Abstract of thesis of

DENMAN SHAW

DEVELOPMENT OF AN INSTRUMENT FOR DETERMINING ACCURACY OF A WATCH

ABSTRACT

An instrument is described which is directed toward measuring quite accurately average frequency associated with the timing mechanism of a watch but which may be applied to the measurement of the average frequency of any low frequency periodic phenomenon which can be converted into an electrical signal and which possesses a wave shape that is not too irregular, provided that this average frequency does not deviate greatly from some given frequency. In the application to the study of a watch the electrical signal is obtained by applying the audible tick to the microphone. Since the voltage thus obtained is approximately 1000 cycles modulated 5 times per second, it is necessary to employ a stage of detection immediately after the amplifier. The signal thus obtained is then fed into a high Q filter tuned to the average frequency in question (5 cycles per second in the case of a watch). This filter serves to improve the wave shape, to lessen the frequency fluctuations, and to decrease the variations in amplitude as well as to remove off-frequency noises. This output is used to control a multivibrator, the amplitude and wave shape of whose output are not greatly influenced by the nature of the incoming signal. This signal in turn is applied to a medium Q 40 cycle filter which thus selects a frequency which is 8 times that of the watch. This filter is sufficiently selective to remove undesired harmonics as well as the fundamen-

tal but not so selective as to attenuate unduly a signal which deviates slightly from the nominal 40 cycle value. After power amplification this 40 cycle signal is used to drive a synchonous motor. By means of a differential gear system the number of revolutions which this motor makes in a given time is compared with the number made by a motor driven by a standard 40 cycle A. C. current. This latter is obtained from a 1.2 kc. crystal by frequency division. The use of the two motors coupled by the differential makes the indicator integrating and direct reading while resembling quite closely the desirable null balance technique of measurement.

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Physics (Major)

- Special Problems
- Electrodynamics
- Quantum Mechanics
- Nonlinear Problems
- Complex Variables
- Nuclear Structure Theories
- X-Rays and Crystal Structure
- Adv. Experimental Physics
- Research for Doctorate

Mathematics (Minor)

- Tensor Analysis
- Readings and Research
- Readings in Modern Algebra
- Partial Differential Equations

DEVELOPMENT OF AN INSTRUMENT FOR DETERMINING ACCURACY OF A WATCH

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by

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ILLUSTRATIONS

I. Introduction

The object of the present work is to develop a method of determining the accuracy of a watch by means of an observation made over a relatively short period. The usual method, of course, is simply to set the watch to agree with some standard timepiece and then to determine the deviation between the readings of the watch and of the standard twenty-four hours later. The long time is necessary because the error of an ordinary watch is of the order of a few minutes a day and, therefore, only becomes noticeable over the course of a long time. The obvious procedure, then, for making the measurement rapidly is to make use of the ticks of the watch since on the one hand they have a much greater frequency then that of the minute hand and, on the other hand, the rate at which the minute hand turns is directly proportional to the mean frequency of the ticks. In addition, the ticks may, of course, be easily converted into an electrical signal by means of a microphone; and it is conventional to use an electronic circuit in precise frequency determination.

Thus, the problem has been converted to that of determining the mean frequency of a low frequency (i.e., 5 cycles per second) electrical wave. The fact that the frequency is low introduces difficulties since standard methods are usually more appropriate for somewhat higher frequencies. In the present instance, the difficulty is increased by the fact that the ticks are a series of pulses rather than a sine wave, that successive pulses differ in amplitude and harmonic content, and that the time interval between successive pulses varies. Finally, the amplitudes as well as the shapes of the pulses differ for different watches.

The general procedure employed may now be sketched with emphasis on the method rather than technical details. The watch tick is first amplified by a high pass amplifier and the resultant signal is then detected to obtain the low frequency component. The detector is followed by a resistance condenser network designed to improve the wave shape. The resulting wave is then passed through a high Q five cycle filter which serves further to improve the wave length and to decrease the frequency variation. This signal is now used to control a 5 cycle multivibrator from the output of which the 40 cycle harmonic is selected by a 40 cycle filter. By means of a pair of synchronous motors and a differential gear system this output is compared with a standard forty cycle wave obtained by frequency division from a 1.2 kc. crystal oscillator. We now consider the actual circuits in more detail.

II. Watch Tick Activated System

A. Tick Amplifier

The tick itself is picked up by a Shure W-56A phonograph pickup which is actually a high sensitivity crystal microphone. In operation, the needle of the pickup is placed in contact with the metal case of the watch. The signal thus obtained is amplified by a conventional three stage coupled audio amplifier. Because of the high resistance of the microphone and of the grid resistor of the first tube, this amplifier has considerable hum pickup. To eliminate this, as well as to diminish the effects of random noise, the unit is built in such a way as to amplify high frequencies (above 1000 cycles per second) in preference to the lower frequencies. This is accomplished by using coupling condenser of rather low capacity which tends to decrease low frequency response. Inasmuch as the tick itself consists of a carrier of over 1000 cycles per second modulated at 5 cycles per second (Fig. 1), the desired signal is passed. The amplifier itself consists of tubes VT-1, VT-2, VT-3, and associated components and has an amplification of 1000 times for a signal of 1000 cycles per second.

B. Detection

The 5 cycle signal is now obtained by passing the signal to a triode detector, (Fig. 2). This consists of a tube (VT-4) biased beyond cutoff so that it responds only to the positive half of the incoming signal. This feeds into a low pass filter consisting of three integrators which act to remove the high frequency signal and to improve the shape of the 5 cycle wave.

C. 5 Cycle Filter

At this point it would be desirable to apply the signal to the 40 cycle filter so that the system would be capable of measuring the per cent of deviation of any frequency which was a sub-multiple of 40, (for example, 2, 2.5, 4 and 5). However, experimentation showed that the signal in question is too irregular in frequency and amplitude to produce a reasonably steady 40 cycle signal after frequency multiplication. The filter[1,2] employed is of the so-called parallel T type which has proven useful in low frequency applications. The tuned element is essentially a three terminal frequency bridge. Thus, the input is connected between one terminal and ground while the output appears between the other terminal and ground, therefore, obviating the need for an isolating transformer. At the null frequency the output is zero. Thus one can obtain a sharply tuned amplifier with the aid of this element in the following manner. The signal to be filtered is fed into a voltage amplifier, the output of which is applied to the input terminals of the parallel

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1. M. P. Givens and John S. Saby, <u>The Review of Scientific Instruments</u>, Vol. 18, 342-346, 1947
2. R. Runyan, unpublished M.S. thesis, U.C., 1948

T network. In turn, the output of the parallel T is returned to the input of the amplifier in such a phase as to produce negative feedback. This attenuates the net amplification for off-frequency signals considerably while not affecting that of signals at the tuned frequency since for such signals there is no output from the tuned network to be fed back. It turns out that the components required for the tuned element are of quite a reasonable size which forms a sharp contrast with the large condensors and inductances which would be required for a convential tuned L-C filter. In this filter circuit, as well as in the 40 cycle filter, we use a method for obtaining feedback with minimum phase shift. In essence the feedback signal is directed into a cathode follower amplifier whose cathode is tied to the cathode of the first amplifier tube of the main filter amplifier.

D. Frequency Multiplier

The five cycle output from the filter is nearly a sine wave (Fig. 3) and, thus, of course, quite low in harmonic content. It, therefore, was decided to obtain a signal with the same fundamental frequency but considerably greater harmonic content by using a 5 cycle multivibrator controlled by the 5 cycle output of the filter. The amplitude of the output is also substantially independent of the aplitude of the synchronizing signal, thus making the operation of the instrument less sensitive to the loudness of the watch. A multivibrator is especially suitable for such controlled operation because the tube cycle of the grid voltage of either tube changes according to the following sequence. There is a period during which this voltage changes slowly, followed by a period of rapid change. The synchronizing signal can thus easily produce a transformation from the part of relatively steady voltage to the region of rapidly changing voltage. The multivibrator is made up of tubes VT-9 and VT-10 and associated components. The grid voltage cycle without and with synchronization is shown by figures 4 and 5 respectively. It may be noted from this figure that the rapidly changing portion of the grid voltage is essentially a pulse and , therefore, has a relatively large harmonic content.

