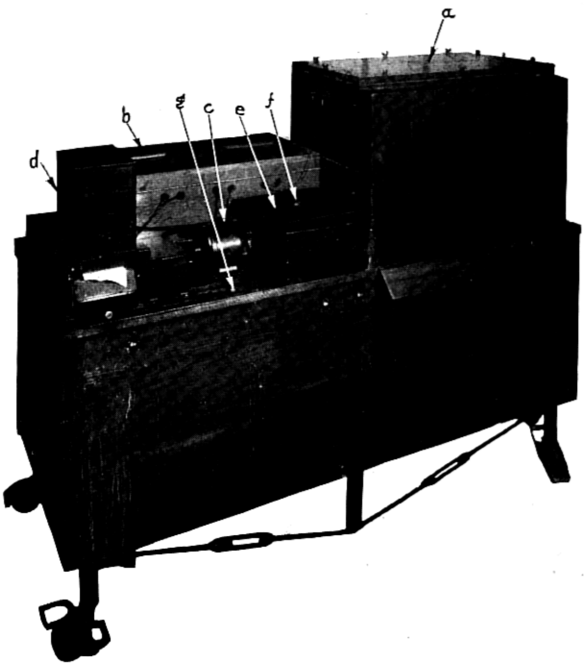

Fig. 5—View of Analyzer Ready for Use

a—Input and tuned circuits
b—Amplifier-rectifier
c—Camera motor
d—Recording meter
e—Control box
f—Starting button
g—Reversing key

particular frequency of tuning, is measured by means of the small transformer T, the amplifier-rectifier and the recording meter.

In addition to operating the tuned circuit a few of the air relays are used to operate the control circuits, mark frequency lines on the chart, etc., uses which required slight modification as indicated schematically in Fig. 3. In two of these control relays only one diaphragm is used, and the switch lever and diaphragm are fastened together by means of a flexible link. It has already been noted that the analyzer is equipped to trace two curves simultaneously on a single record. This is accomplished by means of air relay *B* which is so arranged as to connect two sources of input alternately to the analyzer. These input connections are alternated rapidly and are effected by appropriate punching of the roll.

The above covers the essential features of the analyzer but there

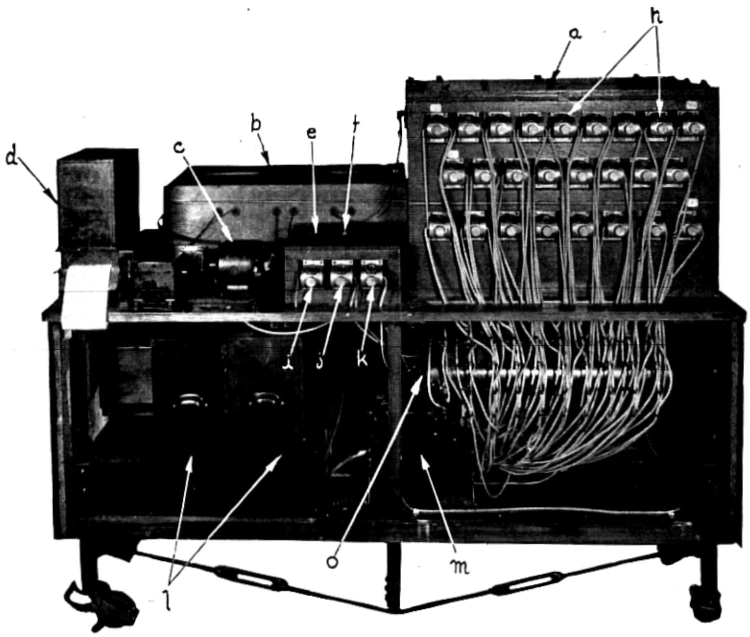

Fig. 6—View of Analyzer with Relay Side Uncovered

a—Input and tuned circuits
b—Amplifier-rectifier
c—Camera motor
d—Recording meter
e—Control box
f—Starting button
h—Condenser relays
i—Holding relay
j—Frequency lamp relay
k—Main control relay
l—Plate battery
m—Air motor
o—Main header

remain a few details having to do with assembly, control, etc., that may be of interest.

