AN INVESTIGATION OF CIRCUIT CONNECTIONS AND CORE MATERIALS FOR MAGNETIC DETECTORS

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PREFACE

Numerous instruments have been constructed and employed to record variations of the earth's magnetic field due to natural or artificial disturbances. There have been very little data recorded that will provide adequate information for comparing magnetic detector circuits and core materials when considering them for a prescribed use. In search for this type information, Professor David L. Johnson concluded there was a definite need for compilation of data to make possible these comparisons. The author's intent was to make available this information to engineers who may be interested in the design and construction of magnetic detection equipment.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Professor David L. Johnson for his guidance and interest in the preparation of this thesis. He also wishes to extend thanks to his friends, who assisted in the procuring of equipment and to those who offered suggestions and criticism.

The author also wishes to acknowledge the assistance and encouragement given him by his wife, Evelyn, who helped greatly in the typing and preparation of this manuscript.

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CHAPTER I

INTRODUCTION

Socrates states in Ion that the mineral lodestone, a natural magnet, will support a chain of iron rings, each held to the one above it by magnetic attraction.[1] Before Socrates time this mysterious mineral was known to attract iron and other pieces of like mineral. Shen Kua indicated in his writings[2] some knowledge of the property of a magnetic needle indicating direction. He lived from A.D. 1030 to A.D. 1093. Since these discoveries of the characteristics of magnets, many theories, most of which have been mysterious in nature, have been advanced. The modern theory of magnetic fields has made possible the development of magnetic detection equipment. The most recently developed detector is one known as the saturable-core magnetometer.[3] The saturable-core magnetometer detects changes in the earth's magnetic field. The earth's magnetic field can be visualized by assuming the north and south magnetic poles to be points of references for orienting a very large bar magnet. This field varies in intensity from 25,000 gammas (1 gamma = 10^{-5} oersted) at the magnetic equator to 65,000 gammas at the magnetic poles. The observations conducted

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1 R.M. Bozarth, "Magnetism," <u>Reviews of Modern Physics</u>, (1947) pp. 30-31.

2 <u>Ibid</u>., p. 30.

3 W.E. Tolles, "Application of the Saturable-Core Magnetometer," <u>Proceedings of the National Electronics Conference</u>, III (1947), pp. 504-513.

in the recording of the included data were made in an area with an earth's magnetic field intensity of approximately 55,000 gammas.[4] The presence of an external magnetic field in the earth's field causes the net field to be increased or decreased in intensity dependent upon the nature of the external field. This disturbance of the earth's field, referred to as an anomaly, is directly proportional to the magnitude of the external field's vector and inversely proportional to the cube of the distance between the point of observation and the point of application of the external field. The point of observation would be the location of the magnetometer in the earth's field. The earth's field would have a particular field vector value dependent upon its direction and magnitude at the point. The magnetometer detects and records any disturbance present.

The purpose of this investigation was to determine the best independent uses and the best combination uses of the three types of known saturable-core magnetometer circuits and the four locally available core materials.

A brief description of the analytical and graphical solution for the iron-clad inductor circuits is included, to provide an approximate solution, which can be used to facilitate design of saturable-core magnetometers. Because of the difficulty encountered when approaching this type of problem, complete analysis is practically impossible. If characteristic

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4 Carnegie Institution of Washington, The Geomagnetic Field, Its Description and Analysis, p. 20.

curves of the core material are plotted, theoretical predictions are possible.[5]

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5 Massachusetts Institute of Technology Electrical Engineering Staff, <u>Electric Circuits</u>, (1943), pp. 670-671.

CHAPTER II

REVIEW OF LITERATURE

A. The Saturable-Core Inductor.

The saturable-core inductor was patented by Alexanderson in 1916. It has been used as the technical basis for the development of the saturable-core magnetometer, which has been developed in the basic forms of: a single magnetometer unit, narrow or wide-base gradiometer, self-stabilized magnetometer and the combination of self-stabilized magnetometers.[1] The magnetic amplifier, Sperry flux valve, Bendix flux gate, and the Thomas and La Pierre compasses are other instruments employing saturable-core inductors.

The saturable-core reactor used in the magnetometer circuits is a magnetic core with many turns of wire wound about it. High initial permeability, abrupt saturation when the magnetic field reaches a certain value and low hysteresis loss are required characteristics of the core material. The magnetizing force H is directly proportional to the number of turns in the coil and the current I flowing in the coil. The product of the flux density B and the cross-sectional area A of the core gives the magnetic flux.

In the core of the saturable-core reactor, a large flux increase is observed with the first small increase of current through the coil surrounding it. This increase in flux becomes

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1 W.E. Tolles, "Applications of the Saturable-Core Magnetometer," Proceedings of the National Electronics Conference, III (1947), pp. 504-513.

smaller as the current is increased until the core reaches a point of saturation, where very large increases of current are required to give small increases in the flux. This point of saturation is an individual property of different types of core materials. The core material is saturated when there is very little flux increase regardless of the current increase. The core used in magnetometer circuits must show large increases in flux for relatively small changes of current at first, but must soon reach the saturation point where large increments of current cause little further increase in flux.

B. Magnetometer Circuits And Their Characteristics.

The simplest magnetometer circuit is the basic magnetometer circuit[2] shown in Figure 1. The reactor behaves like an almost pure inductance as long as core saturation is not reached. If the applied voltage is increased until the point of saturation is reached, the inductive reactance becomes negligible and the circuit becomes predominantly resistive. To permit this condition the generator should have high internal impedance, sinusoidal output and sufficient current. The current rises abruptly at the point of saturation, its magnitude being limited by the series resistance. As the applied voltage is decreased the point of saturation is again reached and the core goes out of saturation. At this point the circuit abruptly becomes inductive and the current decreases. The $L = N \frac{d\phi}{dt}$ is greater over the straight portion of the curve than it is after the point of saturation is reached. This can be observed from the B-H curve, Figure 2. The Ri drop has the effect on the transient state condition of governing the maximum current flow. The resistance has the effect on the steady state of determining the amount of time required for the circuit to reach the steady state

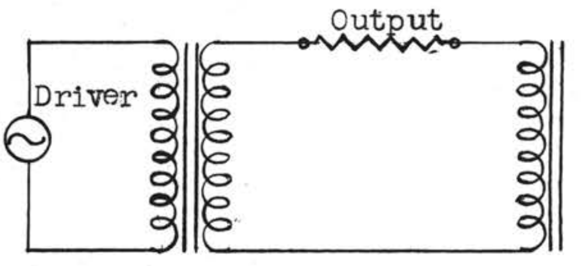

Figure 1. Basic Magnetometer Circuit.

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2 Tolles, op.cit. pp. 505-506.

condition.

The presence of an external magnetic field causes the core to become biased and the applied sinusoidal voltage appears distorted across the load resistance. This occurs because the external field aids the internal field on one-half of the cycle of the applied voltage and opposes it on the other one-half of the cycle. Saturation is reached earlier during the half cycle in which it aids, later during the half cycle in which it opposes. The distortion across the load resistor appears as nonsymmetrical wave shape and can be detected, amplified and used to produce an indication on a meter or other indicating device.

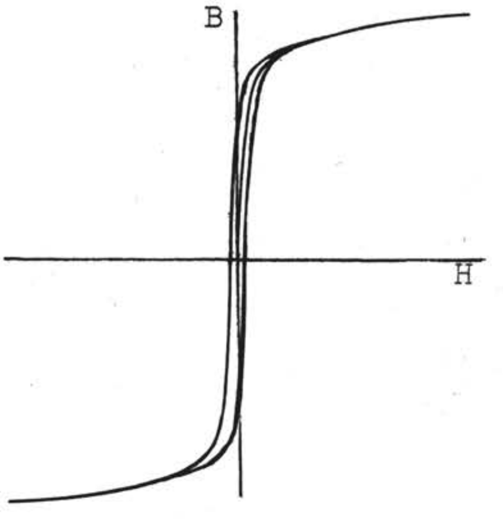

Figure 2. Magnetization Curve and Hysteresis Loop.

A balanced-bridge magnetometer circuit[3] may be made by arranging two identical basic magnetometer circuits so that the secondaries of the input transformer and the magnetometer elements form a balanced-bridge circuit. This circuit is illustrated in Figure 3. The magnetometer elements must be symmetrically located on the core. If the external field is zero and the core

3 Tolles, op. cit., pp. 506-507.

and coils are perfectly balanced, the voltage output across the load resistor is equal to zero. Pulses of current are present in the load resistor if an external field is present because the bridge circuit becomes unbalanced. The voltage output across the load resistor will indicate a voltage difference that increases with the external field strength. This voltage difference appears as pulses and is nonsymmetrical about the zero axis which indicates the presence of even harmonics.

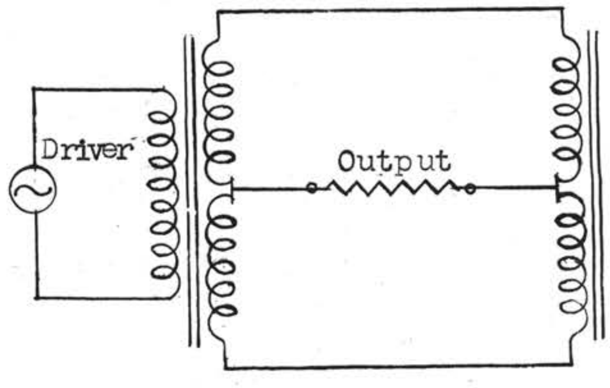

Figure 3. Balanced-Bridge Magnetometer.

The bridge type magnetometer circuit has the advantage of being very sensitive in comparison with the basic magnetometer circuit.

An unbalanced-bridge type circuit may be formed by connecting a resistance in series with, or across one leg of, the balanced-bridge circuit. One form of this bridge is indicated in Figure 4. This circuit provides a lower noise level than the balanced-bridge circuit.[4]

4 Tolles, op. cit., pp. 506-507.

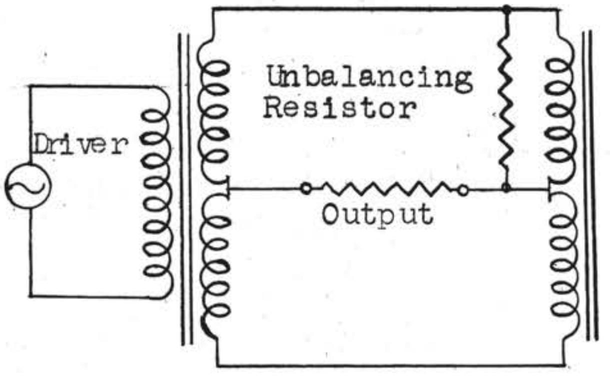

Figure 4. Unbalanced-Bridge Magnetometer.

C. Characteristics of Core Materials.

Rapid growth of the radio and communications field has required the development of core materials with specific characteristics. The characteristics of those required for uses in magnetometer circuits are: high initial permeability, low hysteresis loss, low loss from eddy currents, maximum permeability, reduced coercive force, and low magnetostriction effects.[5,6]

Ordinary magnetic materials show slow increases of initial permeability with temperature increases up to the Curie point where the permeability suddenly decreases. The Curie point is lowered by the addition of non-magnetic materials, such as molybdenum, copper or chromimum, to the alloy.[7] Using proper techniques, initial permeability can be increased, but often with the consequence of mechanical stresses or large eddy current shielding.

Low hysteresis loss may be accomplished by proper alloying and sufficient heat treatment. The magnitude of this loss is indicated by the B-H curve, commonly called the hysteresis loop. This curve shows the peak values H_m, the flux density remaining after the removal of a very large magnetization force B_r, and

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5 "Magnetic Materials," Electronics Buyers Guide, June, Mid-month XXI (1948), p. M20.

6 V.E. Legg, "Survey of Magnetic Materials and Applications in the Telephone System," Bell Telephone System Journal, XVIII, 1939, pp. 438-461.

7 G.W. Elmen, "Magnetic Materials," Bell Laboratories Record 10, II, 1931, pp. 40-46.

the reverse magnetizing force required to bring the flux to zero, which is coercive force H_c. If the core material is caused to go from positive magnetic saturation to negative magnetic saturation and back again, the energy dissipated is indicated by the area of the hysteresis loop. Figure 2 illustrates a hysteresis loop.

Eddy currents may be suppressed by lamination or pulverization of the core material and addition of molybdenum or chromium[8] to the alloy. The addition of these elements causes the resistivity of the material to be increased. Their uses are limited to resistivities of less than 60.

Maximum permeability may be had by proper treatment of the material. The addition of nickel accompanied by magnetic anneal increases the permeability. The magnetic anneal is accomplished by magnetizing the material several oersteds during the annealing process, keeping the temperature 400° to 600° centigrade.[9]

Reduced coercive force also results from the magnetic annealing. Coercive force is a function of mechanical strain and the heat during anneal relieves these strains.

Magnetostriction is a term used to relate magnetization and the change of length of a material. A large amount of nickel will reduce this effect to a negligible amount.[10]

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8 Ibid., pp. 40-46.

9 Electronics Buyers Guide, loc. cit.

10 Ibid., p. M20.

A large number of alloys possessing the requirements outlined have been developed. Those most widely used in magnetometer apparatus are: Permalloy, Permalloy 4-79, Supermalloy and Mu Metal.[11] Because these four materials were available, they were used to perform the test for this investigation.