The peak in question has a magnitude of about 100 volts and, after reduction by means of a voltage divider, is applied to a 40 cycle parallel T filter to obtain the desired harmonic. This filter is designed so as to produce an amplification at 35 and 45 cycles about 10% of that at 40 cycles. Since the watch frequency, after smoothing by the cycle filter, varies only slightly from nominal frequency, this filter produces little attenuation in the desired harmonic while effectively removing other harmonics and the fundamental. This filter consists of VT-11, Vt-12, and VT-13, (Fig. 6).

III Measurement of Frequency Deviation

A. General Considerations

As the result of the operation of the previous circuits, we have obtained a 40 cycle wave whose mean percent deviation from nominal is the same as that of the watch. There are now available two main methods for determining this error. First it is possible to send the signal into a very sharply tuned 40 cycle filter and to measure the percent response. Since the freqrency deviation is in no case very great, this would in turn be a measure of percent error. The second procedure is that of comparison with a standard. This second method is the more commonly used since it is relatively easy to obtain a standard of very high precision. In addition, many of the methods of comparison of two frequencies provide for an integration of the error. This is desirable for the present case for the following reasons.

In the first place, as mentioned before, the frequency of the watch tick itself is not absolutely constant; and, therefore, we wish to measure the mean rather than the instantaneous deviation. Although a considerable amount of this variation in question is removed by the operation of the five cycle filter, we cannot expect that all of it will be gone. Secondly, the pulse corresponding to the watch tick is rather irregular and it is likely that for different pulses the multivibrator will not always be activated by the same portion of the pulse. Let us assume then that for the five cycle wave the region to which the multivibrator responds is about one radian in extent. If then we wish to measure a watch's error as small as ten seconds a day, the inherent error of the system should represent no more than about five seconds a day. Since five seconds a day represents about one part in 17,000, the measurement should extend over a large enough number of cycles, N, such that

$$\frac{1}{2\pi N} = \frac{1}{17,000}$$

This gives for N approximately 3,000 cycles which corresponds to 600 seconds or ten minutes. Thus we desire a system of frequency measurement which can give an easily read indication of the integrated error at the conclusion of the ten minute period as well as indicating its direction. There are a number of techniques which with suitable modification can be made to suit these requirements. For instance, one might use a Lissajou figure formed by the standard and the unknown or one might beat the two frequencies together and rectify the resulting output. Both these methods have objections, of course. For instance, the variations in the frequency of the unknown frequency might make the Lissajou figure difficult to follow and would make it necessary to build an oscilloscope into the instrument. On the other hand, in order to determine whether the watch was fast or slow it would be necessary to use a standard somewhat different from the frequency to be measured.

There is available, however, a relatively simple technique for performing the task, namely the use of a pair of synchronous motors coupled through a differential gear system.[3] Experience has shown synchronous motors to be highly reliable in following the input frequency, and they are generally used in conjunction with standards. On the other hand a differential gear system presents a simple method for recording the difference in revolutions of the two motors no matter which direction the difference takes.

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3. This idea was suggested by Dr. Podolsky

B. Standard Frequency

The primary standard is a 1200 cycle crystal oscillator employing VT-16. The crystal itself is a Western Electric type 20 J duples crystal which is characterized by a temperature coefficient of frequency sufficiently low that the frequency remains constant within limits of ± .005% when the temperature ranges between 15 and 45 C. The 1200 cycles obtained from this crystal is introduced into a buffer amplifier which contains tube VT-17. The output of this amplifier is then used to synchronize the frequency of a multivibrator employing tubes VT-18 and VT-19. The multivibrator is adjusted so that its nominal frequency is 240 cycles per second and it is, therefore, triggered by every fifth wave of the crystal oscillator. After passing through the buffer amplifier making use of VT-20, the 240 cycle signal controls in like manner a 40 cycle multivibrator which contains VT-21 and VT-22. By this method a signal is obtained from the latter multivibrator whose frequency is exactly 1/30 that of the crystal.

C. Output Stages

The 40 cycle signal controlled by the watch tick is subjected to a further stage of voltage amplification employing tube VT-14. The output of this stage (Fig. 7), in turn, drives a transformer coupled Class A power amplifier VT-15 tuned to 40 cycles. The load of this power amplifier is a Telechron type B 3 four watt synchronous motoer which is equipped with a gear system such that the nominal speed is

The 40 cycle standard obtained from the controlled multivibrator has a high harmonic content and is, therefore, introduced into an amplifier using VT-23, terminated by a low Q 40 cycle filter which serves to improve the wave shape. The resulting signal is used to drive another Class A transformer coupled power amplifier VT-24 tuned to 40 cycles whose load is a synchronous motor geared down to 40 R. P. M.

As mentioned above, the difference between the total number of revolutions of the two motors is recorded by means of a differential. The gear system is such that the total number of revolutions of the output shaft is equal to ½ this difference. The relation between the rotation of the output shaft and the error of the watch may be computed as follows: Assuming a period of operation of ten minutes and letting θ be the rotation of the shaft in degrees, the corresponding % error is:

$$\frac{2\theta}{360} \times \frac{100}{40 \times 10} = \frac{\theta}{360 \times 2} \%$$

On the other hand the number of minutes per day is 60 x 24 so that the corresponding error in minutes is:

$$\frac{60 \times 24\theta}{360 \times 200} = \frac{\theta}{50}$$

Thus 50° correspond to 1 minute a day and 8-1/3° to 10 seconds a day. The rotation of the output shaft is indicated by a dial calibrated in degrees. Since the instrument is designed only to measure with an accuracy of 10 seconds a day, the reading is quite easy to make. Further, a clockwise rotation indicates a slow watch and a counterclockwise rotation, a fast one.

In actual operation one simply places the phonograph pick-up on the watch, waits one minute for transients to disappear, sets the friction held dial to read zero, waits ten minutes, and takes the final reading. Thus almost no technical skill is required for operation.

IV. Power Supplies

The filaments are simply supplied by 60 cycle A.C. of appropriate voltage obtained from three different power supplies. The D. C. voltages for the power amplifiers are obtained from an ordinary, unregulated power supply. To prevent interaction among the power amplifiers, the watch tick activated circuit, and the 40 cycle standard, the latter two are operated from separate D. C. supplies. Furthermore, to obtain stability of operation and to prevent undesirable interstage coupling, each of the last two is a regulated supply.

V. Results

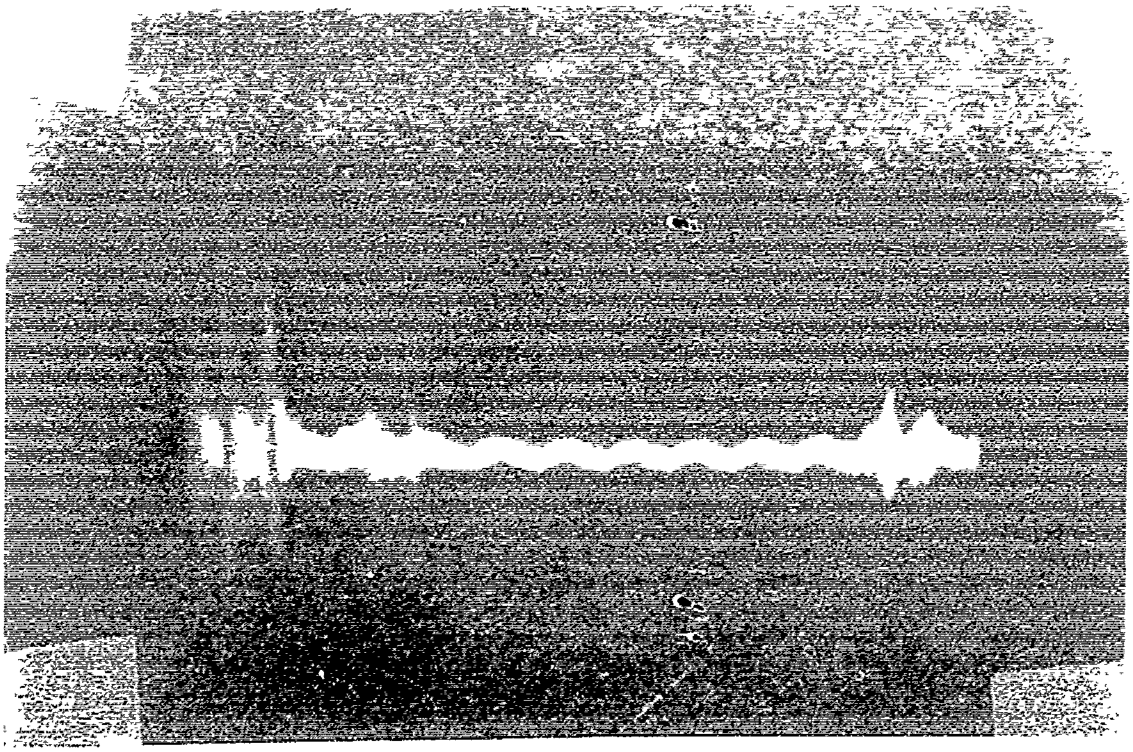
Because the 1200 cycle per second crystal oscillator had not been adjusted, no sets of measurements have been made to determine accuracy. However, qualitative agreement between measurements made with 4 watches and the owners' experience was obtained. In addition, a quantitative estimate of the precision was made and the following was obtained. Two sets of consecutive runs were made upon the writer's watch. The results are:

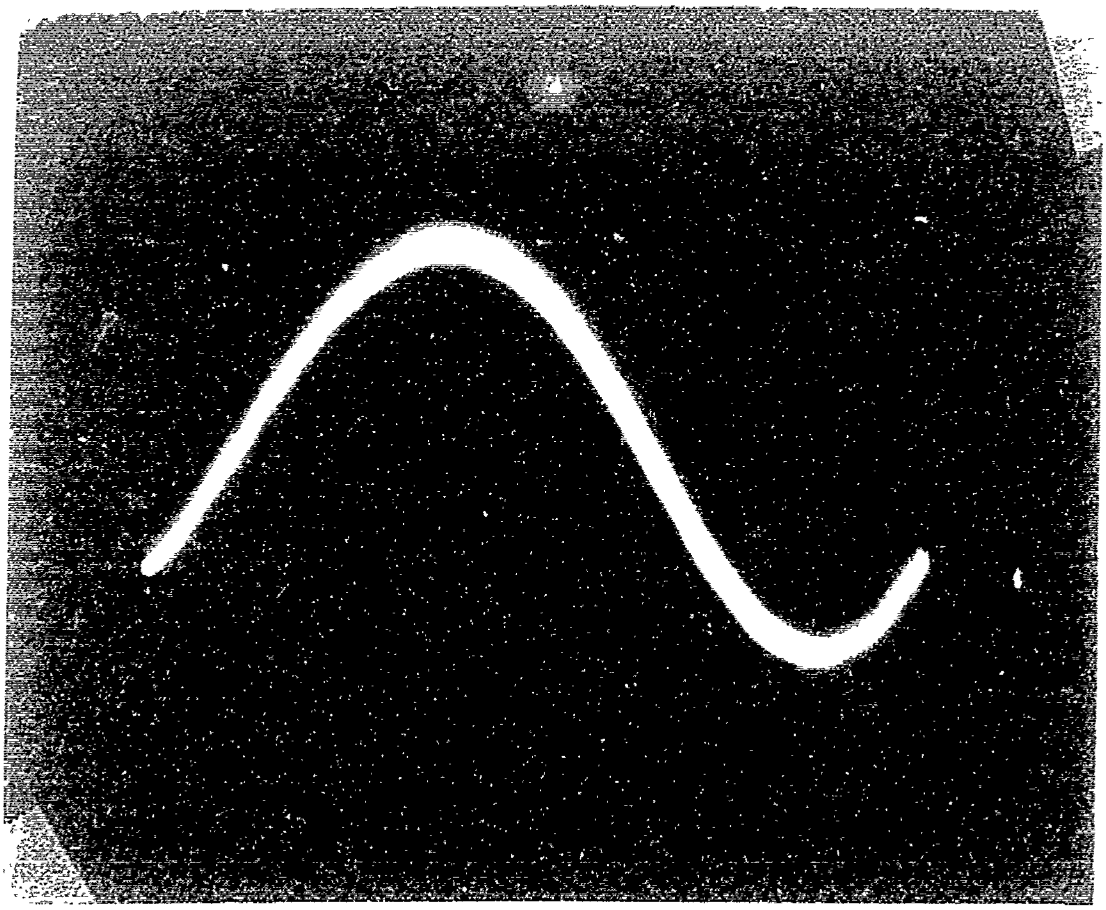
First Set: 29°, 30°, 30°

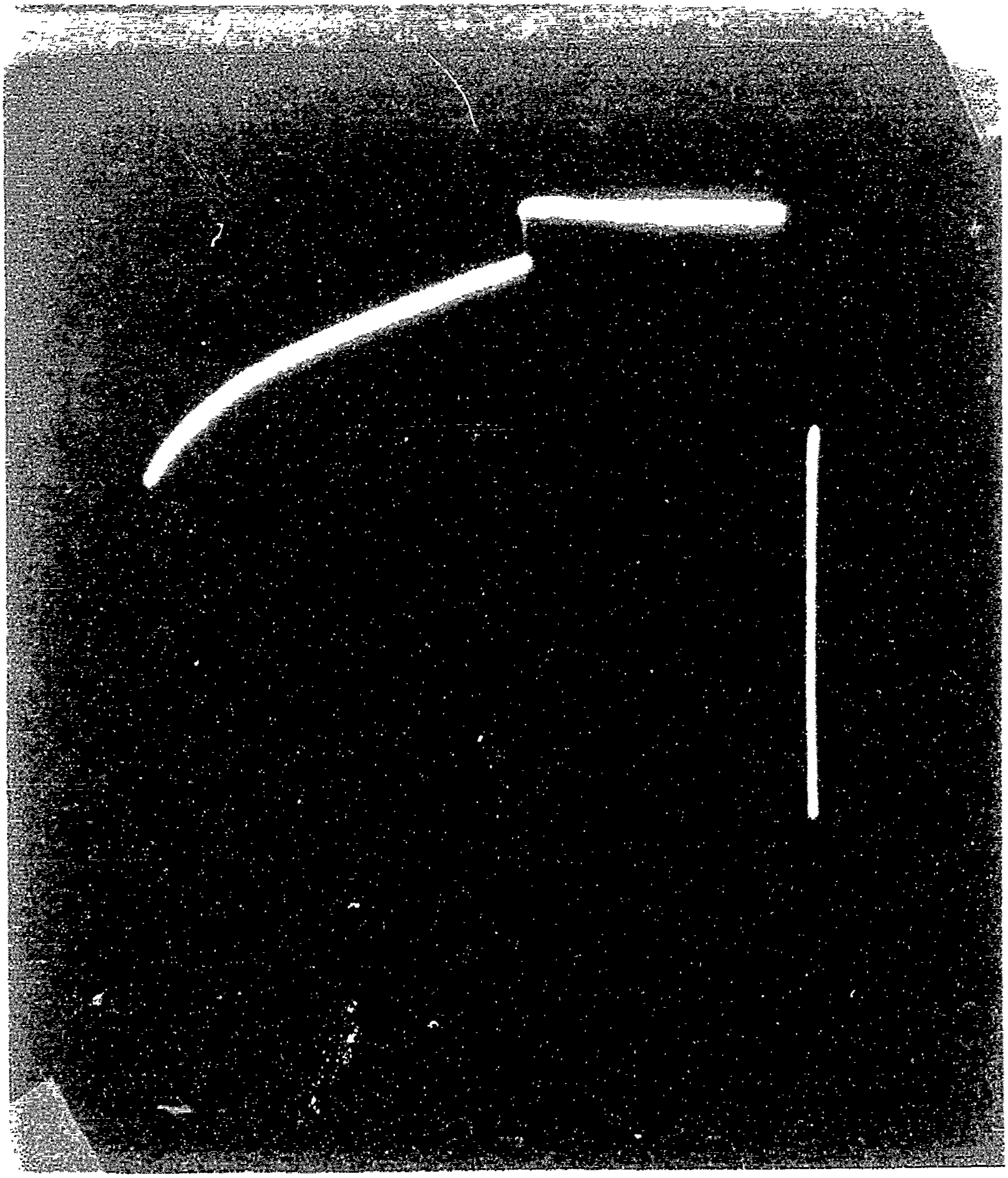
Second Set: 29°, 31°, 32°, 33°

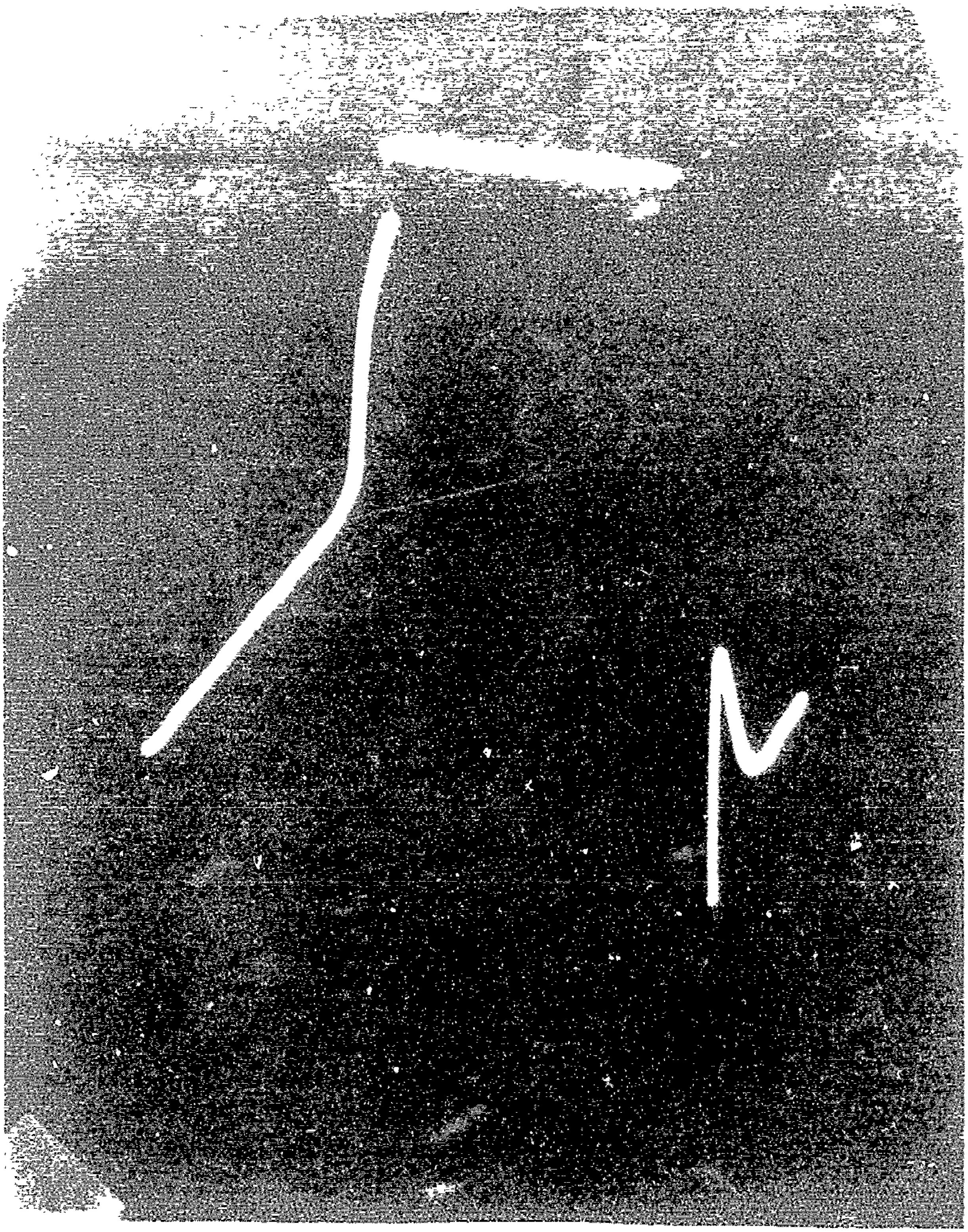
VI. Acknowledgments

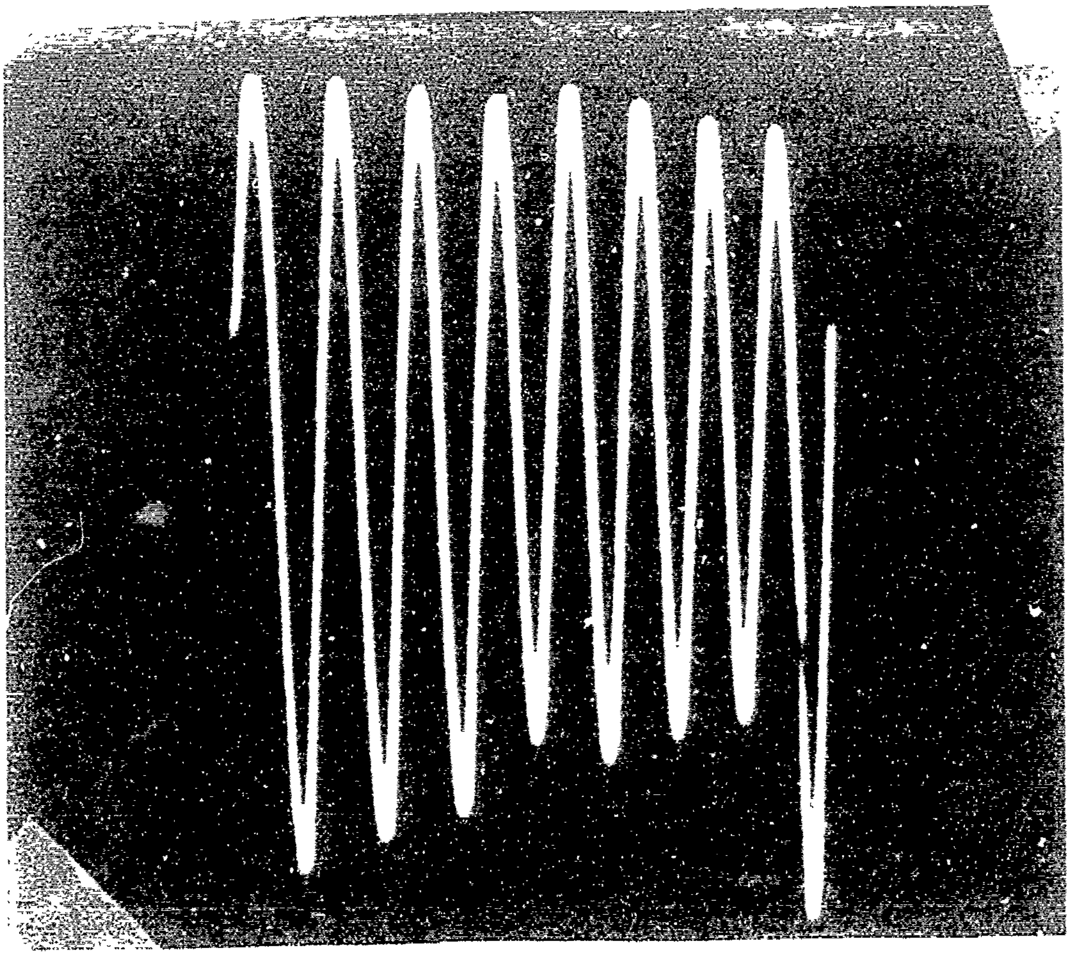
The writer wishes to thank his thesis advisor, Dr. Podolsky, for his many helpful suggestions and his continued encouragement; Mr. Warren F. Stubbins for the use of a regulated power supply which was designed by him and which was employed in conjunction with the standard; and Mr. William Lyon for construction of the differential gear system, and Mr. Frank Maixner for his wiring and drafting and other general assistance.