Fig. 5 shows the analyzer as completed and ready to operate. The apparatus is assembled on a two-deck, structural-steel table equipped with castors for convenience in handling. Much of the equipment is inclosed for protection against moisture and dust. The recording meter, camera motor, amplifier-rectifier, control relays, and input and tuned circuits are placed on the top. Below are mounted the batteries, the vacuum pump with its motor, and the tracker bar with paper roll mechanism. The arrangement is clearly shown in Figs. 6 and 7 taken with the protecting panels removed. In Fig. 6, *a* is a moisture-proof box containing the input and tuned circuits. The inductance coil is placed in the center of the upper half of this box together with the switch for connecting the windings

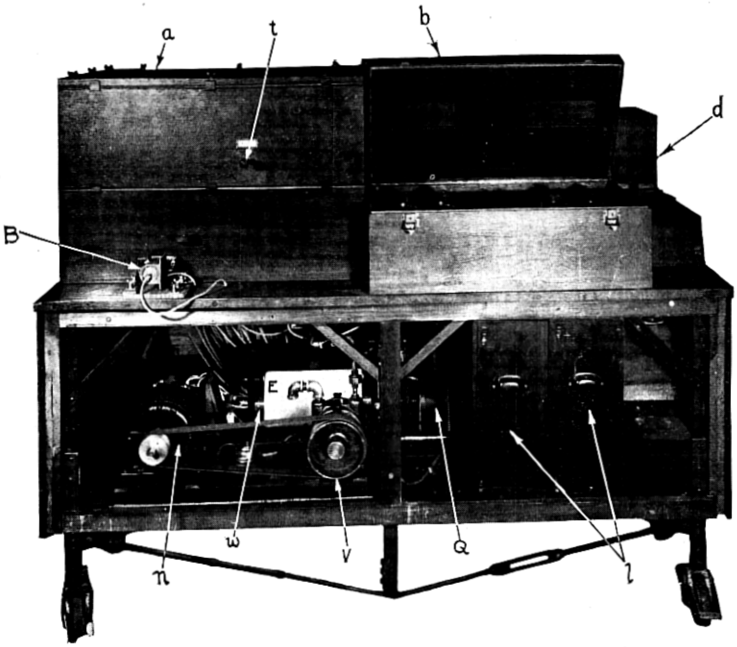

Fig. 7—View of Analyzer with Pump Side Uncovered

a—Input and tuned circuits
B—Amplifier-rectifier
c—Source-alternating relay
d—Recording meter
E—Paper roll
l —Plate battery
n—Pump motor
Q—Reversing solenoid
t —Series-parallel coil switch
v —Vacuum pump
w—Tracker bar

in series or parallel. The smaller capacitances are of mica and are arranged around the coil and switch assembly in such a way that they may be connected with a minimum length of lead to the air relays which are located on one side of the box. The larger capacitance units are made up of paper condensers and are placed in the lower half of the box. The metal lined box *b* contains the amplifier-rectifier, and at *d* is shown the recording meter. Box *e* contains the control circuits with the necessary relays. The method of mounting the air relays, main vacuum header (attached to underside of table top), air motor, etc., is also clearly shown in this figure. Each air relay is equipped with two rubber tubes leading to adjustable cocks on the header which in turn are connected to the tracker bar. The three-control relays are also shown in Fig. 6. The vacuum pump is shown at *v* in Fig. 7. The piano roll *E* moves over the tracker bar *w* and is reversed by means of solenoid *Q*. In boxes *l* are placed the plate batteries for the amplifier-rectifier.

The control apparatus by means of which the analyzer becomes practically an automatic machine will now be described. Referring again to Fig. 3 it will be seen that there is provided an auxiliary header and an electrically operated slide valve. The functions of these devices will be discussed presently.

The machine is started by pressing the starting button which should be kept closed for a few seconds while normal vacuum is being established in the headers. The air motor then starts and the paper roll *E* begins to travel across the tracker bar. Perforations in the roll are so made that when the roll is in its initial position an opening allows air to enter chamber *N* of the holding relay. As soon as the paper starts, however, this opening is closed, chamber *N* is exhausted, and contacts *K* close. This short-circuits the starting button which the operator may now release, and the machine is in full operation. It will be noted that the closing of the contacts of the starting button or contacts *K* puts into operation motors which drive the vacuum pump and the camera apparatus. Simultaneously recording meter lamp *H* and scale-line lamp *I* are lighted. The latter illuminates the record through small holes in an opaque scale strip thus marking horizontal lines due to the motion of the record.