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11 Stephen S. Atwood, Electric and Magnetic Fields, 3d Edition, pp. 325-355.

CHAPTER III

THE INVESTIGATION

A. Introduction.

Because the object of this investigation was to determine the characteristics of the different combinations of the three known saturable-core circuits and the four locally available core materials, it was decided to investigate various combinations of conditions and to record the results of significant changes of conditions by means of oscillograms, with the respective conditions recorded in tabular form.

The investigation was conducted with the three known circuits acting as the main basis for test with a number of other conditions varied.

The basic magnetometer circuit was the first one investigated. The variable conditions included were load resistance, frequency of driver voltage, core material and external magnetic field intensity.

The balanced-bridge magnetometer circuit was the second one investigated. The variable conditions were the same as those for the basic magnetometer circuit.

The third circuit investigated was the unbalanced-bridge magnetometer. The variable conditions were load resistance, frequency of driver voltage, core material, external magnetic field intensity and unbalancing resistance.

The driver voltage was kept constant at a value of twenty-five volts across the secondary of the balanced input transformer. This voltage was chosen because it was the optimum value in that it was the highest value that could be maintained at all frequencies used without causing saturation of the unbalanced input transformer.

B. Magnetic Detector Circuits.

The three magnetic detector circuits investigated were the basic magnetometer, the balanced-bridge magnetometer and the unbalanced-bridge magnetometer. These three circuits were used as the basis for investigation with other conditions varied to permit comparison of the circuit characteristics for each set condition. Conditions were set up, readings recorded in the table, comments noted and oscillograms taken for each condition that gave an indication sufficient to determine any of the operating characteristics of the circuit under test.

The first circuit investigated was the basic circuit. Secondary voltage of the input transformer was kept at a constant value of twenty-five volts for all readings. The four core materials available were interchanged for each set condition to determine the effect of core material on circuit characteristics. The frequencies used to determine the changes in sensitivity with a frequency change were between 200 and 2000 cycles per second. The load resistance value was changed to evaluate the optimum load range. The values used were 150 ohms, 1500 ohms, 15,000 ohms and infinite resistance. Each combination of the listed variables was checked for sensitivity by changing the value of the external field. The values used were zero and 13,274 gammas, in addition to any magnetic field force of the earth. This odd value was calculated for 1500 milliamperes flowing through the Helmholtz coils. The basic circuit is known to be the least sensitive of the three known circuits. For this investigation it was used to permit a basis of comparison for the other two circuits. The circuit diagram is illustrated in Figure 5.

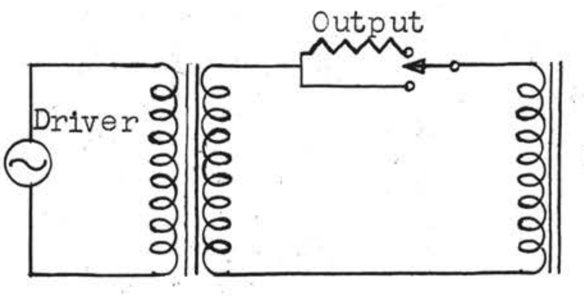

Figure 5. Basic Magnetometer With Variables.

Two basic circuits were connected in a balanced-bridge arrangement to get the balanced-bridge magnetometer. The conditions varied were the same as those varied in the basic circuit. This circuit is shown in Figure 6. The balanced-bridge circuit is a more sensitive circuit than the basic circuit, but requires more components to construct. The components required must be well matched to permit balance.

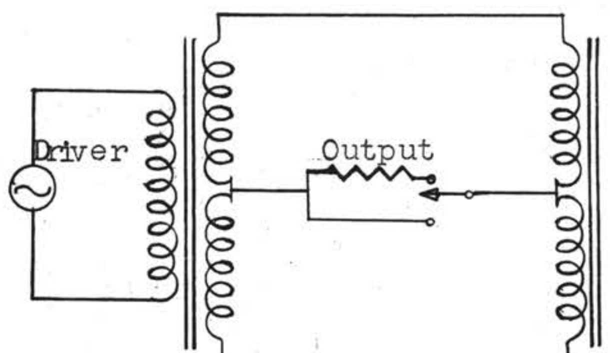

Figure 6. Balanced-Bridge Magnetometer with Variables.

The unbalanced-bridge magnetometer employes the bridge circuit similar to the balanced-bridge except that one leg of the bridge is caused to become unbalanced, which causes the voltage across the load resistor to be unsymmetrical. This circuit may be unbalanced by inserting a resistance in series with one of the bridge legs, by shunting one side of the secondary of the input transformer with a resistance or by shunting one of the magnetometer coils with a resistance. The circuit used is indicated in Figure 7. This circuit is also more sensitive than the basic circuit. Of the three circuits, it has the disadvantage of requiring the greatest number of components. To permit best calibration this circuit should be constructed from well balanced components but this requirement is not as essential as it is with the balanced-bridge magnetometer.

Unbalancing Resistors a,b,c.

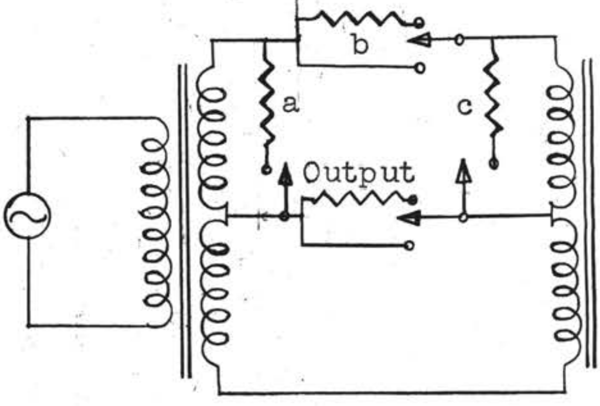

Figure 7. Unbalanced-Bridge Magnetometer with Variables.

C. Magnetic Core Materials.

The magnetic core materials investigated were Permalloy, Permalloy 4-79, Supermalloy and Mu Metal. All of these materials possess the requirements essential for use in magnetometer circuits. They are nickel-iron alloys ranging from 35 per cent to 90 per cent nickel.

The Permalloy used here is of the 45 Permalloy type. This material shows the highest values for residual flux density. The addition of chromium, copper or molybdenum to this material increases its resistivity which controls the eddy current loss.

Permalloy 4-79 shows lower values of residual flux density, B_r and H_c. Its resistivity values are not high enough for some applications[1] but are usable ones in magnetometer circuits.

Supermalloy has the characteristics of high initial permeability, high H_m and low H_c. This material is annealed in the presence of hydrogen gas at 1300°C. [2]

Mu Metal has the characteristic of low values of residual flux densities, B_r. It is annealed at 900°C and then quenched.

The following table[3] shows the material, composition and characteristics of the four alloys used to perform this investigation.

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1 W.E. Rudder, "New Magnetic Materials," Proceedings of I.R.E., October 1942, pp. 437-440.

2 Stephen S. Atwood, Electric and Magnetic Fields, 3d Edition, p. 346.

3 V.E. Legg, "Survey of Magnetic Materials and Applications in the Telephone System," Bell Telephone System Journal, XVIII, 1939, p. 440.

TABLE 1

Magnetic Material	Chemical Composition					Initial Perme-ability (Oer-steds)	Maximum Perme-ability H_m (Oer-steds)	Satura-tion (Gauss)	Resi-dual Flux Densi-ty B_r from 10000 Gauss	Coer-cive Force H_c (Oer-steds)
	Ni	Fe	Mo	Cu	Mn					
Permalloy	45	54.4		.2	.6	2500-2700	23000-25000	16500	8000	.3
Permalloy 4-79	79	16.4	4		.6	22000	72000	8500	4500	.05
Super-malloy	79	15	5		.5	125000	800,000-1,000,000	8000	-	.05-.07
Mu Metal	74	20		5	1	7000-25000	80000-110000	8500	2300-6000	.05-.06

D. Description of Equipment Used.

The apparatus containing the magnetometer coils and core materials was constructed by the author. Figure 8 shows a working diagram of the coil arrangement. The magnetometer coils were precision wound and of local manufacture. Their characteristics were: Coil number 1 had a resistance of 96 ohms, an inductance of 2.38 millihenrys and 3000 turns; coil number 2 had a resistance of 96.3 ohms, an inductance of 2.38 millihenrys and 3000 turns.

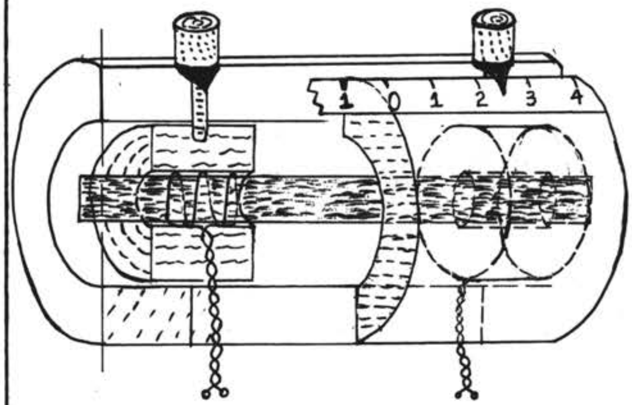

Figure 8. Magnetometer Coils Arrangement. Cutaway Assembly Drawing.

The balanced push-pull input transformer was made by the Audio Development Company at Minneapolis 7, Minnesota. It was transformer number 40604 ADC 14. The primary had 20,000 ohms impedance and the secondary had 250 ohms impedance each side of center tap.

The Helmholtz coils mounted on the chassis were arranged by using two U.S.A.F. airborne type radio compass loops. Each loop had eight turns of wire wound on a form with a radius of ten centimeters. The Helmholtz arrangement consists of two coils, of identical construction, placed vertically radius distance apart.[4] This generates a very uniform field some distance either side of the mid-point between the coils, if a current is caused to flow through the coils. The magnetic intensity[5] at the mid-point can be expressed as:

$$H = \frac{32\pi i}{5^{3/2}\, a\, 10} = \frac{2.86\,\pi i}{10\, a}$$

where H is in oersteds
i is in amperes
a is in centimeters

Table 2 shows the values used.

TABLE 2

i in milliamperes	H in oersteds	H in Gammas
250	.0221	2210
750	.0664	6647
1000	.0885	8850
1500	.1327	13270
4600	.4071	40710

The values of current were obtained by adjusting a rheostat in series with a standard cell, a milliammeter and both loops. These loops and the holder for the magnetometer coils may be observed in Figure 10.

The signal generator was locally manufactured. It generated a sine wave at frequencies from 20 c.p.s. to 3500 c.p.s. with sufficient voltage output to maintain 25 volts across the secondary of the balanced transformer. The output of the generator was fed to a push-pull voltage amplifier the output of which was passed through a twin -T[6] sharp-cutoff filter adjusted

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4 Golding, Electrical Measurements and Measuring Instruments, pp. 31-32.

5 Page and Adams, Principles of Electricity, p. 269.

6 Valley and Wallman, Vacuum Tube Amplifiers, Radiation Laboratory Series, Volume XVIII, 1st Edition, 1948. pp.387-388.

to remove a 60 c.p.s. component interference. The push-pull amplifier and the twin-T filter were both of local manufacture.

The voltage across the secondary of the balanced push-pull transformer was read on a vacuum-tube audio voltmeter RCA type WV-73A.

The resistors were precision, tublar, carbon type.

Four magnetic core materials were used. Their characteristics were explained in part C of this chapter.

Observations were made on a Dumont Cathode Ray Oscilloscope Model 250 H. The Oscillograms were made with a Dumont camera connected to a hood designed to fit the Dumont C.R.O.

E. Test Procedure.

The procedure used in this investigation was as follows:

1. Connect the desired circuit.
2. Set the signal generator to the desired frequency.
3. Adjust the generator output to produce 25 volts across the secondary of the balanced push-pull transformer as indicated by the RCA vacuum-tube voltmeter.
4. Insert the desired core material with the magnetometer coils at the zero position.
5. Check various positions of the magnetometer coils to observe any change in output waveform as indicated on the C.R.O.
6. Connect the d-c source to start current flow through the Helmholtz coils to produce magnetic fields. This current was varied to observe changes, if any.
7. Adjust the C.R.O. for proper settings.
8. Take the picture of the waveform.
9. Disconnect this circuit and reconnect the next desired circuit to perform a similar test on it. This may consist of only a change of load resistance value or in some cases a complete change of circuit types. This information is indicated in the table of data.
10. Repeat steps 2 through 8 for the new circuit.