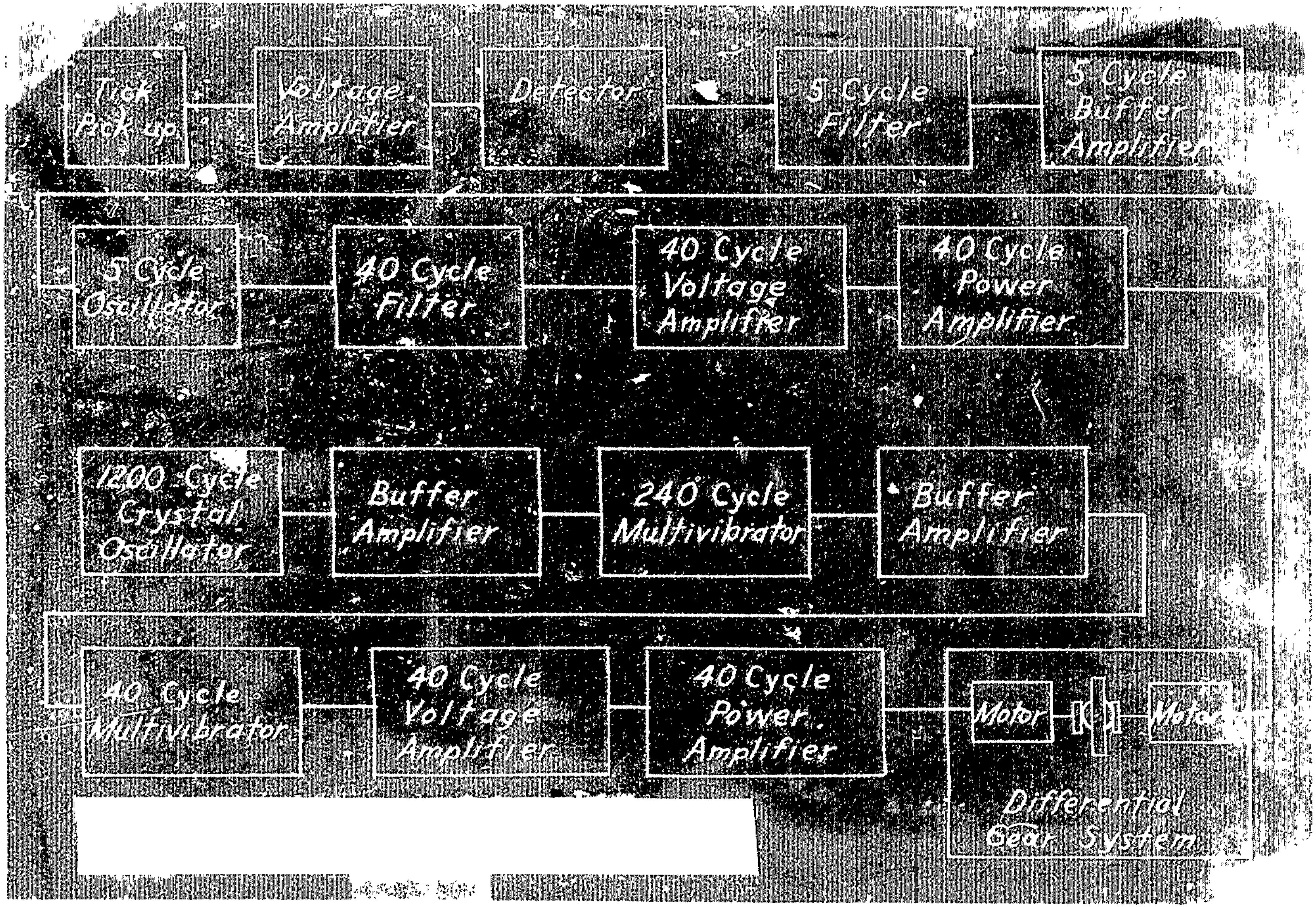


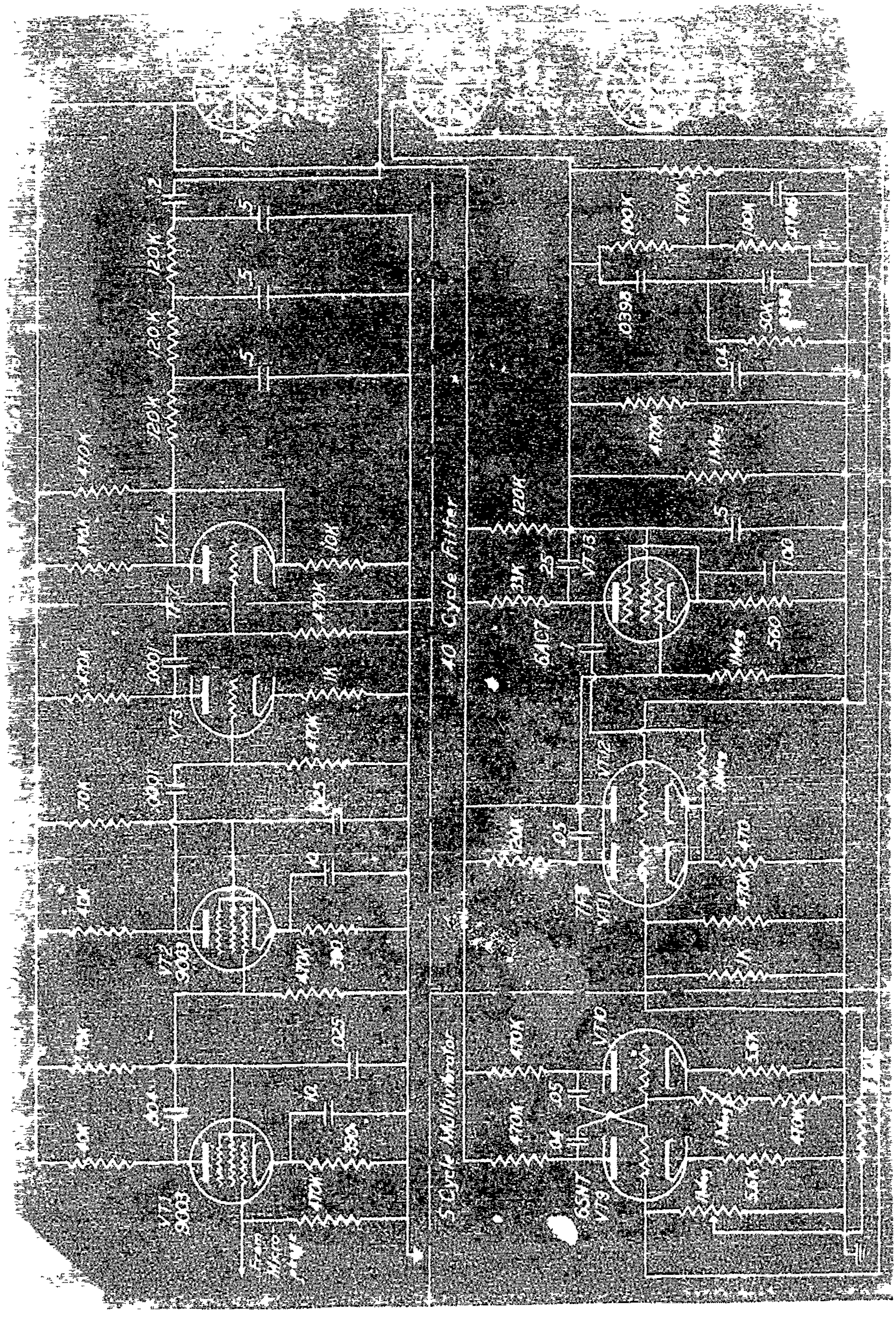









Tick Pick up
Voltage Amplifier
Detector
5 Cycle Filter
5 Cycle Buffer Amplifier
5 Cycle Oscillator
40 Cycle Filter
40 Cycle Voltage Amplifier
40 Cycle Power Amplifier
1200 Cycle Crystal Oscillator
Buffer Amplifier
240 Cycle Multivibrator
Buffer Amplifier
40 Cycle Multivibrator
40 Cycle Voltage Amplifier
40 Cycle Power Amplifier
Motor
Motor
Differential Gear System