As the roll *E* traverses the tracker bar, appropriate perforations control the condenser relays so as to switch the proper condensers into and out of the tuned circuit. Proper perforations also control the frequency lamp relay which flashes frequency lines on the record by means of Lamp *G*. Relay *F* is inserted in order to make the flash of short duration.

The tracker bar-paper-roll apparatus was received as a unit from the manufacturer and was installed after making modification in the reversing mechanism as mentioned above. This was done in the interest of automatic control. The paper roll is kept in its proper course over the tracker bar by means of an automatic adjusting device such as used in practically all high grade player pianos.

As the paper progresses over the tracker bar a point is finally reached where the last condenser connections are made and it becomes necessary to rewind the roll and to restore the entire mechanism

Fig. 8—Output of Carbon Button Driven at an Excessive Amplitude

to its starting condition. This is accomplished by means of a perforation at the end of the record which admits air to chamber *M* of the main control relay, thus closing contacts *J*. Relay *S* then operates since its circuit to ground is completed through contacts *P*. Operation of relay *S* opens contacts *T* thus disconnecting lamps *H* and *I*, and closes contacts *U* and *V*. It will be seen that the closing of contacts, *U* operates the reversing mechanism, and rewinding of the roll begins immediately. The closing of contacts *V* operates the slide valve thus releasing the vacuum on the main header, allowing the roll to be rewound with minimum mechanical drag.

It may be noted that means are also provided for rewinding the roll from any point in its forward travel by admitting air manually at the reversing key. This will cause the main control relay to operate so that rewinding will begin. Vacuum is kept on the auxiliary header during the rewind so that control of the analyzer may be maintained to the end of the operating cycle.

When the paper has been completely rewound perforations allow air to enter simultaneously chamber *O* of the main control relay and chamber *N* of the holding relay. This action opens contacts *J* and *K*, thus bringing the entire mechanism to rest in its initial starting condition.

Applications

To show the variety of problems in which the analyzer is a useful means of investigation, a few illustrative records have been made and will be discussed. These records were taken in each case to illustrate the use of the analyzer and are not parts of investigations to which they are related. They cannot, therefore, be taken as representative of the performance of the apparatus tested.

One of the uses of the analyzer has been in the study of the performance of microphone buttons. Fig. 8, for example, illustrates the character of the distortion in a button when driven at an excessive amplitude. The button was mounted so that its movable electrode could be driven at a single frequency by a very heavy reed at its natural frequency so that the motion was very nearly sinusoidal. The frequency of the motion was a little less than 450 cycles corresponding to the second peak on the record. The amplitude of motion was 0.001 centimeters or 0.0004 inches which is of course much greater than normally obtains in a transmitter. The circuit consisted simply of the button and a battery in series with the analyzer so that the record is an analysis of the current fluctuations in the button. The record shows two series of frequencies generated