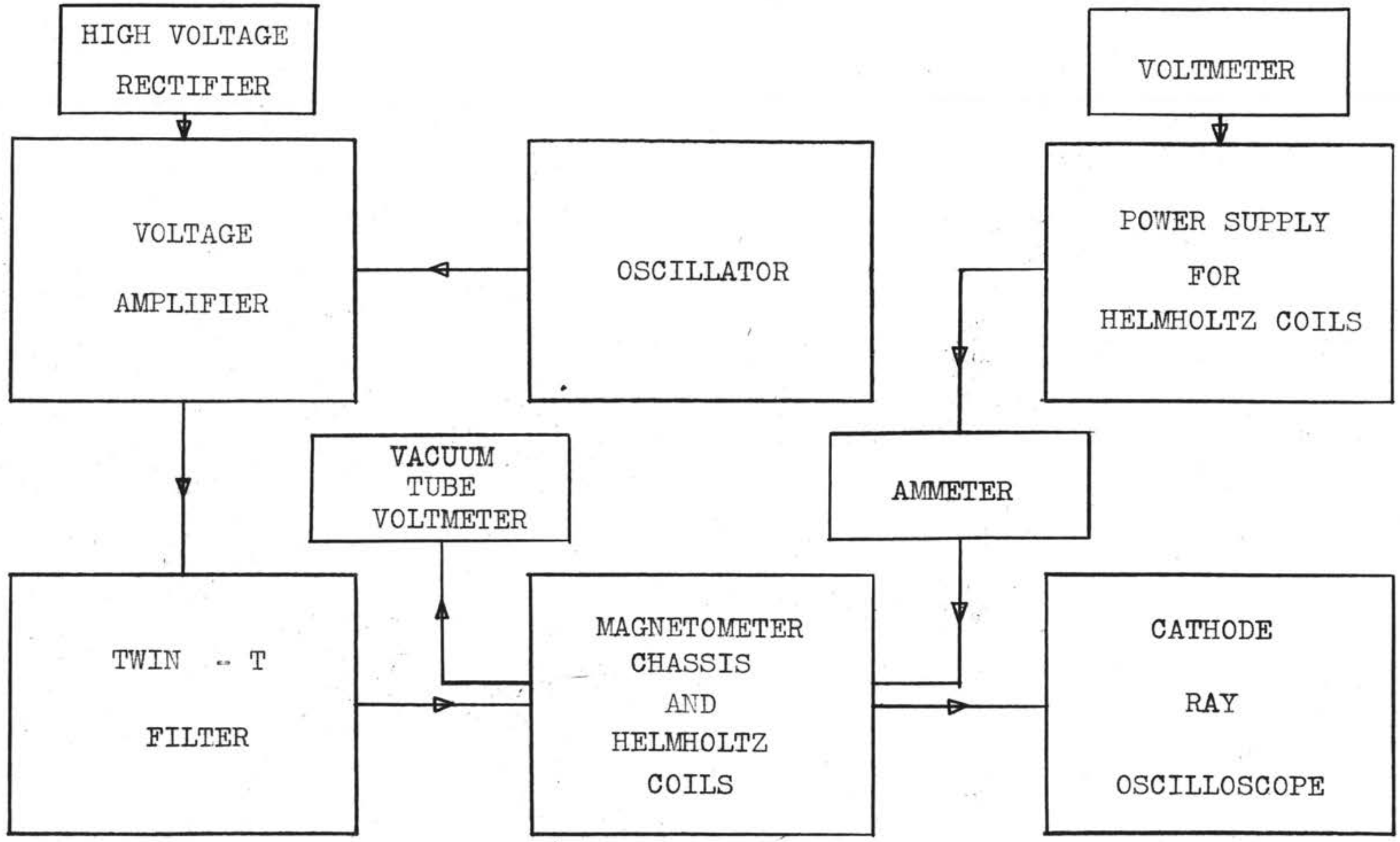


Figure 9. Block Diagram of Test Equipment

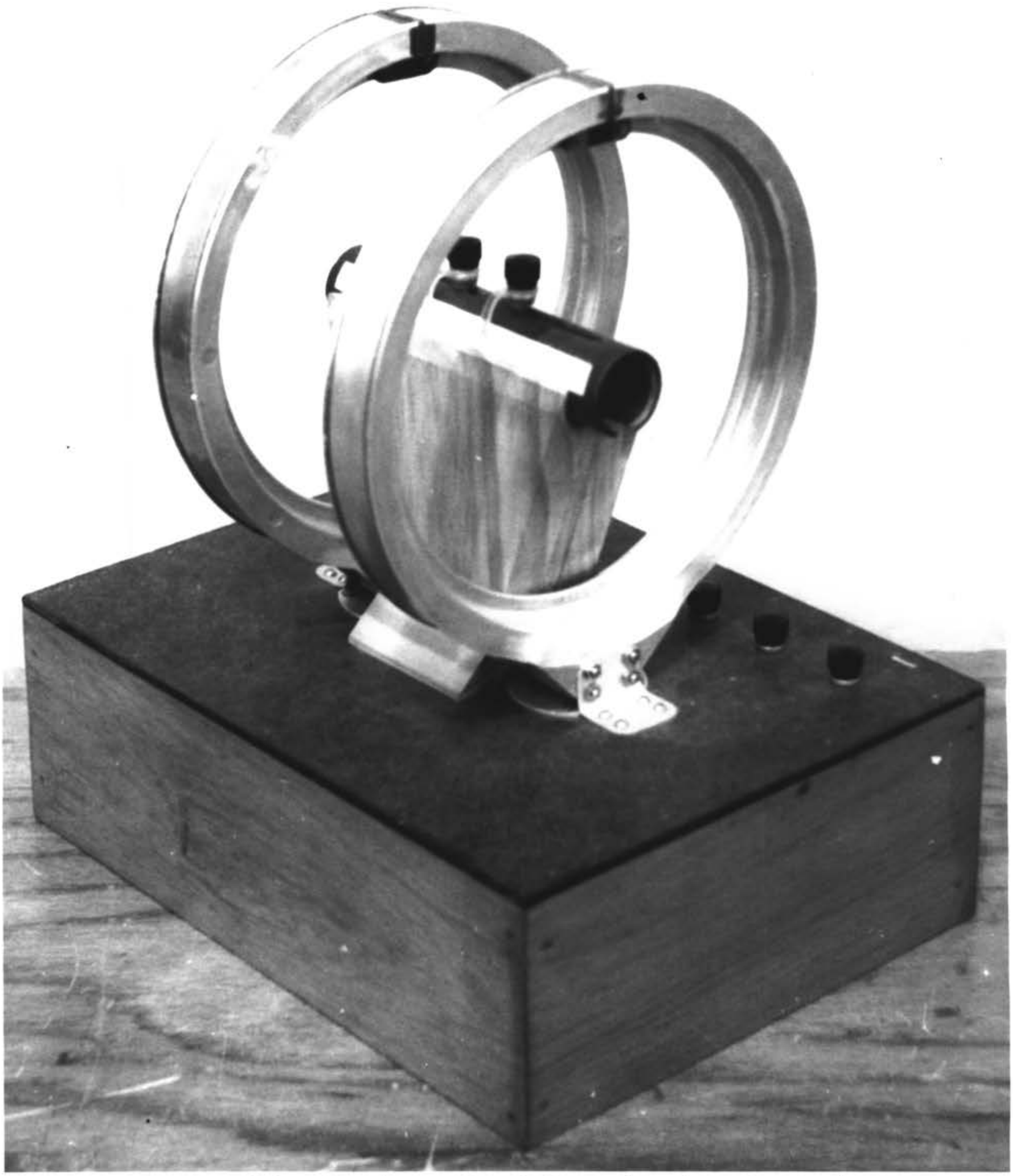


Figure 10. Photograph of Magnetometer Apparatus and Helmholtz Coils.

F. Data.

The data listed in the following table are those used by the author in conducting the investigation. The oscillograms that follow this table indicate any change of importance, as observed by the author.

KEY TO TABLE

	Numbers Assigned
Circuits	
Basic	1
Balanced-Bridge	2
Unbalanced-Bridge	3
Load Resistance Values	
150 Ohms	1
1500 Ohms	2
15000 Ohms	3
Infinite Resistance (Open Circuit)	4
Zero-Resistance (Short Circuit)	5
One Ohm	6
60 Ohms	7
100 Ohms	8
300 Ohms	9
3000 Ohms	10
Frequencies	
200 c.p.s.	1
300 c.p.s.	2
600 c.p.s.	3
700 c.p.s.	4
1000 c.p.s.	5
2000 c.p.s.	6
Core Materials	
Permalloy	1
Permalloy 4-79	2
Supermalloy	3
Mu Metal	4
Magnetic Fields Generated by Helmholtz Coils	
Zero Gammas	1
177 Gammas	2
442 Gammas	3
708 Gammas	4
885 Gammas	5
1327 Gammas	6
13270 Gammas	7

KEY TO TABLE

(Continued)

Points of Voltage Reading by C.R.O. - Oscillogram Component	Numbers Assigned
Load Resistance	1
Magnetometer Coil	2
Secondary of Balanced Transformer (c.t. to lead)	3

Magnetometer coil positions were read directly from the scale shown in Figures 8 and 10.

The voltage across the secondary of the balanced transformer (c.t. to lead) was held constant at 25 volts.

TABLE 4

TABLE OF DATA

OSCILLOGRAM NUMBER	CIRCUIT NUMBER	LOAD RESISTANCE NUMBER	FREQUENCY NUMBER	CORE MATERIAL NUMBER	MAGNETIC FIELD NUMBER	OSCILLOGRAM COMPONENT NUMBER	COIL POSITION NUMBER	CRO Y' GAIN NUMBER	CRO ATTENUATOR NUMBER
1	1	1	1	4	1	1	0	30	100-1
2	1	1	3	4	1	1	0	20	100-1
3	1	2	1	4	1	1	0	30	100-1
4	1	1	1	4	1	3	0	30	100-1
5	1	4	1	4	1	2&3	0	40	100-1
6	1	1	1	4	7	3	0	30	100-1
7	1	1	1	4	1	1	0	30	100-1
8	1	1	1	3	1	1	0	30	100-1
9	1	1	1	2	1	1	0	30	100-1
10	1	1	1	1	1	1	0	30	100-1
11	1	1	1	4	7	1	0	30	100-1
12	1	1	1	3	7	1	0	30	100-1
13	1	1	1	2	7	1	0	30	100-1
14	1	1	1	1	7	1	0	30	100-1
15	2	4	1	4	3	1	0	60	100-1
16	2	4	1	4	4	1	0	60	100-1
17	2	4	1	4	2	1	0	60	100-1
18	2	1	1	4	3	1	0	30	100-1
19	2	3	1	4	3	1	0	30	100-1
20	2	3	1	4	3	1	0&3	30	100-1
21	2	3	1	4	3	1	0&3	30	100-1
22	3	4	1	4	3	1	0	30	100-1
23	3	4	1	4	4	1	0	30	100-1
24	3	4	1	4	2	1	0	40	100-1
25	3	1	1	4	3	1	0	40	100-1
26	3	3	1	4	3	1	0	40	100-1
27	3	3	1	4	3	1	0&3	40	100-1
28	3	3	1	4	3	1	0&3	40	100-1
29	3	4	1	4	3	1	0	40	100-1
30	3	4	1	4	3	1	0	40	100-1
31	3	4	1	4	4	1	0	40	100-1
32	3	1	1	4	2	1	0	40	100-1
33	3	4	2	1	3	1	0	40	1-1

TABLE 4

(CONTINUED)

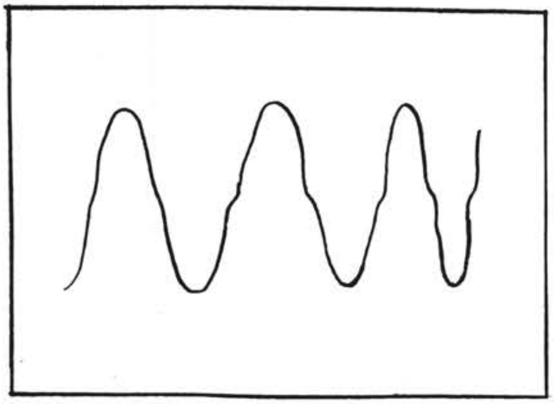
OSCILLOGRAM NUMBER	CIRCUIT NUMBER	LOAD RESISTANCE NUMBER	FREQUENCY NUMBER	CORE MATERIAL NUMBER	MAGNETIC FIELD NUMBER	OSCILLOGRAM COMPONENT NUMBER	COIL POSITION NUMBER	CRO Y' GAIN NUMBER	CRO ATTENUATOR NUMBER
34	3	4	2	2	3	1	0	40	1-1
35	3	4	2	3	3	1	0	40	1-1
36	3	4	2	4	3	1	0	40	1-1
37	3	4	3	4	3	1	0	40	10-1
38	3	4	5	4	3	1	0	40	10-1
39	3	4	6	4	3	1	0	40	10-1
40	2	4	3	4	3	1	0	30	10-1
41	2	1	3	4	3	1	0	50	1-1
42	3	4	3	4	3	1	0	60	10-1
43	3	5	2	4	3	1	0	20	1-1
44	3	5	2	4	3	2	0	60	10-1
45	3	6	2	4	3	1	0	100	1-1
46	3	7	2	4	3	1	0	100	1-1
47	3	8	2	4	3	1	0	100	1-1
48	3	9	2	4	3	1	0	100	1-1
49	3	10	2	4	3	1	0	40	1-1
50	3	10	2	4	3	2	0	60	10-1
51	3	4	2	4	3	1	0	30	1-1
52	3	4	2	4	3	2	0	60	10-1
53	3	4	2	4	3	1	0	60	10-1
54	3	4	2	4	3	1	0	60	10-1
55	3	4	2	4	3	1	0	60	10-1
56	3	4	2	4	3	1	0	60	10-1
57	3	4	2	4	3	1	0	60	10-1
58	3	4	2	4	3	1	0	60	10-1
59	3	4	2	4	3	2	0	40	10-1
60	3	4	2	4	3	2	0	40	10-1
61	Calibration Oscillogram - Peak to Peak 10 Volts								10-1
62	3	4	4	4	1	1	0	90	10-1
63	3	4	4	4	3	1	0	90	10-1
64	3	4	4	4	5	1	0	90	10-1
65	3	4	4	4	6	1	0	90	10-1

G. Oscillograms.

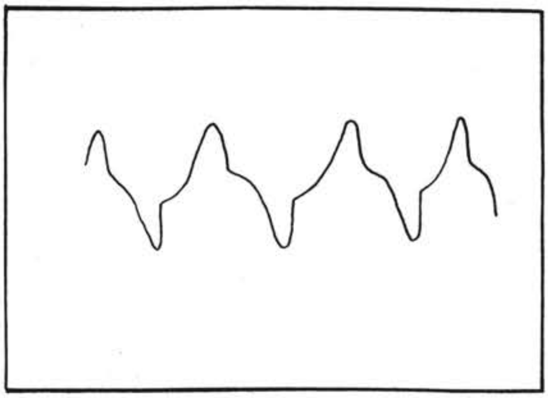
The following oscillograms are numbered according to the oscillogram number listed in the table of data.