From Micro-phone
VT1
9003
VT2
9003
VT3
VT4
7F7
40 Cycle Filter
5 Cycle Multivibrator
6AC7
VT15
VT12
VT11
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VT9
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120K
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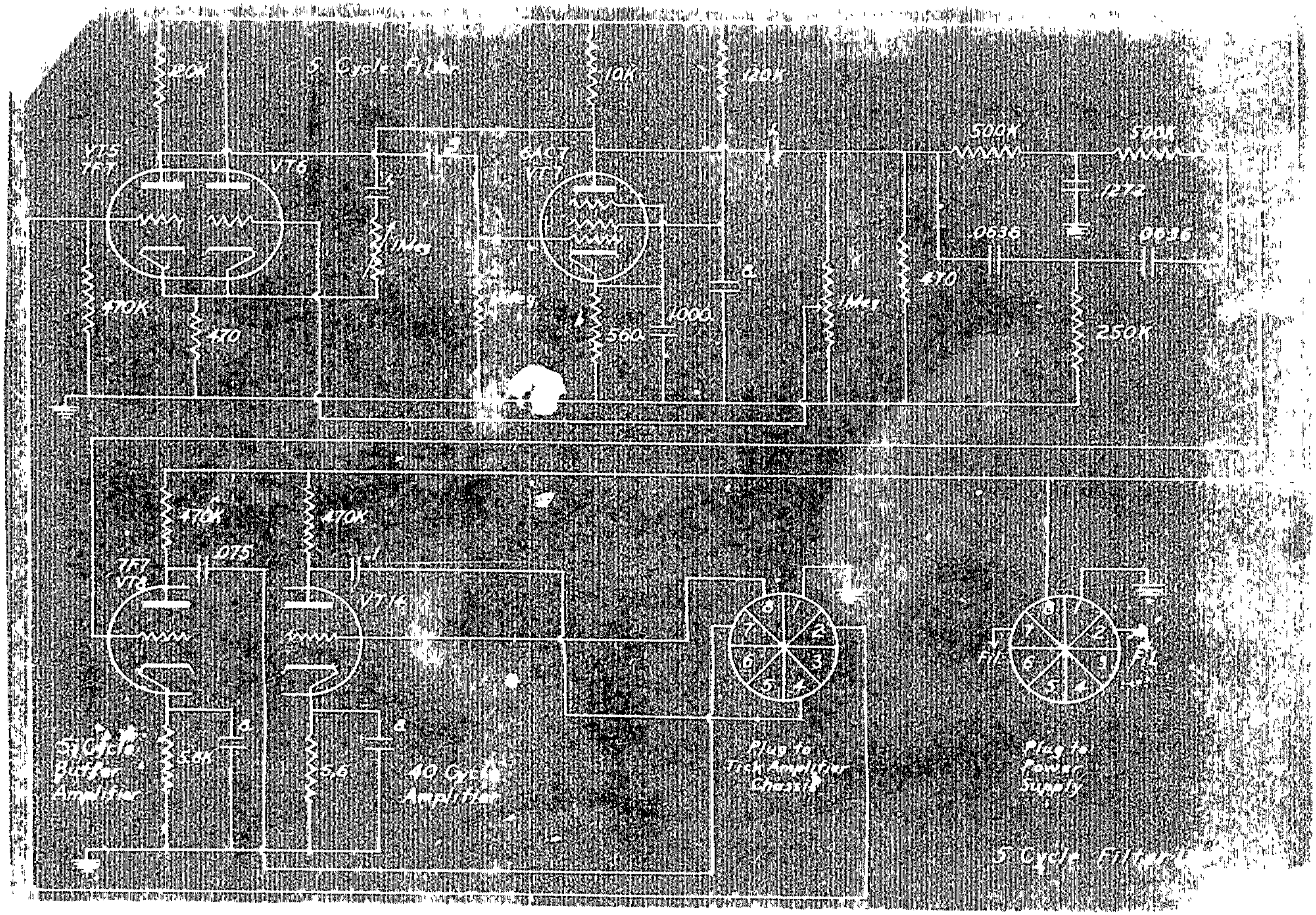
20K
5 Cycle Filter
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VT8
VT14
5 Cycle Buffer Amplifier
5.6K
5.6
40 Cycle Amplifier
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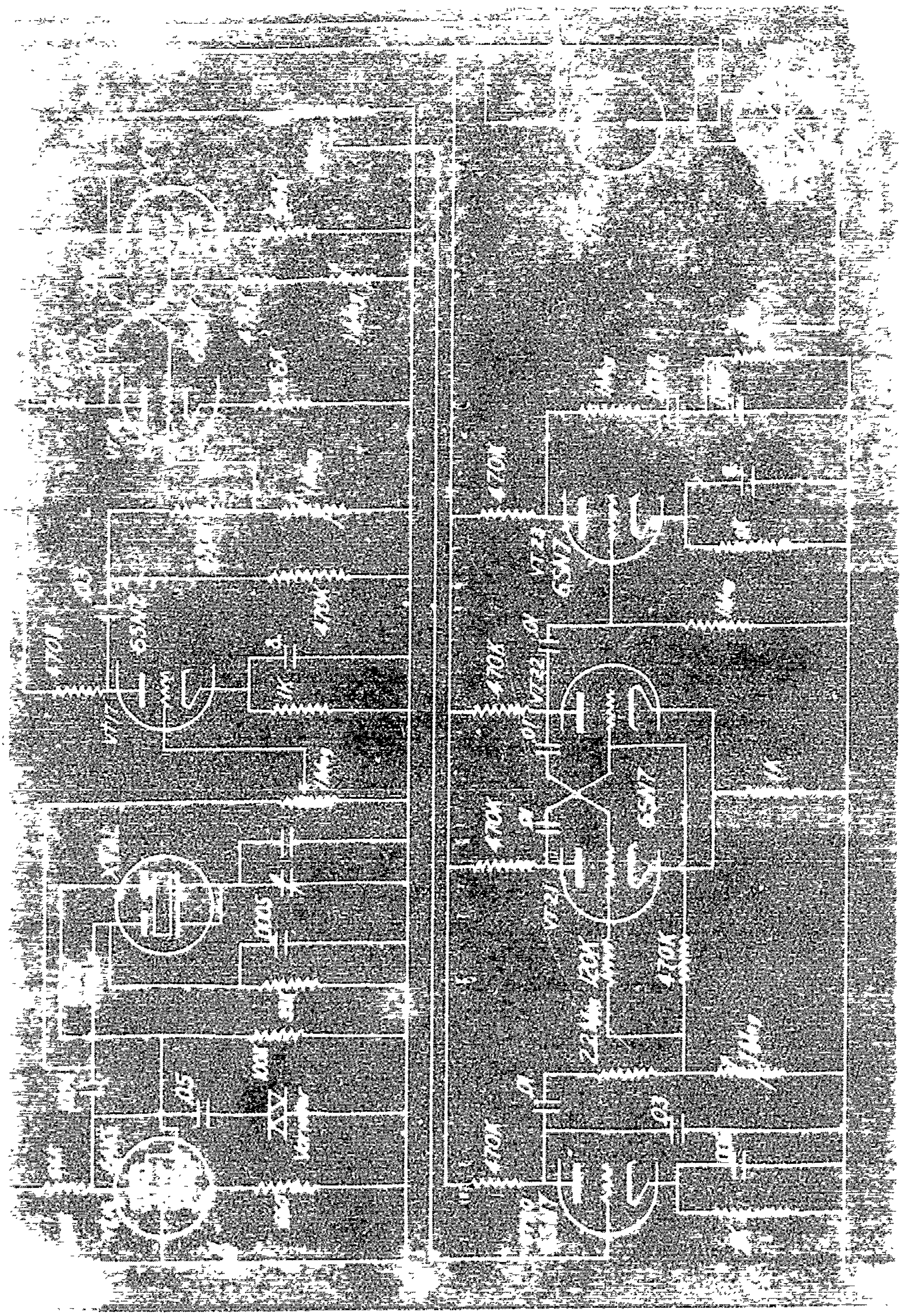
Fil.
Plug to Power Supply
5 Cycle Filter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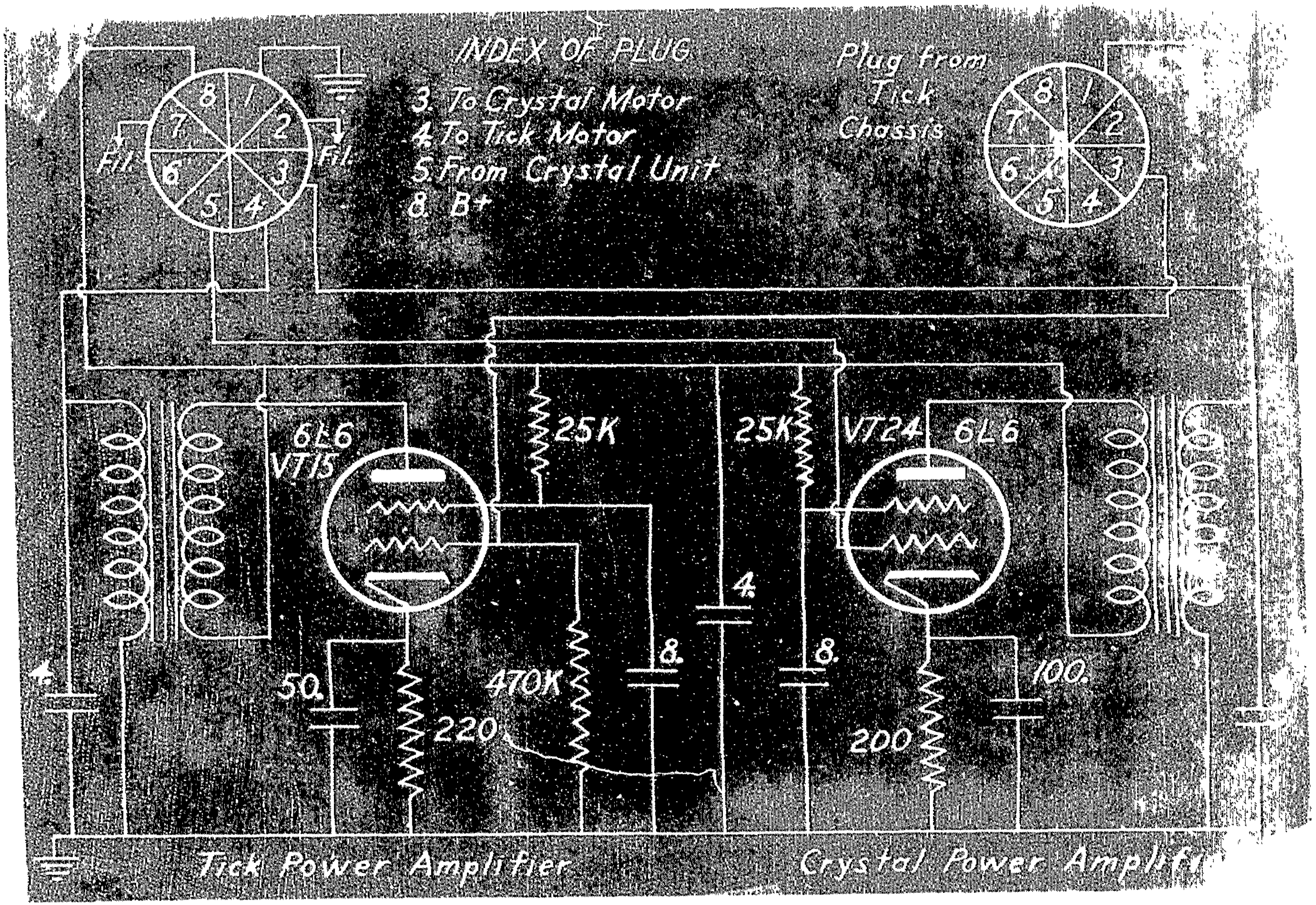
V17
V21
V22