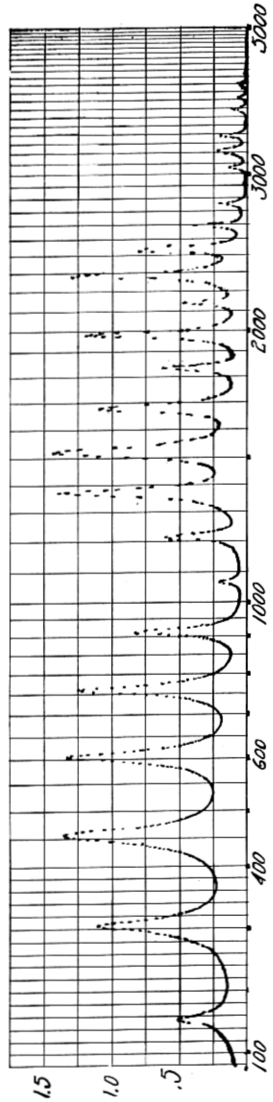

Fig. 9—Noise in Room as Picked up by Condenser Transmitter

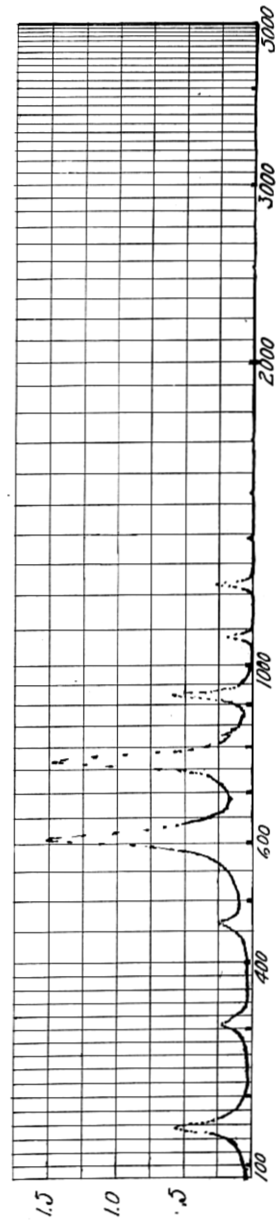

Fig. 10—Noise in Room as Picked up by Telephone Receiver Used as a Transmitter

by the button; a primary series having for its fundamental the driving frequency, 450 cycles, and a subsidiary series, having for its fundamental half the driving frequency or 225 cycles. The even harmonic components of the secondary series coincide, of course, with the frequencies of the primary series. The primary series can be accounted for by the fact that with such large amplitudes the changes in resistance are not a linear function of the amplitude of

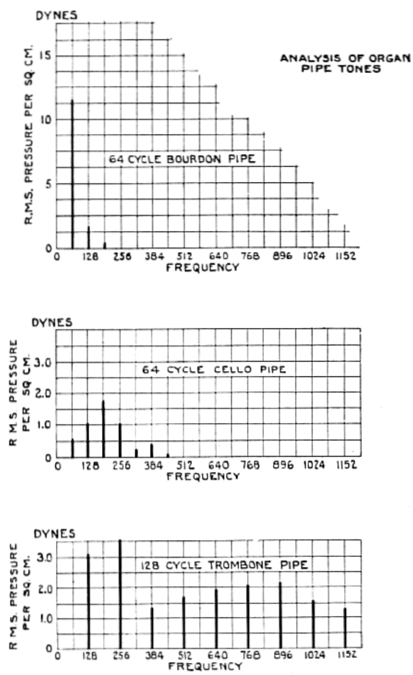

Fig. 11—Analysis of Organ Pipe Tones

motion. The subsidiary series is due to the non-symmetrical effect of the inertia of the carbon grains in vibration, the motion being so violent that some of the grains are thrown free from their contacts. For small amplitudes such as those ordinarily encountered in a transmitter, a record would show only 450 cycles, the other frequencies occurring in negligible amount; for intermediate amplitudes the primary series only occurs.

The analyzer has been used in connection with the study of sustained sounds and of the performance of acoustical apparatus. Fig. 9 is a record of the noise in a room originating from a buzzer as