The oscillograms pictured in this thesis are tracings made from negative prints. Every measure possible was taken to assure that the retracing did not alter the proportions of the oscillogram pulses in shape, height or width. Since these are the comparative dimensions all information of value has been retained.

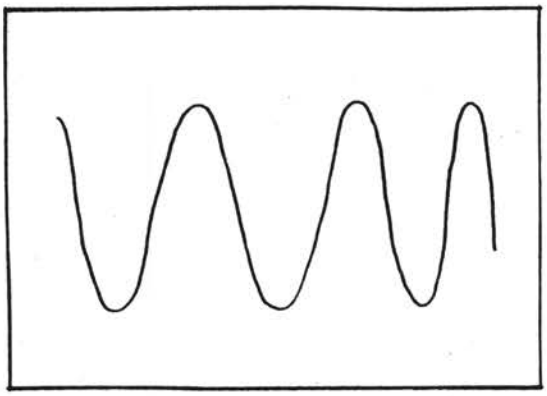
OSCILLOGRAMS



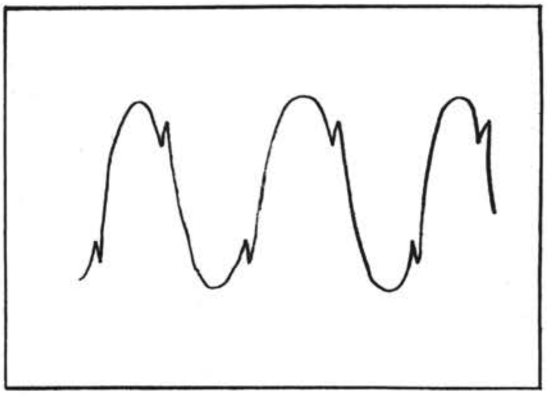
OSCILLOGRAM 1



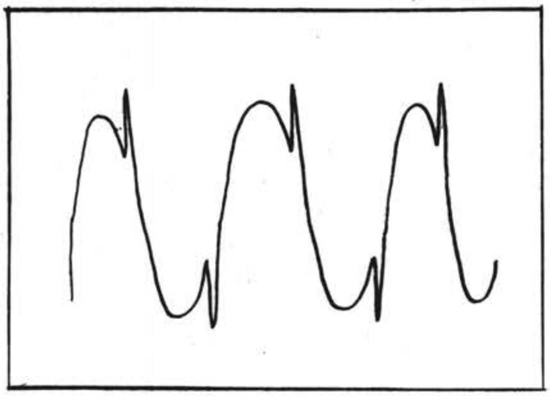
OSCILLOGRAM 2



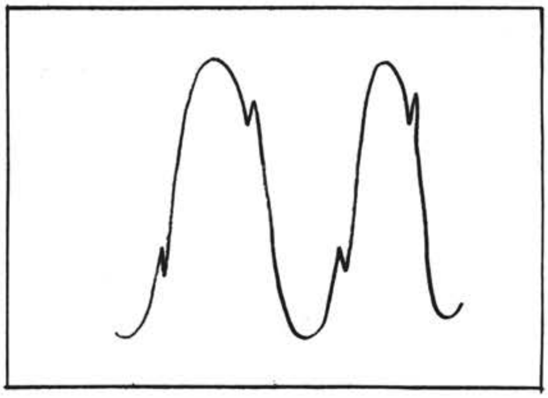
OSCILLOGRAM 3



OSCILLOGRAM 4

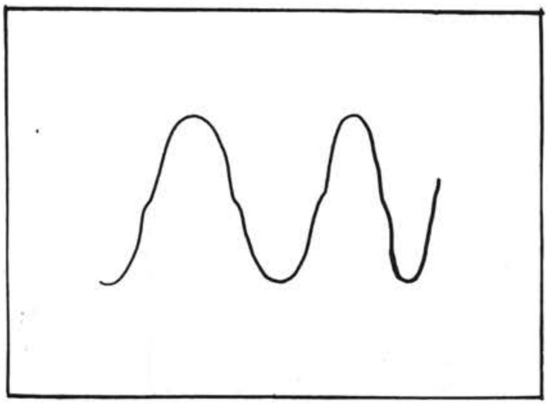


OSCILLOGRAM 5

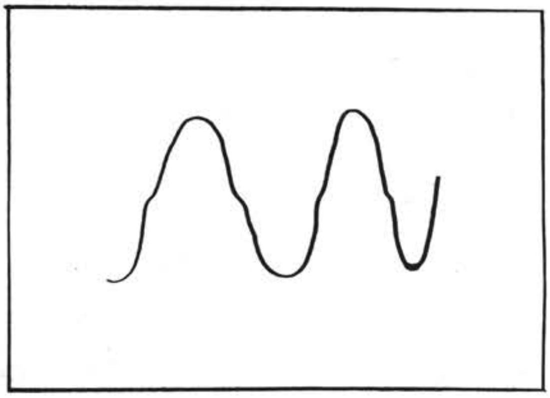


OSCILLOGRAM 6

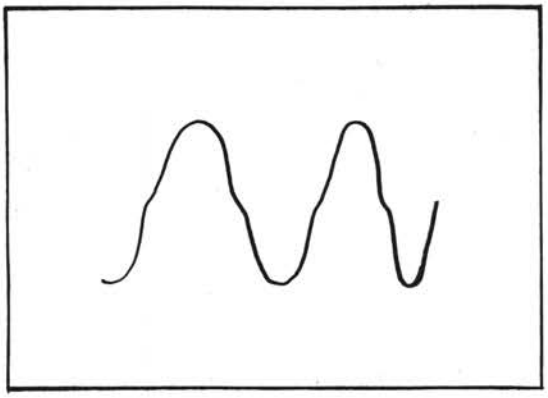
OSCILLOGRAMS (Continued)



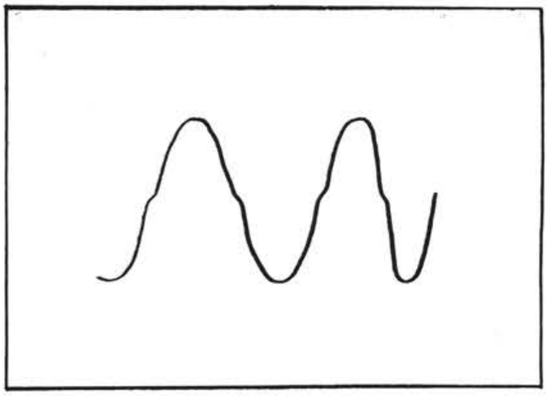
OSCILLOGRAM 7



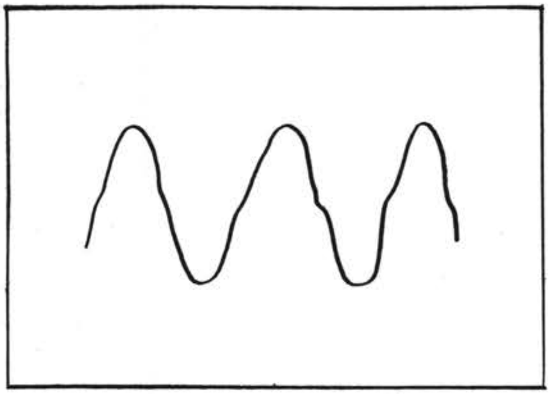
OSCILLOGRAM 8



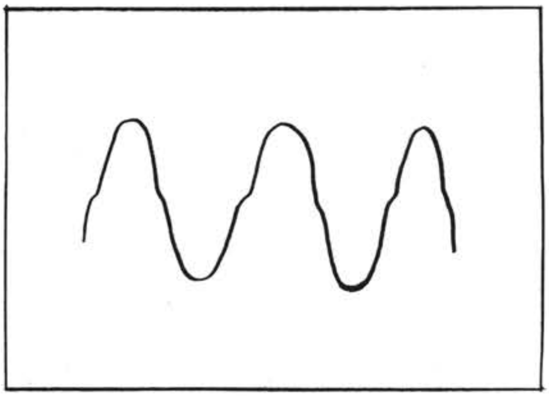
OSCILLOGRAM 9



OSCILLOGRAM 10

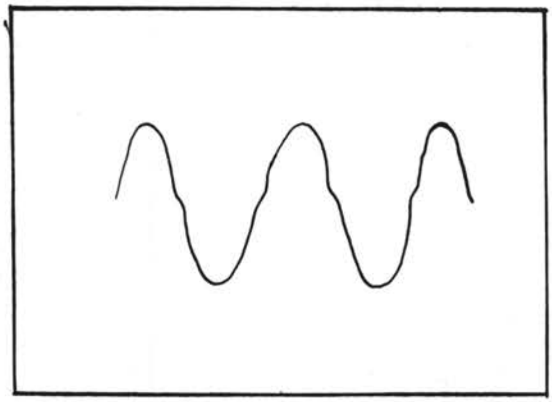


OSCILLOGRAM 11

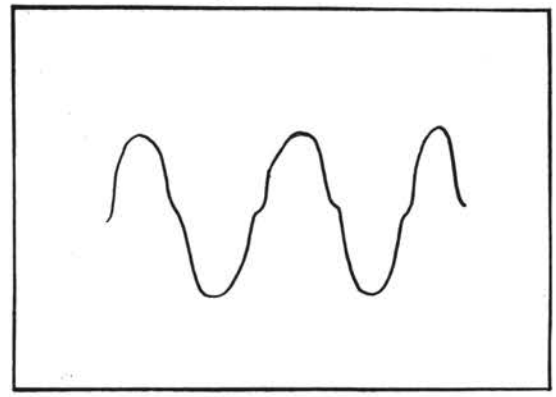


OSCILLOGRAM 12

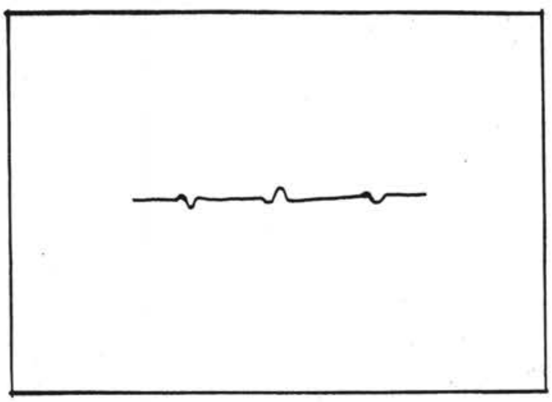
OSCILLOGRAMS (Continued)