INDEX OF PLUG
3. To Crystal Motor
4. To Tick Motor
5. From Crystal Unit
8. B+
Plug from Tick Chassis
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6L6
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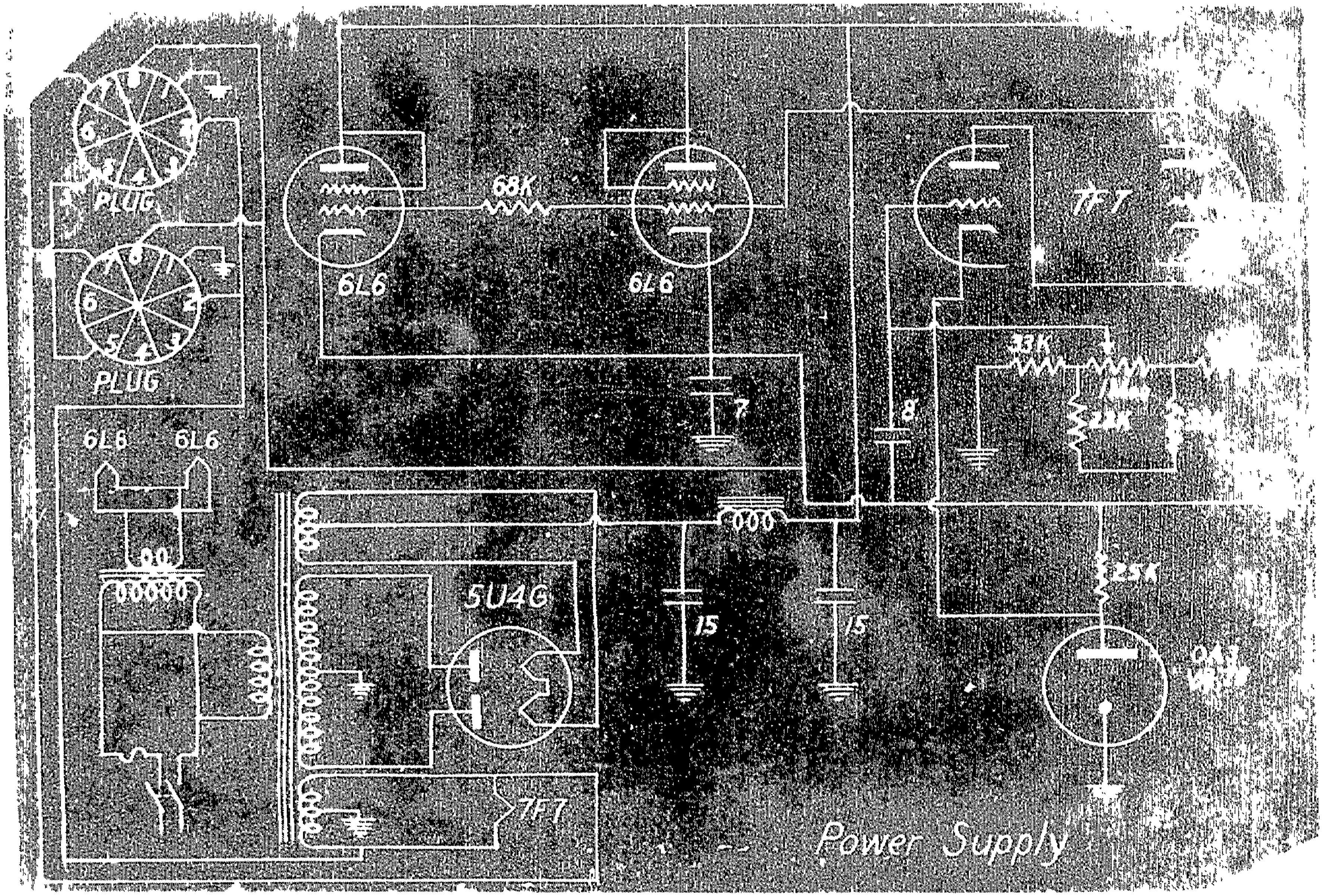