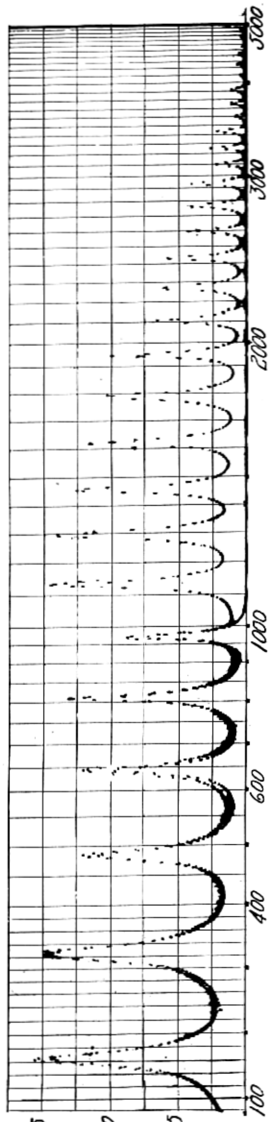

Fig. 12—Record Showing Action of Low Pass Filter

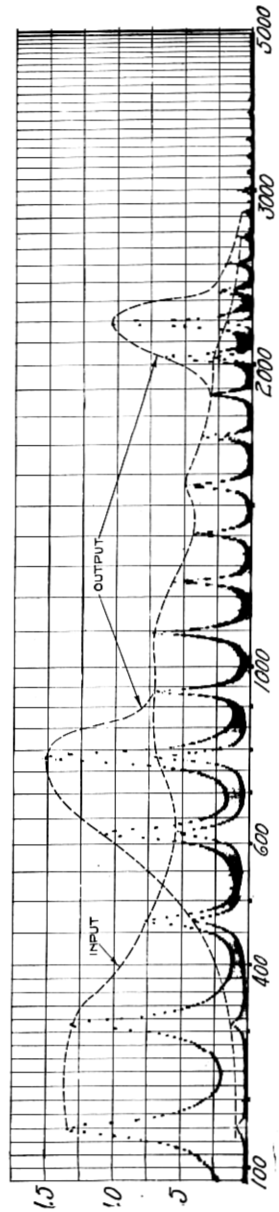

Fig. 13—Records of Electrical Input and Acoustic Output of a Common Type of Loud Speaking Receiver

picked up by a condenser transmitter.[3] The reverberation in the room probably had a large effect on the character of this record. With such a source of frequency the analyzer may be used to study the acoustics of rooms. Fig. 10 is a record of the same noise as in Fig. 9 but as picked up by a common type of telephone receiver placed in the same position as the condenser transmitter. A comparison of Figs. 9 and 10 will show the inadaptability of such a receiver for use as a transmitter. The receiver, owing to the resonance of its diaphragm, is seen to be relatively sensitive in the region of 600 to 800 cycles and insensitive at most other frequencies. When this instrument is placed against the ear, as when used as a receiver, the diaphragm resonance is damped so as to give more nearly uniform response.

By means of the calibration of the condenser transmitter and its amplifier, it is possible to make an analysis of the absolute intensity of a sustained sound in the air. This method has been used to study the frequency characteristics of musical instruments. Fig. 11 shows the analyses of three low-frequency organ pipes. These are plots of r. m. s. pressure change in the sound wave as obtained from the analyzer records. Each vertical line corresponds to a peak on the original record. The upper chart shows the almost pure tone given by a 64-cycle Bourdon pipe. In the case of the cello pipe, also having a fundamental of 64 cycles, the third harmonic is seen to be more prominent than the fundamental or second harmonic. The third chart is for a 128-cycle trombone pipe which was found to be rich in harmonics. The pressure in the single components of the cello and trombone pipes is less than in the case of the Bourdon pipe, and a larger scale of ordinates is therefore used.

To illustrate the use of the attachment which permits the making of two simultaneous analyses, a few double records will be presented. An electric wave filter which has been used in the study of telephone quality was connected to the buzzer source whose output is shown in Fig. 2. Simultaneous analyses of the current delivered to and transmitted through the filter are shown in Fig. 12. This filter is designed to pass all frequencies below 1000 cycles and to suppress all others. The input is represented by a more or less continuous series of peaks along the entire length of the record. The peaks corresponding to the output coincide rather closely with the input

[3] "A Condenser Transmitter as a Uniformly Sensitive Instrument for the Absolute Measurement of Sound Intensity." E. C. Wente, *Physical Review*, July 1917.

"The Sensitivity and Precision of the Electrostatic Transmitter for Measuring Sound Intensities." E. C. Wente, *Physical Review*, May 1922.