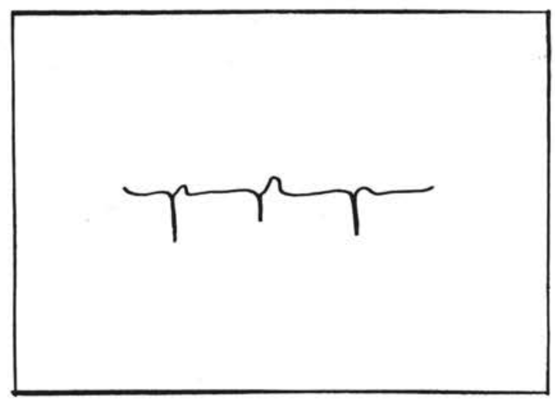
OSCILLOGRAM 13



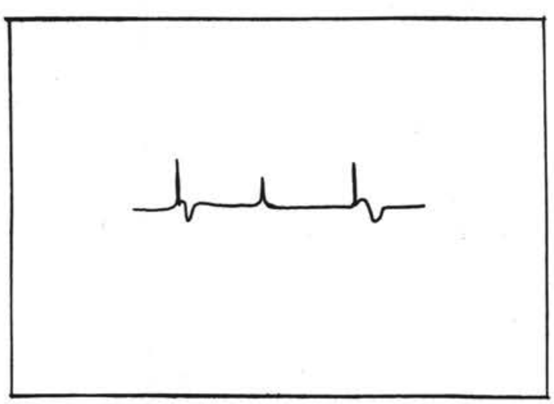
OSCILLOGRAM 14



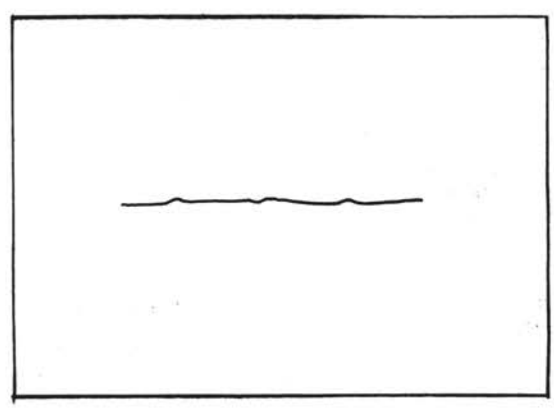
OSCILLOGRAM 15



OSCILLOGRAM 16

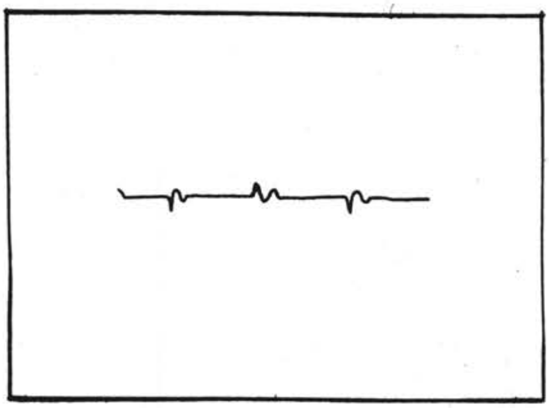


OSCILLOGRAM 17

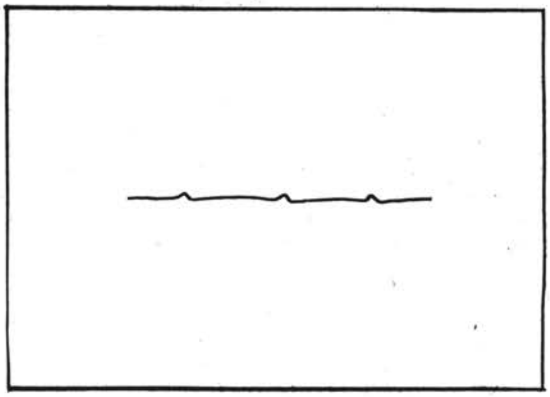


OSCILLOGRAM 18

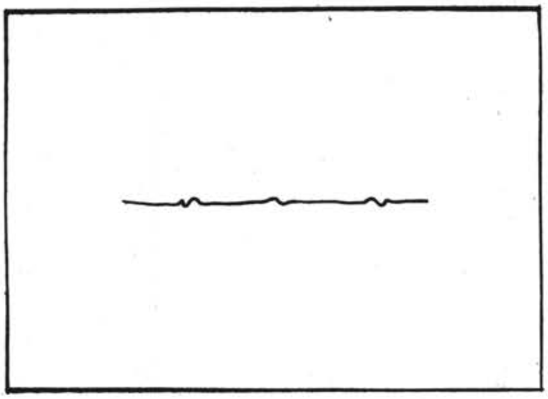
OSCILLOGRAMS (Continued)



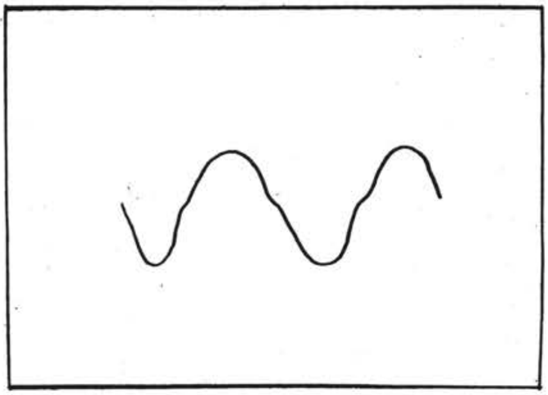
OSCILLOGRAM 19



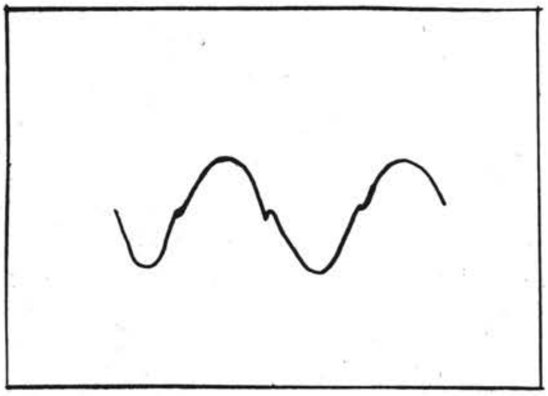
OSCILLOGRAM 20



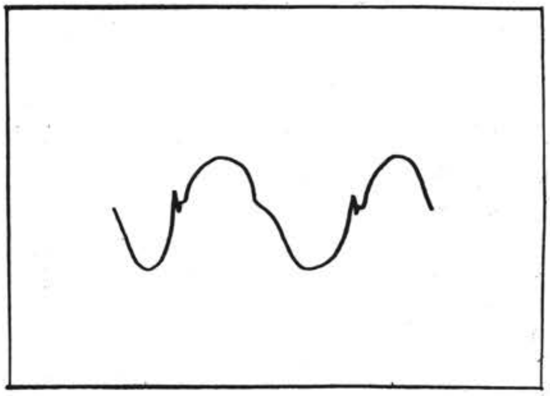
OSCILLOGRAM 21



OSCILLOGRAM 22

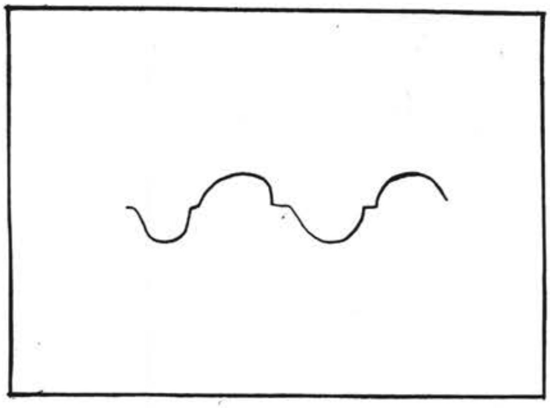


OSCILLOGRAM 23

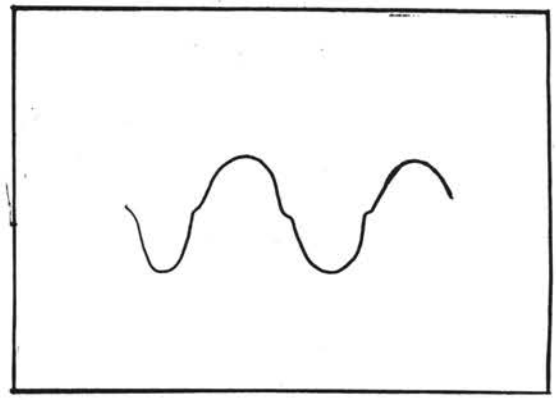


OSCILLOGRAM 24

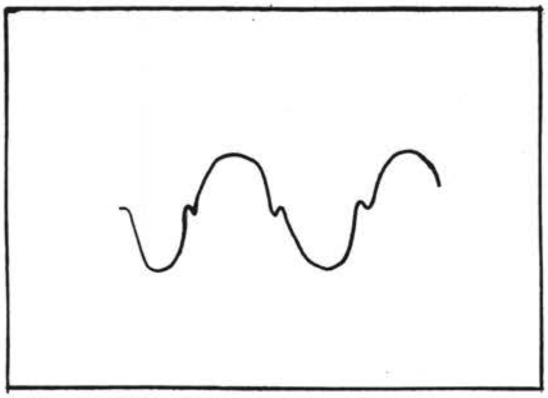
OSCILLOGRAMS (Continued)



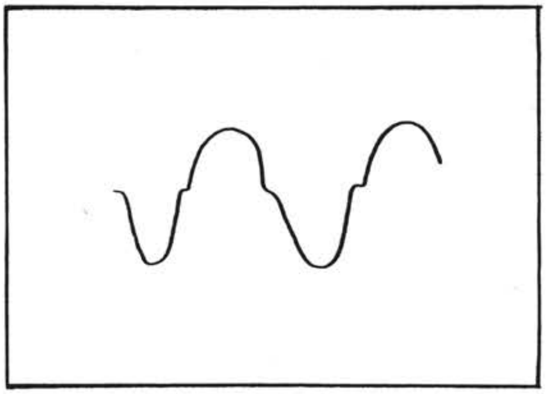
OSCILLOGRAM 25



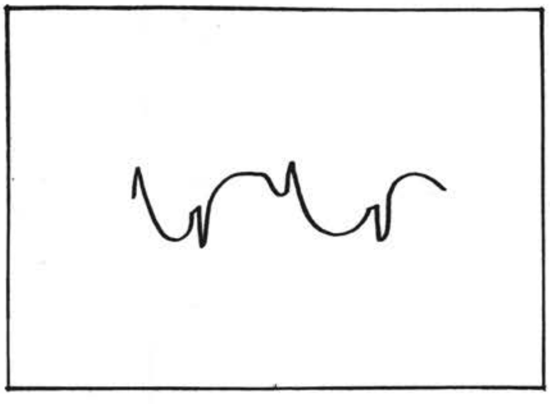
OSCILLOGRAM 26



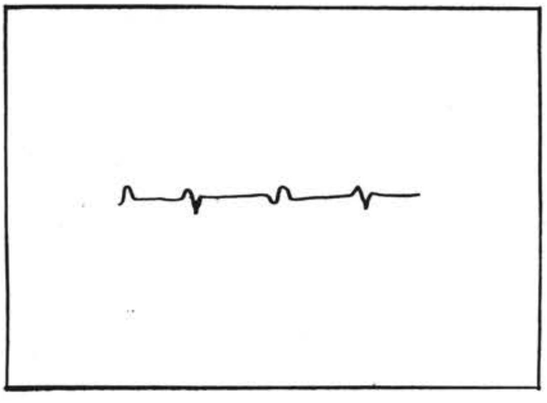
OSCILLOGRAM 27



OSCILLOGRAM 28

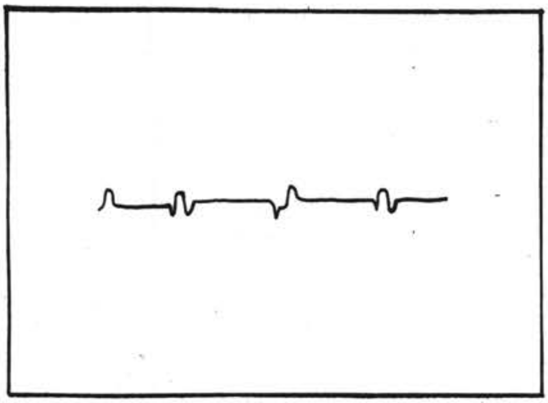


OSCILLOGRAM 29

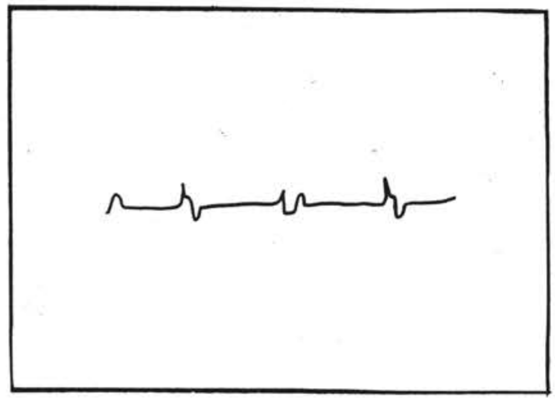


OSCILLOGRAM 30

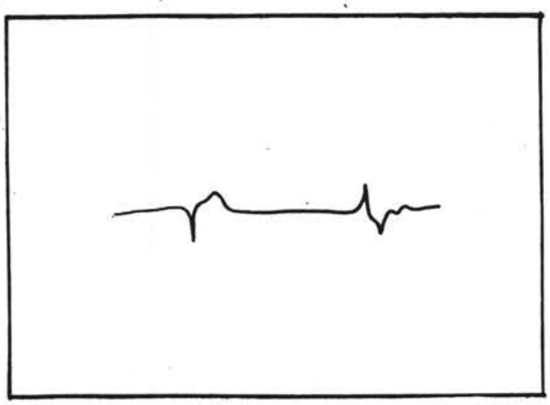
OSCILLOGRAMS (Continued)