Crystal Power Amplifi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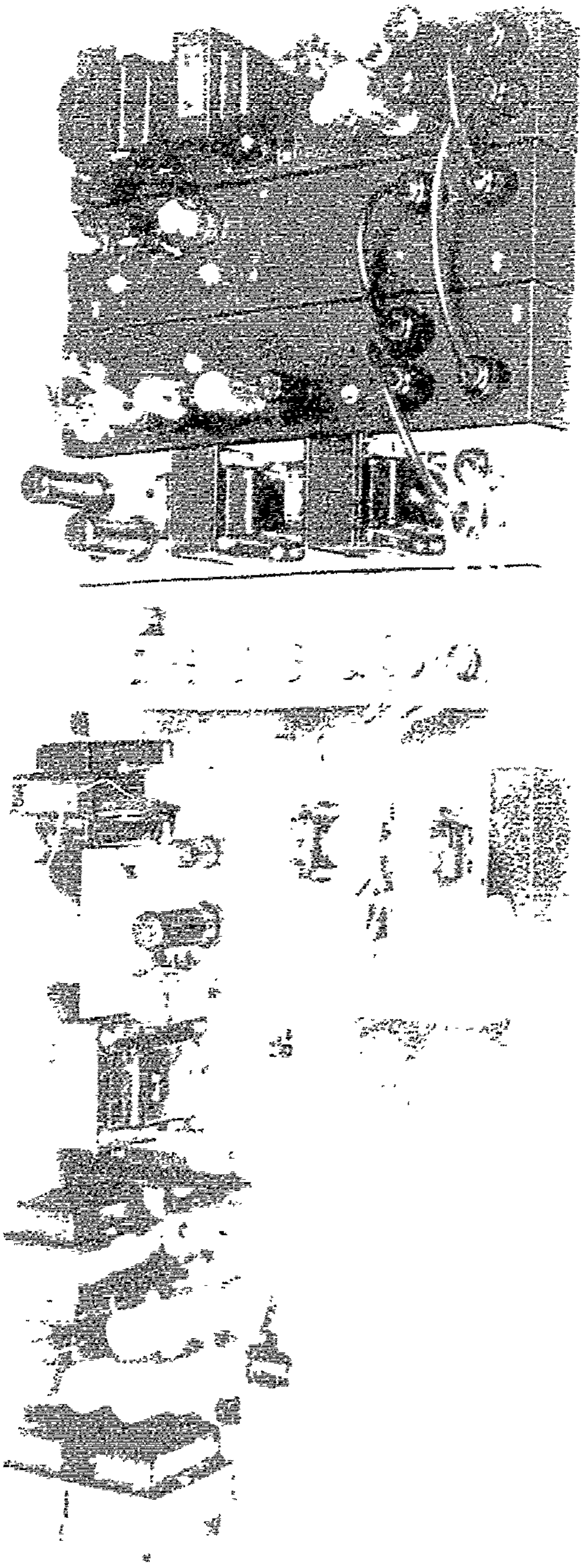
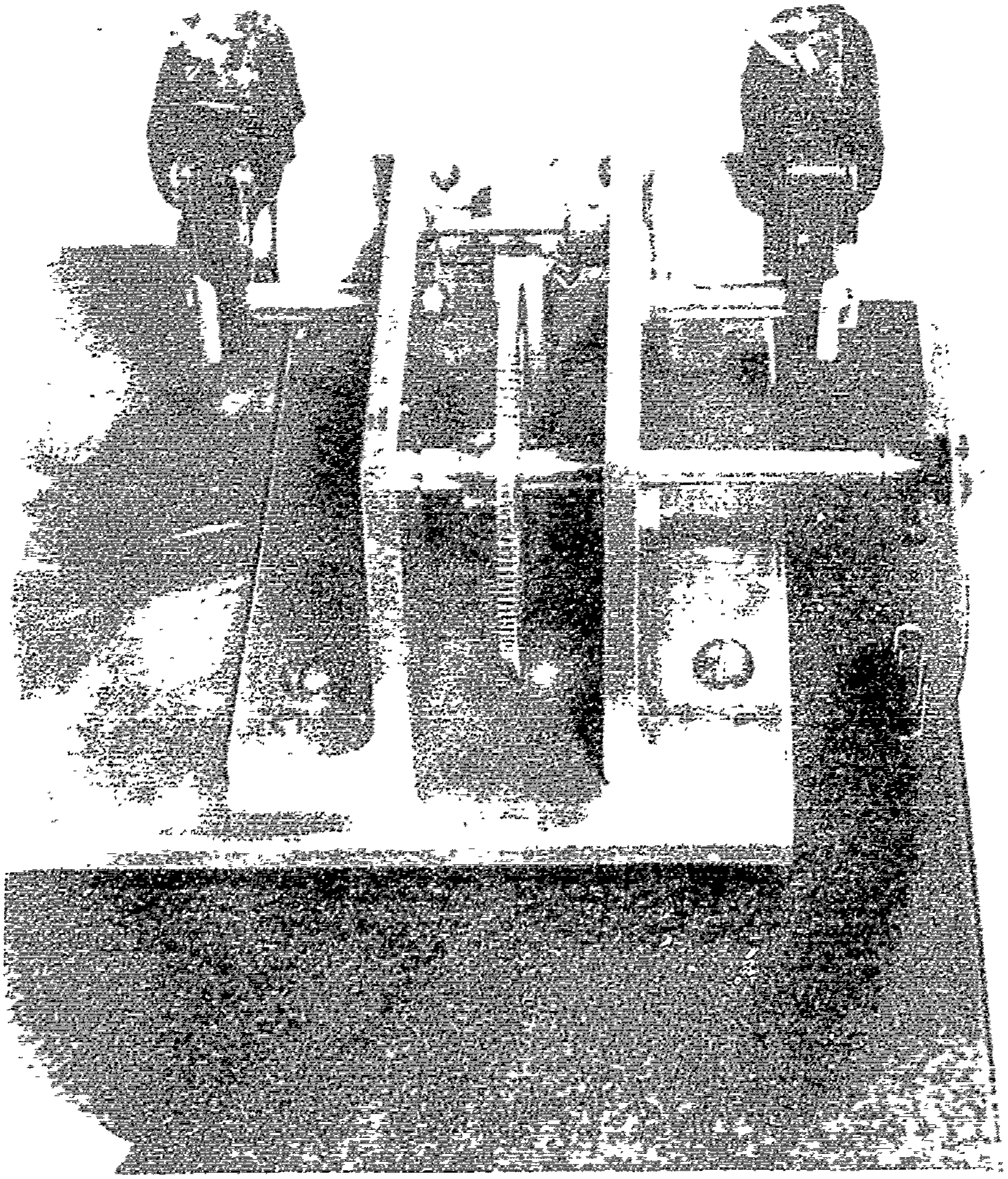
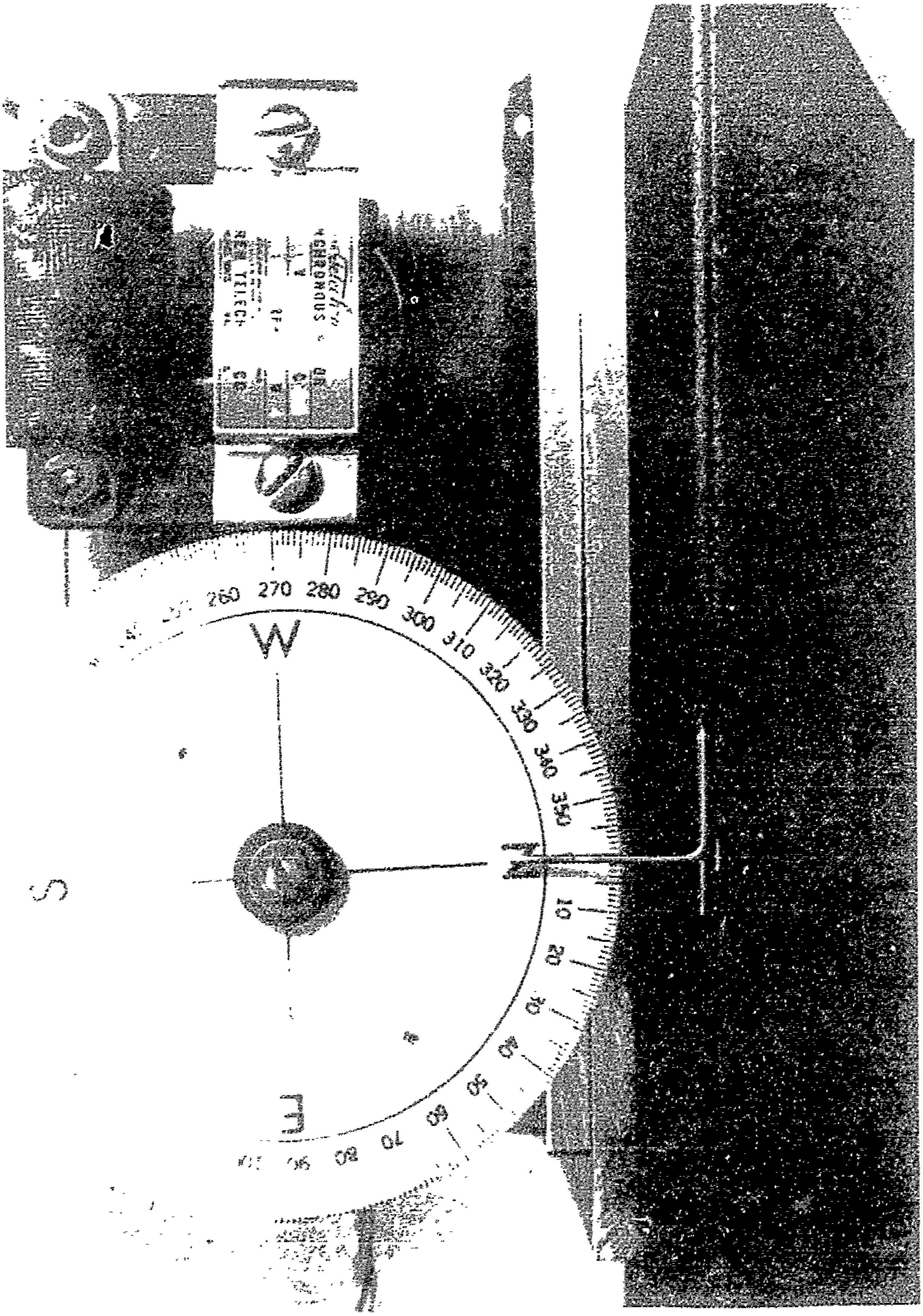
Power Supply






CHRONOUS
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