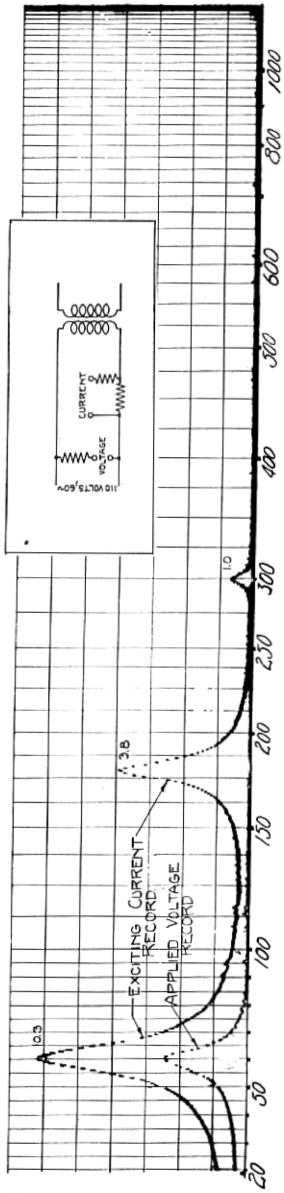

Fig. 14—Record Taken on Transformer at No Load

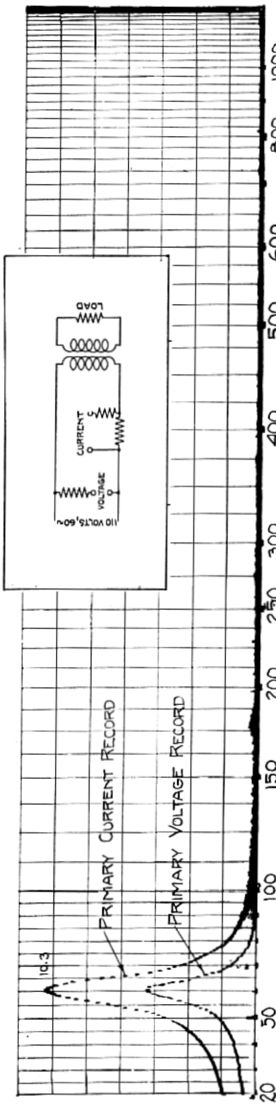

Fig. 15—Record Taken on Transformer Under Load

peaks for all frequencies below 1000 cycles and are not detectable for the higher frequencies.

Fig. 13 is a double record showing the analysis of the wave from a buzzer as fed into a common type of loud speaking receiver and the acoustic output as picked up by a condenser transmitter placed in front of it at a distance of about 15 inches. The analysis of the input current wave to the loud speaker is shown by the comparatively continuously decreasing series of peaks. The acoustic output is represented by the series having maxima in the neighborhood of 800 cycles and 2200 cycles. This record cannot be taken as an adequate analysis of this loud speaker because of probable reverberation effects in the room.

The analyzer has thus far not been used in the study of power problems. A few illustrative records have been taken, however, on transformers and generators and will be shown as suggestive of the use of this method of attack in such problems.

Fig. 14 is a double record showing applied voltage and exciting current of a small 110-volt, 60-cycle transformer operating at normal voltage and frequency under the no-load condition. The presence of the well known third and fifth harmonics in the exciting current is clearly shown. Because of the rise in the calibration curve of the analyzer at the low end of the lower frequency range, a scale of ordinates is not shown on this record. Instead, the values of the analyzer current at each frequency are noted on the record. The circuit used in making this record is drawn on the figure. A computation of the components of the exciting current from the record and constants of the circuit shows that at 60 cycles the current was 175 milliamperes, at 180 cycles, 65 milliamperes and at 300 cycles, 17 milliamperes. The total r. m. s. exciting current was therefore 187 milliamperes.

The operation of this transformer under full load is shown in Fig. 15, where, as before, the primary voltage and current are analyzed. The transformer load consisted of a pure resistance. It will be noted that the third and fifth harmonics have become very small compared with the fundamental. The analyzer currents at each frequency are again noted on the record. In obtaining the analysis of the current it was necessary to further shunt the analyzer. The primary current was 310 milliamperes.