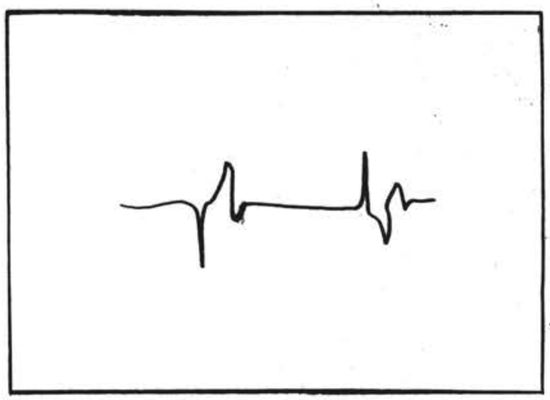
OSCILLOGRAM 31



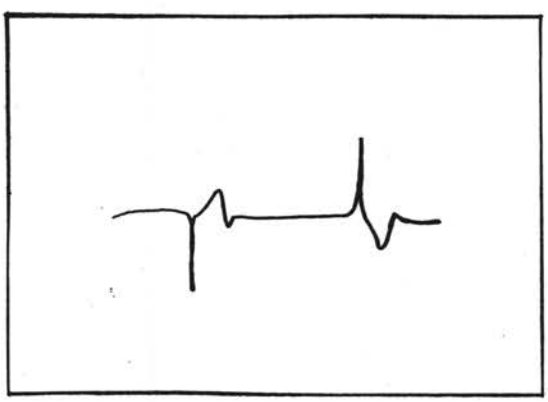
OSCILLOGRAM 32



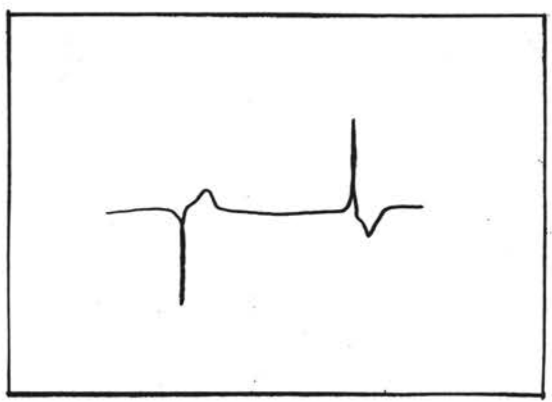
OSCILLOGRAM 33



OSCILLOGRAM 34

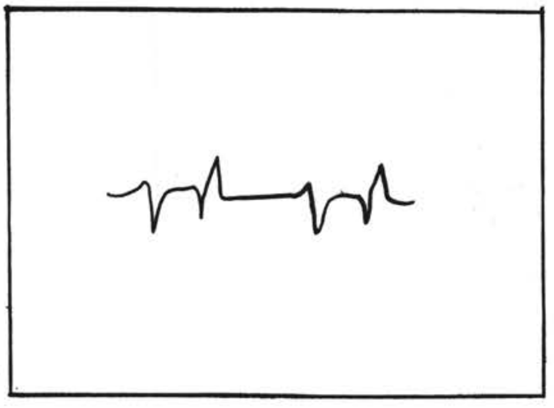


OSCILLOGRAM 35

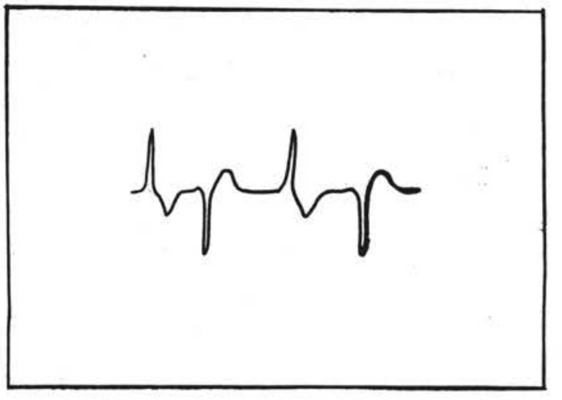


OSCILLOGRAM 36

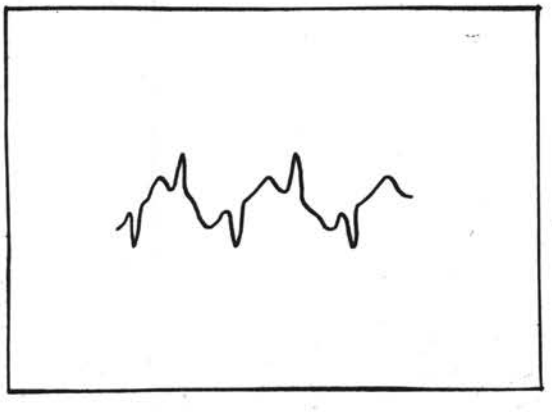
OSCILLOGRAMS (Continued)



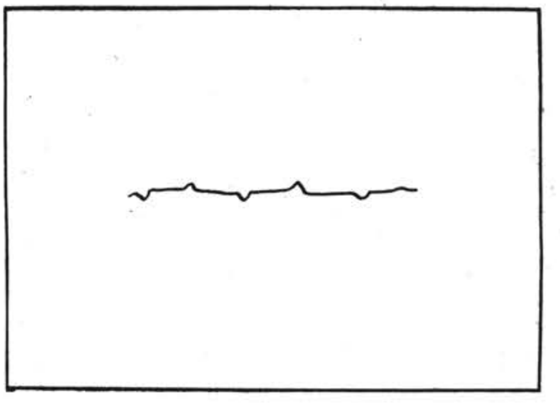
OSCILLOGRAM 37



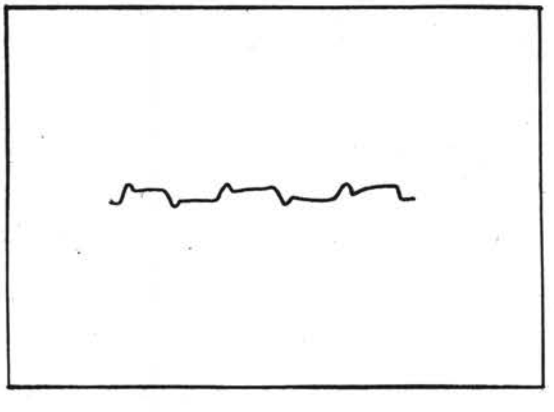
OSCILLOGRAM 38



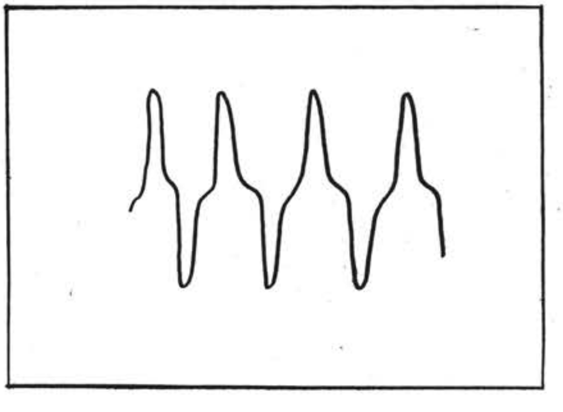
OSCILLOGRAM 39



OSCILLOGRAM 40

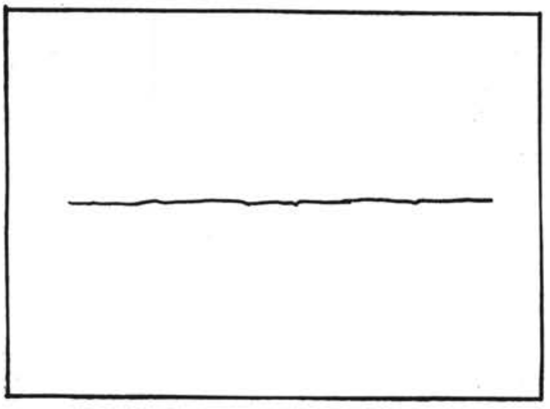


OSCILLOGRAM 41

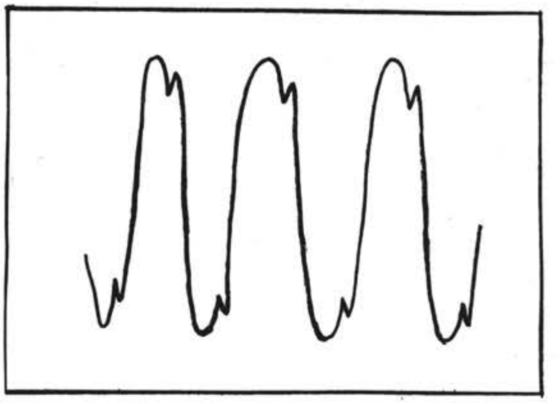


OSCILLOGRAM 42

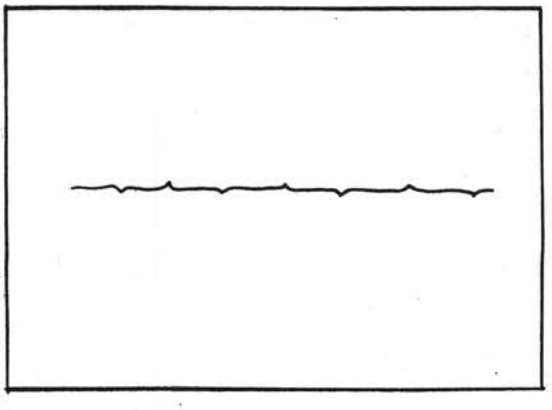
OSCILLOGRAMS (Continued)



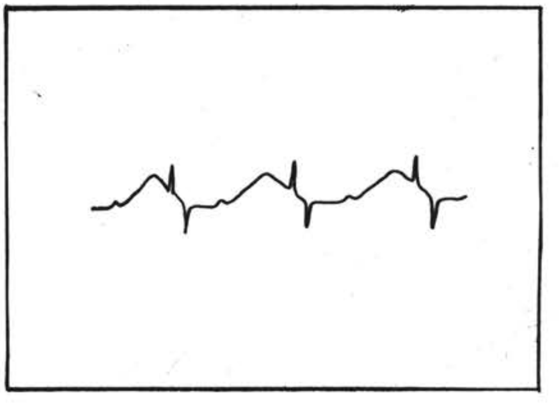
OSCILLOGRAM 43



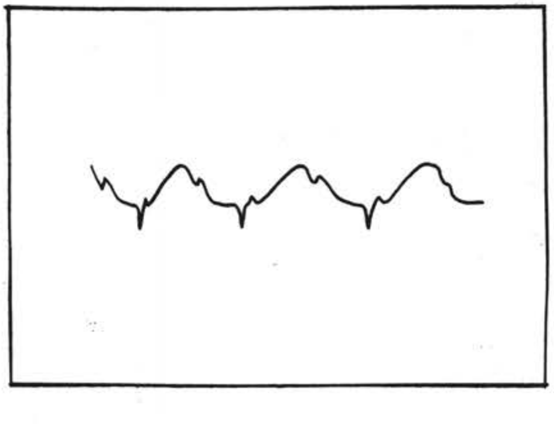
OSCILLOGRAM 44



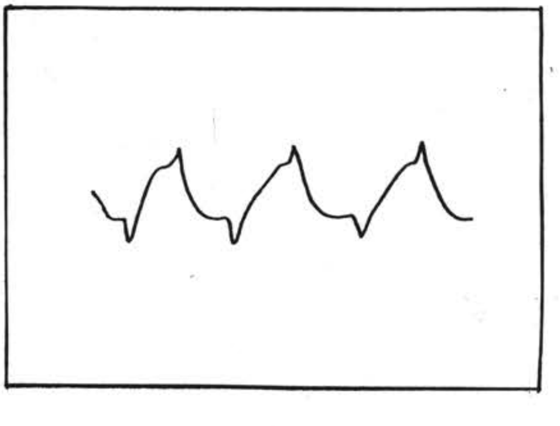
OSCILLOGRAM 45



OSCILLOGRAM 46

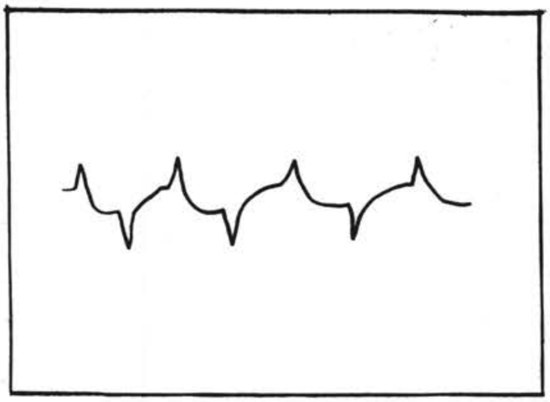


OSCILLOGRAM 47

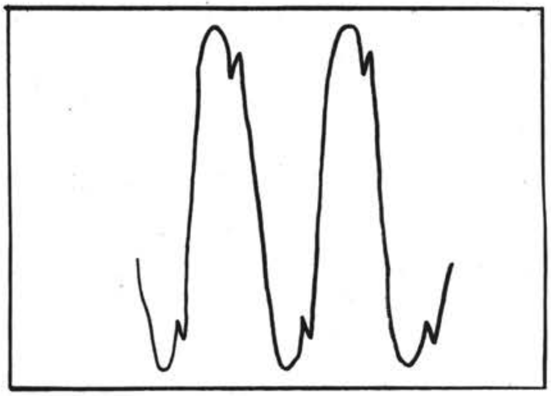


OSCILLOGRAM 48

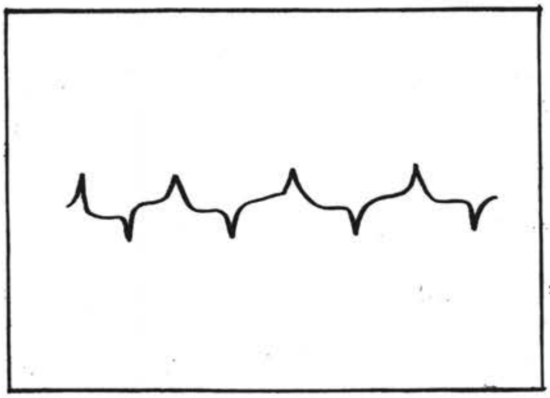
OSCILLOGRAMS (Continued)



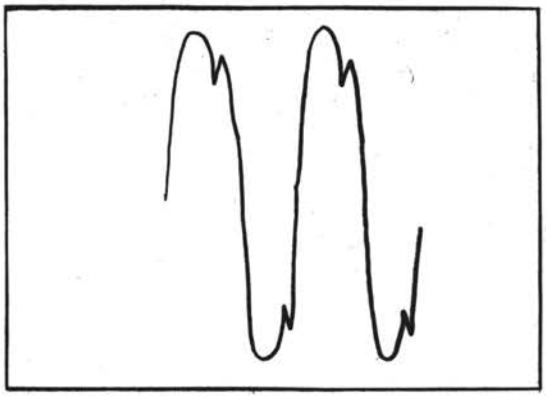
OSCILLOGRAM 49



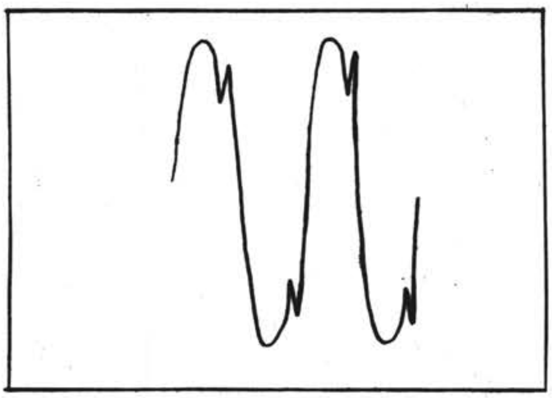
OSCILLOGRAM 50



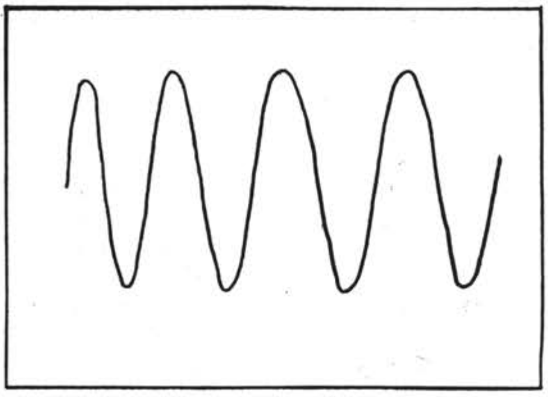
OSCILLOGRAM 51



OSCILLOGRAM 52

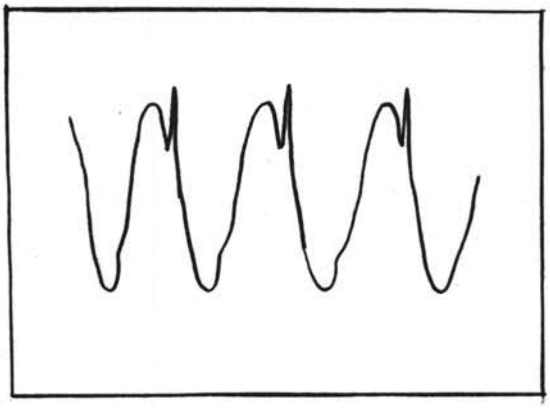


OSCILLOGRAM 53

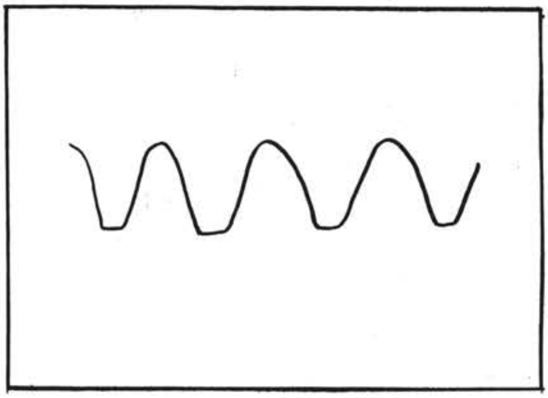


OSCILLOGRAM 54

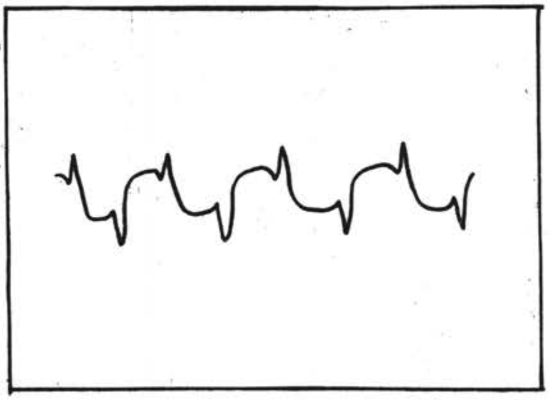
OSCILLOGRAMS (Continued)



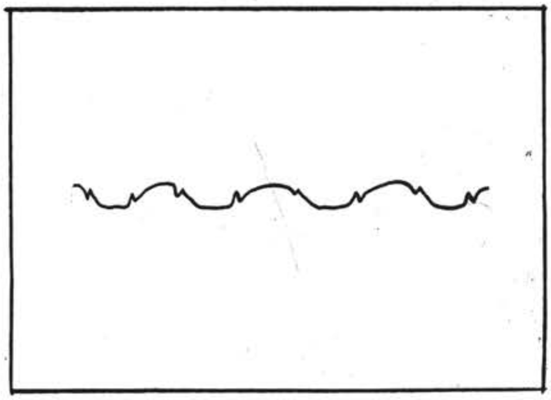
OSCILLOGRAM 55



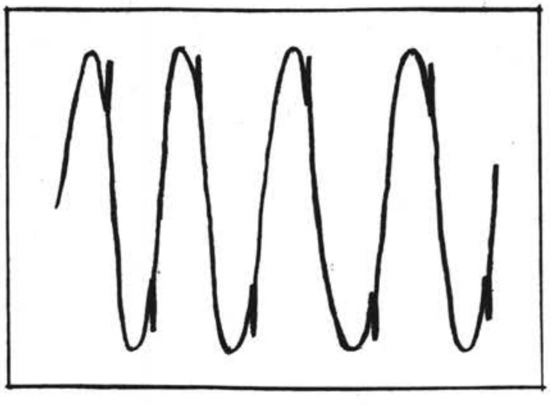
OSCILLOGRAM 56



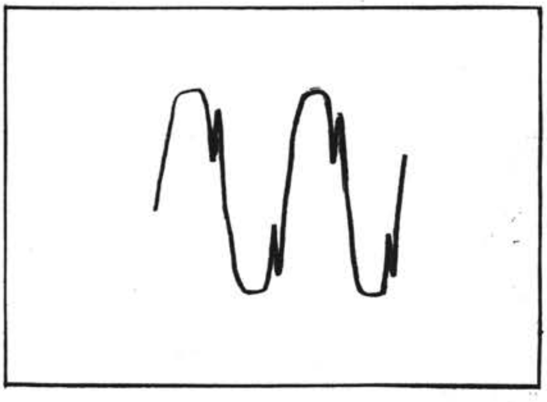
OSCILLOGRAM 57



OSCILLOGRAM 58

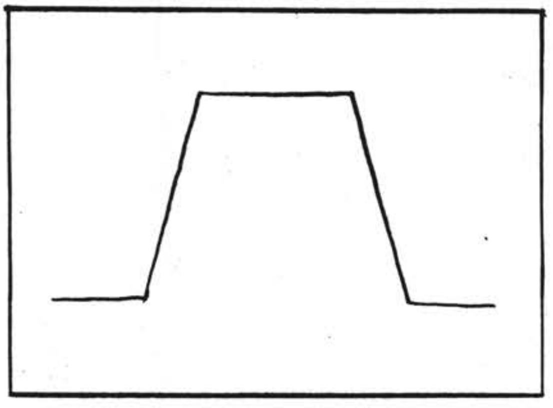


OSCILLOGRAM 59

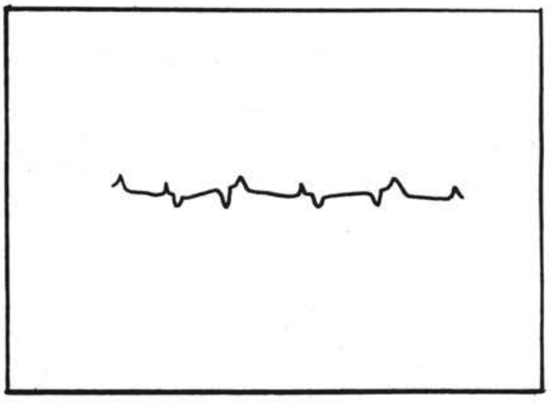


OSCILLOGRAM 60

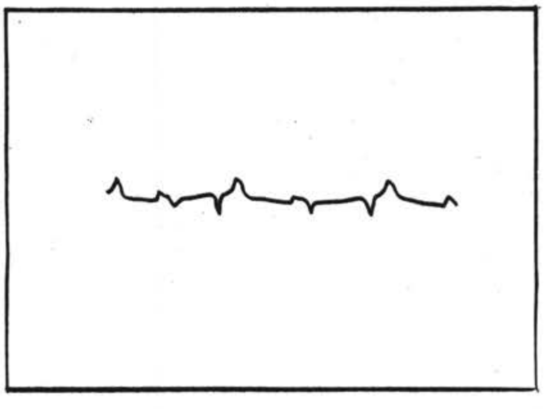
OSCILLOGRAMS (Continued)



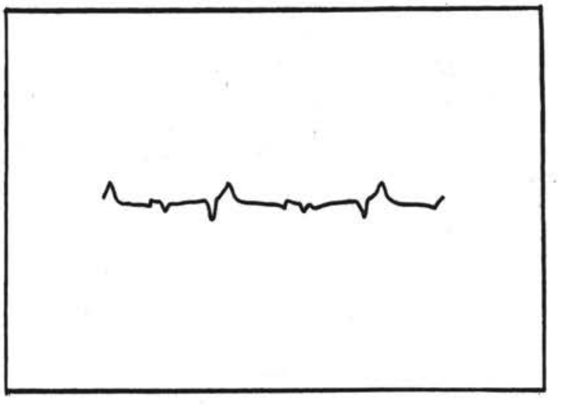
OSCILLOGRAM 61



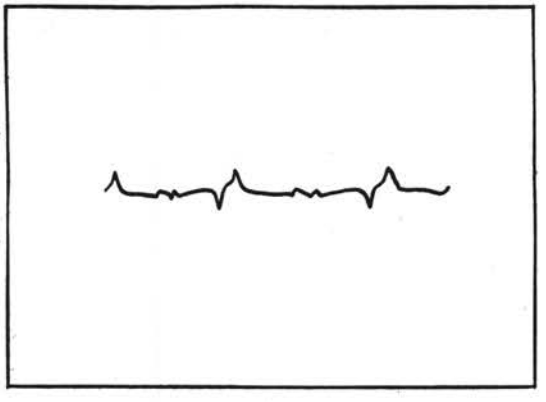
OSCILLOGRAM 62



OSCILLOGRAM 63



OSCILLOGRAM 64



OSCILLOGRAM 65

H. Analytical and Graphical Solution.

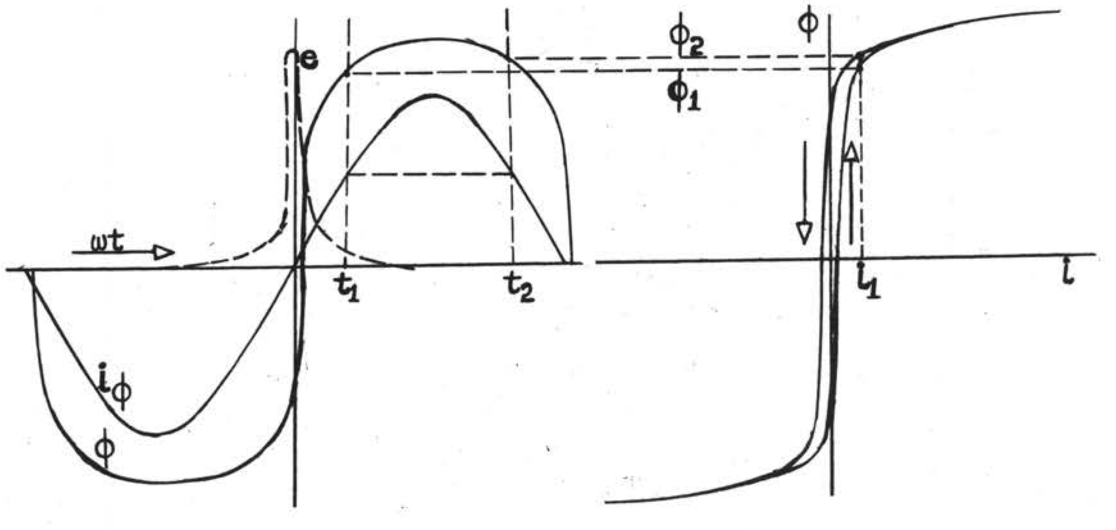
The iron-clad inductor belongs to a large class of circuit elements known as non-linear parameters. The study of non-linear circuits has become an important branch of electrical engineering. The most general type of circuit is the non-linear type, although usually circuits are treated as linear systems to simplify analysis.