Problems relating to commutation may also be conveniently studied qualitatively and quantitatively by means of the analyzer. The use of an apparatus which will indicate the source and measure the extent of parasitic frequencies is obvious. Information has

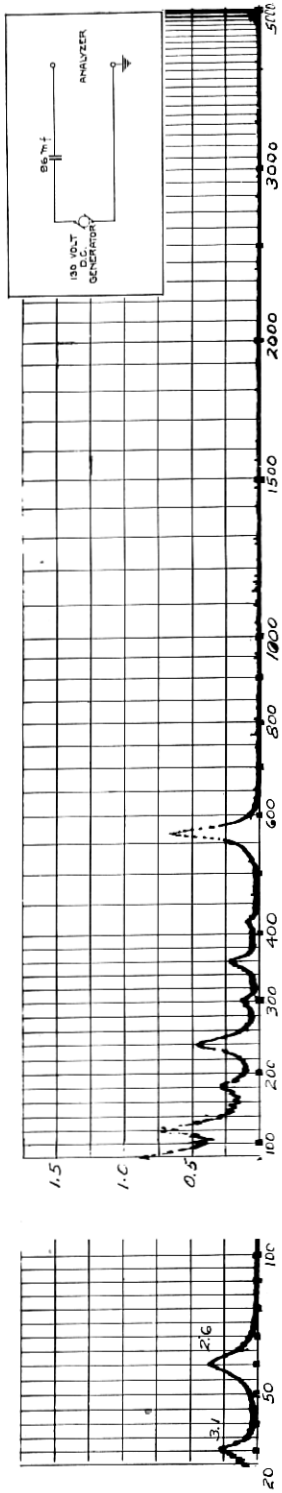

Fig. 16—Record Taken on D. C. Generator at No Load

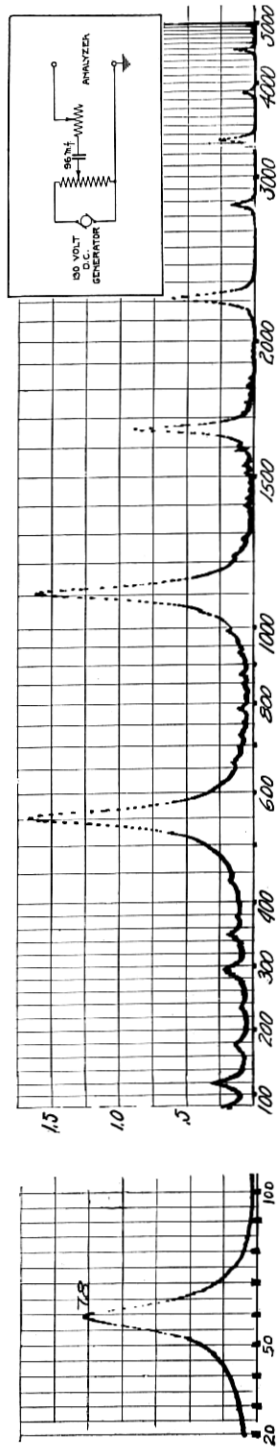

Fig. 17—Record Taken on D. C. Generator Under Load

been obtained on a small machine direct-driven by a ½-h. p., 60-cycle single-phase motor. Data of importance relating to the generator tested are as follows:

Capacity of Generator	¼ kw.
Number of Poles	2
Speed	1725-1800 r. p. m.
Voltage	125
Field	Shunt-connected
Diameter of Commutator	2.75 in.
Number of Commutator Bars	38
Number of Armature Slots	19
Size of Brush	⅜ in. square
Yoke	Ring type

Records obtained from this machine when operating under no-load and half-load conditions are shown in Figs. 16 and 17, respectively. The corresponding speeds are approximately 1800 and 1750 r. p. m. In order to show what frequencies the machine gives out over the entire range 20 to 5000 cycles each figure is made up of two parts: a portion of a 20-1250 record and a complete record over the range 80-5000 cycles. On each figure is drawn the circuit connecting the d-c. generator to the analyzer. It will be noted that a large condenser is inserted to prevent the passage of heavy direct current through the analyzer.

The consideration of these records leads to the conclusion that there are at least three independent major causes of alternating voltage operating in this d-c. machine. The fundamental frequencies due to these causes are 30, 60 and 570 cycles. It will be noted that the 30-cycle peak occurs only on the no-load record under which condition the average speed is practically 30 revolutions per second. Sixty cycles and a series of its harmonic overtones are seen to be present under both conditions of load. Under load the 60 cycles is augmented whereas its harmonics are reduced. No harmonic overtones of 30 cycles except such as might coincide with the harmonics of 60 cycles are found in either case. This indicates the existence of independent causes of the 30 and 60-cycle frequencies, that the 30-cycle cause produces an almost sinusoidal voltage, and that the 60-cycle cause under no load produces an irregular wave which becomes smoother as the machine is loaded.