In the complete solution of linear-circuit theory one equation may be written for each mesh in terms of current, impedance and voltage and an answer obtained by the classical method of solution. This is possible because mathematicians know methods of solution for equations linear in the derivatives and the function itself. Superposition holds for this type problem. The more recent Heaviside's operational methods or Laplacian transforms may be used with less difficulty than would be encountered by the classical method if the engineer prefers to use them.

If there is in the circuit a non-linear parameter which is a function of the current through it or voltage across it, the circuit equations become differential equations that are not linear. Mathematicians do not have general methods of solutions for these equations nor does the principle of superposition hold. Special non-linear differential equations may be solved by special means such as series expansions by Bessel's equation, but the solutions are unsatisfactory for most problems because the results become too involved.

The need for methods of solution are becoming more important each day. The intention in this section is to present one of the typical approaches to this type problem. This method is the graphical solution as it is presented by the Electrical Engineering Staff of the Massachusetts Institute of Technology in the text Magnetic Circuits and Transformers, pages 164-166. The magnetic core material chosen for this presentation was Permalloy.

If the current from the generator is a known sinusoidal function of time, for the basic magnetometer circuit the curves of the flux and the voltage across the inductance can be determined as shown in Figure 11.



a. Sinusoidal Curve of Exciting Current.

b. Symmetrical Loop Relating Flux and Current Determined by Means of a Ballistic Galvanometer.

Figure 11. Demonstration of Graphical Solution

Curve b is the loop of flux-current relations with a-c magnetic effects of eddy currents neglected.

From curve a the times t_1 and t_2 are equal. An increasing value may be observed at t_1 and a decreasing value at t_2. The values of current for times t_1 and t_2 show different corresponding values for flux in b. The curve for flux, ϕ, in a can be produced by combining graphically the instantaneous values of the i_ϕ curve with the hysteresis loop. The presence of only odd harmonics in the flux variations is indicated by the symmetrical hysteresis loop. Hysteresis causes the flux to lag the exciting current as shown in a.

The induced voltage waveform shown in a can be produced graphically by determining the slope of the flux wave. This voltage is proportional to the slope $\frac{d\phi}{dt}$ of the flux wave.

The approximate method introduced here is one of the few that may be used to predetermine the flux wave and the voltage wave in an iron-clad inductor circuit.

A mathematical method for predetermining the approximate maximum value of the transient exciting currents in an iron-clad inductor with an alternating voltage applied is demonstrated in Electric Circuits written by the Electrical Engineering Staff at the Massachusetts Institute of Technology, pages 699 to 702.

Operational Circuit Analysis by Bush, pages 92, 93 and 212, indicate further mathematical treatment of the iron-clad circuit.

Kerchner and Corcoran in their text Alternating Circuits, page 532, show methods of analysis of the iron-clad R-L circuit energized by an alternating potential difference.

Waveform changing is treated by Leonard R. Crow on pages 130, 137 and 172 to 176 of Saturating Core Devices.

Gardner and Barnes show solutions for two-loop networks with mutual inductances in their book Transients in Linear Systems Volume I, pages 139 to 150.

"An Experimental Verification of a Method of Calculating the Characteristics of Saturated Iron Cored Reactors" has been written in a thesis by Rueben E. Alley, Jr., at Princeton University. The verified methods of calculations are by series expansions.

The functional relationships between parameters and the dependent or independent variables must be known to make possible a graphical or analytical solution of the iron-clad circuit.

Magnetic materials are subjected to test to acquire information to be used to plot characteristic curves of the material to make possible desired predictions. Purely theoretical predictions are not possible since the theory of magnetic materials has not been sufficiently established.

Non-linear relationships may be approximately established with the uses of graphical forms, models or full-scale experimentation, step-by-step calculations, straight-line approximations and the differential analyzer. These methods are possible approximating ones that may be used to estimate expected conditions.

CHAPTER IV

INTERPRETATION OF DATA AND CONCLUSIONS

The purpose of this investigation was to compile data on known saturable-core magnetometer circuits. This information is very valuable when considering the design of a magnetometer for a specific use. This thesis seems to be the only source of information available. Saturable-core magnetometers have been constructed by various engineers but the design procedures, such as the process of development and decision as to the most suitable circuit or components to employ have not been published.

The non-linear nature of the saturable-core circuits complicate their mathematical solutions. No attempt has been made in this thesis to show a complete analysis of this type of circuit. The graphical approach has been indicated on pages 42-45. Some methods of solution have been attempted by various authors. A partial listing of these follow the graphical solution. Many recent articles and papers have been written showing solutions for magnetic amplifiers which can be partially used to solve the saturable-core magnetometer circuits. The increasing uses of the saturable-core reactors are making information of this nature more necessary. There is much to be done before the engineer will have adequate information to completely design a particular magnetometer on the basis of applications of established theory. Magnetometers have been constructed from laboratory models and their operations have been proven successful.

The following analysis of the oscillograms indicates the reason the author has concluded that the basic magnetometer is the least sensitive and the unbalanced-bridge magnetometer is the most sensitive; that, of the four core materials tested, Mu Metal is the best to employ for most uses; and that the less sensitive circuits could be economically used for particular applications.

Oscillogram 3 shows that the basic magnetometer has a maximum indication of saturation with a driving signal of 600 c.p.s.

Oscillogram 5 indicates the waveform taken across infinite load resistance, or across an open circuit. This is the same as observing the waveform across the magnetometer coil in series with the secondary of the balanced transformer (c.t. to lead). These two oscillograms (3 and 5) indicate Mu Metal to be the most desirable magnetic core material, 600 c.p.s. driving signal to be the preferred frequency for a load resistance of 150 ohms, and a driving frequency of 200 c.p.s. for an infinite load. Both of the waveforms of 3 and 5 show definite increases of current at the point of saturation of the core material. These could be used to give indications on a meter or similar indicating device or could be used as the input voltage to following amplifier stages.

Oscillogram 16 shows the balanced-bridge with sufficient external magnetic field to produce equal voltage peaks from both legs. Oscillograms 17 and 18 show values of an external magnetic field equal amounts above and below the balanced value. The first adds to the value necessary for balance, the second subtracts from it. The subtractive value shows a little larger response than the additive value.

Oscillograms 19, 20 and 21 were taken to indicate the effects of placement of the magnetometer coils on the core-material strip. Oscillogram 20 shows that best results were obtained when one of the coils was displaced from the center position about one-fourth the length of the core strip.

Oscillograms 22, 23 and 24 show no appreciable change of waveform with a change of external field, indicating these conditions do not provide a very sensitive circuit. Number 22 shows the most distinct change of voltage waveform when core saturation is reached. This is the result of an infinite load for the unbalanced-bridge.

The next five oscillograms through number 29 show that the most desirable load is an open circuit. This can be observed in number 29.

Oscillograms 30, 31 and 32 were taken of the unbalanced-bridge to show the effects of the three external magnetic field values that were used in the basic magnetometer. The subtractive value indicated more response in the unbalanced-bridge magnetometer, as it did in the basic magnetometer.

Oscillograms 33, 34, 35 and 36 were taken with a 300 c.p.s. driving voltage applied to permit comparisons of the core materials. For this driving frequency, Mu Metal indicates the maximum voltage peaks with the smoothest waveforms at the points of saturation.

Numbers 37, 38 and 39 show the effects of changes in the frequency of the driving voltage. Mu Metal, the optimum core material determined in the test above, was used to produce these comparisons. The frequencies checked were respectively 600, 1000 and 2000 c.p.s. to compare with oscillogram 36 which was a test for Mu Metal with a driving voltage frequency of 300 c.p.s. Of the last three checked, the 600 c.p.s. gave the best results, but the 300 c.p.s. frequency was better than any of these three.

Oscillograms 40 and 41 were ones to check results of a higher frequency input voltage for Mu Metal used in the balanced-bridge circuit. This frequency was 2000 c.p.s. This frequency was not a better value to use than 300 c.p.s. Number 42 was taken to facilitate comparison of the balanced-bridge with the unbalanced-bridge when a frequency of 2000 c.p.s. was used as the driving voltage and an infinite load was present.

Since the optimum frequency was determined to be 300 c.p.s. and the optimum core material was Mu Metal the remaining portion of the investigation, performed for the unbalanced-bridge magnetometer, was done with these two conditions kept constant. Oscillograms 43 through 60 were taken to determine the optimum load resistance and the optimum unbalancing resistance. Oscillograms 55, 57 and 59 show the optimum value for load resistance to be an infinite load, with lower values showing decreases of output voltage and the optimum unbalancing resistance to be 2000 ohms.

Oscillograms 61 through 65 were taken to give comparison pictures on a calibrated scale of four different values of external field which were respectively zero, 442, 885 and 1327 gammas. Number 61 was the calibration oscillogram and it shows a peak to peak voltage of 10 volts. These tests were made with 700 c.p.s. used as the driving voltage frequency applied to a balanced-bridge magnetometer.

When considering a core material the manufacturer's conditions of anneal are very important. This for the most part determines the values for minimum coercive force and maximum permeability. An example is the processing of Supermalloy. The presence of hydrogen during the anneal produces both of the desired characteristics. The hydrogen in this case chemically reacts with the magnetic-material molecules to produce the desired results.

Another consideration of importance is to make sure during the placement of the core material that it is free from mechanical strain or distortion. There should be no cracks, breaks or other similar defects in the strip and it should be uniform in shape.

It is intended that this investigation will supply information that will help in selecting proper circuit, core material, driving-voltage frequency, load resistance and components across which a voltage change may be observed.

The characteristics of operation of the saturable-core magnetometer and its physical adaptability suggest its uses as a basic instrument for making physical measurements. Some of its suggested adaptations are:

1. The arrangement of two parallel magnetometer elements to form a gradiometer.
2. An anomaly detector for use in submarine detection or water surveys for unobservable magnetic objects.
3. A geological survey instrument to detect magnetic deposits from the air or surface.
4. In the laboratory to measure permanent and induced

magnetic moments of ferromagnetic bodies, magnetic fields arising from eddy currents induced by conducting materials moving in the earth's field, or the impurities of ferromagnetic materials in non-ferrous materials.

5. To measure minor variations of the earth's magnetic field due to solar sources.
6. To observe magnetic disturbances of the earth's field due to terrestrial or atmospheric sources.
7. As a magnetic-field probe to give both direction and magnitude of existing magnetic fields.
8. To act as navigational indices for local operation or remote controlled airborne equipment when used in conjunction with an instrument furnishing another set of coordinates.
9. As an instrument to furnish more accurate navigational indices than are presently available with airborne navigational aids.

Each of the above adaptations suggests many other uses for the magnetometer. The possibilities for this phase of instrumentation are great in number. In this instrument there appear to be the accuracies and possible applications hoped for by many engineers. This phase of measurement investigation is in its infancy and the possibilities are unlimited for the agressive engineer desiring research in this field of study.

BIBLIOGRAPHY

Alley, Rueben E. "An Experimental Verification of a Method of Calculating the Characteristics of Saturated Iron Cored Reactors." Unpublished Bachelor's Thesis. Princeton, New Jersey: Princeton University, 1938.

Atwood, Stephen S. Electric and Magnetic Fields. 3d Edition; New York: John Wiley and Sons, Inc., 1949.

Bozarth, R.M. "Magnetism." Reviews of Modern Physics, XIX, I, (1947), 30-31.

Bush, Vannevar. Operational Circuit Analysis. I, New York: John Wiley and Sons, Inc., 1937.

Carnegie Institution of Washington. The Geomagnetic Field, Its Description and Analysis. Washington, D.C.: Carnegie Institution of Washington, 1947.

Crow, Leonard R. Saturating Core Devices. Ann Arbor, Michigan: Edwards Brothers, Inc., 1949.

Elmen, G.W. "New Permalloys." Bell Laboratories Record 10, I (September, 1931). 40-46.

Fleming, J.A. Terrestial Magnetism and Electricity. New York: Dover Publications, 1949.

Gardner and Barnes, Transients in Linear Systems. New York: John Wiley and Sons, Inc., 1942.

Gray, Alexander. Principles and Practice of Electrical Engineering. 3d Edition; New York: McGraw-Hill Book Co., Inc., 1924.

Golding, Edward W. Electrical Measurements and Measuring Instruments. 3d Edition; London: Sir I. Pitman and Sons, 1940.

Johnson, David L. "An Electronic Magnetometer," Unpublished Master's Thesis. Stillwater, Oklahoma: Oklahoma A and M College, 1950.

Kerchner and Corcoran. Alternating Circuits. 2d Edition: New York: John Wiley and Sons, Inc., 1948.

Legg, V.E. "Survey of Magnetic Materials and Applications in the Telephone System." Bell Telephone System Journal, XVIII, (1939), 440.

"Magnetic Materials." Electronics Buyers Guide. June Mid-Month, XXI, (1948), M20.

Massachusetts Institute of Technology Electrical Engineering Staff. Electric Circuits. New York: John Wiley and Sons, Inc., 1943.

Page and Adams. Principles of Electricity. New York: D. Van Nostrand Company, Inc., 1932.

Rudder, W.E. "New Magnetic Materials." Proceedings of Institute of Radio Engineers, (October 1942), 437-440.

Tolles, Fredrice E. "Applications of the Saturable-Core Magnetometer." Proceedings of the National Electronics Conference, III (1947), 504-513.

Valley and Wallman. Vacuum Tube Amplifiers. Radiation Laboratory Series, XVIII, I, New York: McGraw-Hill Book Co., Inc., 1924.

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