The no-load record, Fig. 16, shows 570 cycles with no harmonics while the load record, Fig. 17, shows 570 cycles with a complete series of harmonics. This indicates that at no load the cause of 570 cycles feeds a relatively smooth wave to the line while under load this cause feeds an irregular wave to the line. The fact that 1140 cycles is about as strong as the fundamental and that its harmonics are stronger than alternate ones which are overtones of 570 only, suggests the likelihood of a fourth cause having a frequency of 1140 cycles. Small irregularities at frequencies other than those already mentioned occur in the record. These are more prominent under load than at no load and indicate the presence of small, more or less irregular pulses, which increase with load. All of the above frequencies may be accounted for by a consideration of the construction and operating condition of the machine.

The generator was driven by a single-phase, 4-pole, 60-cycle motor which may give rise to torque fluctuations once per revolution, or 30 times per second. Under no load this may produce considerable corresponding fluctuations in speed while under load conditions the generator acts as a damper, eliminating these oscillations.

The 60-cycle peak may be due to any one or some combination of a number of causes, *e. g.*, eccentricity of generator armature, non-uniform winding, non-uniform thickness of mica separators in commutator, high mica between one or more pairs of segments, etc. The records show that for this particualr machine in its present condition (new) at normal speed the 60-cycle voltage developed increases considerably with load indicating strongly that the cause is largely influenced by an IR drop somewhere in the machine. The most likely causes therefore appear to be commutator eccentricity, irregular spacing of the segments, or high mica.

The peak at 570 cycles may be accounted for by cyclic variation of flux entering the armature core as the teeth pass the pole faces. At no load the speed is approximately 1800 r. p. m. The number of teeth being 19, it is obvious that there will be 570 fluctuations of air-gap reluctance per second. Under no-load conditions the record shows a comparatively pure wave form for this cause. This is to be expected because of the comparatively uniform distribution of flux under the pole faces at no load. As the machine is loaded, however, the field is distorted and shifted giving rise to an irregular wave form of voltage which is responsible for at least a part of the large harmonic content shown by the load record.

The presence of 1140-cycle peak which is present only under the load condition may be due to the cyclic variation of voltage produced by the commutator bars leaving the brushes. Inasmuch as the speed is roughly about 29 revolutions per second the frequency with which bars leave brushes is about 1100 cycles. This frequency is present under the load condition only, thus indicating that it is due to an IR drop at the brush contacts or to an e. m. f. developed in the short-circuited coil with the brush off the magnetic neutral.

The very small irregularities on the record shown particularly between peaks above 550 cycles on the load record are probably due to slight chattering of the brushes.

It is of interest to note that the so called frequency of commutation does not appear in either of the records. For this machine this frequency at no load is approximately 346 cycles per second.

From these records it is possible to determine the r. m. s. value of the alternating voltage at any frequency of interest. This is computed from a knowledge of the circuit constants and analyzer impedance. We thus obtain for the 550-cycle peak (Fig. 17) a value of 0.8 volts and for the 60-cycle peak a value of 1.1 volts.

In general the records taken by means of the analyzer on this commutating machine, confirm quantitatively the well known fact that such machines may give rise to frequencies in the audible range. Consideration of the records indicates that these frequencies may be divided into two classes: First, those pertaining to and controlled by design, and second, those caused and controlled by the physical condition of the machine at any particular time. It is also interesting to note that the driving motor may produce an appreciable effect, particularly under the no-load condition.

Summary

In the above paper there has been given a short statement of the theory and construction of an automatic, recording, electrical frequency analyzer, together with illustrations showing its use and limitations in various fields.

This apparatus has been found very useful in the laboratory in the investigation of many different types of problems chiefly because of the speed with which records can be made and harmonic analyses obtained without computation.

In conclusion the authors wish to express their appreciation to Mr. C. E. Lane and Mr. C. E. Dean, of the Western Electric Company, Inc., for their assistance in the building of this machine and the preparation of this paper.