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STANDARDIZATION OF FREQUENCY

By

Seikichi JIMBO

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ELECTROTECHNICAL LABORATORY,
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SYNOPSIS

This paper consists of the following articles:

I. Measurement of frequency.
   1. Stroboscopic method.
   2. Phonic motor method.
   3. Harmonic comparison method.

II. Standard frequency oscillators.
   1. Introduction.
   2. Clock-controlled oscillator.
   3. Tuning-fork oscillator.
   4. Quartz oscillator.

III. Resonators.
   1. Theory of resonator.
   2. Experimental results.

In various methods of measuring frequency, the author has recommended

Stroboscopic method and Phonic motor method. The accuracies in these methods can be nearly one a hundred thousandth. The stroboscopic method in this paper stands on a high sensitive speed governor which is a modified form of Hough and Wenner's type improved by the author. The harmonic comparison method presented in this paper consists of a multi-frequency oscillator, a selector circuit and a frequency bridge.

The author has proposed various oscillators as the primary standard of frequency which must be furnished with the following conditions.

(1) The frequency does not depend on the circumference, such as the ambient temperature.

(2) Permanency of frequency.

The clock-controlled oscillator contrived by the author consists of a valve-maintained tuning-fork oscillator and a chronometer, and its principle has been illustrated by the automatic synchronization in mechanical vibrating system. The performances of various kinds of tuning-fork oscillators have been investigated, and it has been pointed out that the important factor to exert a remarkable effect on the frequency is the magnetization of fork. The author has presented a tuning-fork oscillator which has such a magnetic device as the electromagnetic controlling force acting on the fork is extremely small.

The performances of quartz oscillators have been investigated about the longitudinal, lateral and torsional vibrations of quartz.

The author has proposed various resonators as the working standard of frequency which must be furnished with the following conditions.

(1) The resonant frequency slightly depends on the circumstance such as the ambient temperature.

(2) Resonant sharpness must be as great as possible.

The author has classified the resonators into the electrical type and the mechanical type. Various frequency bridges and wave meter belong to the former, while fork-type frequency meter, sonometer-type resonator and quartz resonator belong to the latter. The resonant sharpness has been defined and those of various resonators have been investigated theoretically and experimentally. The resonant sharpness of these resonators have been tabulated.

CONTENTS

STANDARDIZATION OF FREQUENCY

By

Seikichi JIMBO

CHAPTER I. INTRODUCTION.

Recently, the precise measurement of frequency is becoming more and more important. The author has endeavoured to establish the standard of frequency.

In this paper, firstly the absolute measurement of frequency has been described and secondly various primary standards of frequency have been investigated theoretically and experimentally. Finally, the behaviour of working standard of frequency has been studied.

Since the frequency is the reciprocal of time, the standard of time as well as the measurement of time-interval will be most important factors throughout the present problem. As the primary standard of time in this experiment, the author has used a standard clock—Clemens Riefler Co., B type—which has been corrected against the standard clock at the astronomical observatory at MITAKA by means of the radio-signal. As the working standard of time, a chronometer—Nardin Co., first class, (48 hours)—has been used. The time-interval is measured by the chronometer and a strip chronograph as shown in Fig. 1. The former is corrected against the standard clock before and after the measurement, and the latter can be operated at the constant speed and the distance between the dots on tape per second is 250 mm. So that in this device, we can expect so large accuracy in the time-interval as four thousandth per second, and the measurement during only six minutes will enable us satisfactorily to obtain an accuracy such as one a hundred thousandth.

CHAPTER II. MEASUREMENT OF FREQUENCY.

1. Stroboscopic Method.

The radio frequency will be usually measured by means of harmonic comparison with an audio frequency standard. Then the absolute measurement of audio frequency must be firstly concerned.

The author recommends Stroboscopic method as well as Phonic motor method as the most precise method of measuring audio frequency. As already known, the measuring device in stroboscopic method consists of a sector revolving at a constant speed and a glim-lamp illuminating the above sector, as shown in Fig. 3. If the frequency of pressure striking the glim-lamp is equal to that of revolution of pattern in the sector, the pattern looks as if it stands still. When the pattern moves so slowly as the rate of its movement can be counted, the frequency of pressure f can be written as

$$f=f_m \cdot N \pm n/T \quad \ldots\ldots\ldots\ldots \quad (1)$$

where f_m is the revolving speed of the sector disc, N the number of patterns in the sector, T the measured time interval required to n displacements of pattern. n/T must be ~~positive~~ negative when the direction of movement of pattern coincides that of the sector disc.

The most important point in stroboscopic method will be the constancy in running of the sector disc. There are many devices of the constant speed-governor, such as that by Prof. E. Giebe. The author has succeeded to perform a highly sensitive speed governor as shown in Fig. 2. The author's device is somewhat similar to that by R. H. Hough and F. Wenner in its principle, while there is a remarkable improvement in the present device. The principle of this governor stands on the synchronism of the running of motor with the vibration of tuning fork. In the new device, a half ring commutator is on the shaft of a D. C. motor which is separately excited. Two brushes on this commutator are connected to the terminals of a non-inductive adjustable resistance r in the field circuit of motor through the commutator brushes which are the wires stretched tangentially on the commutator operated by a phonic motor.

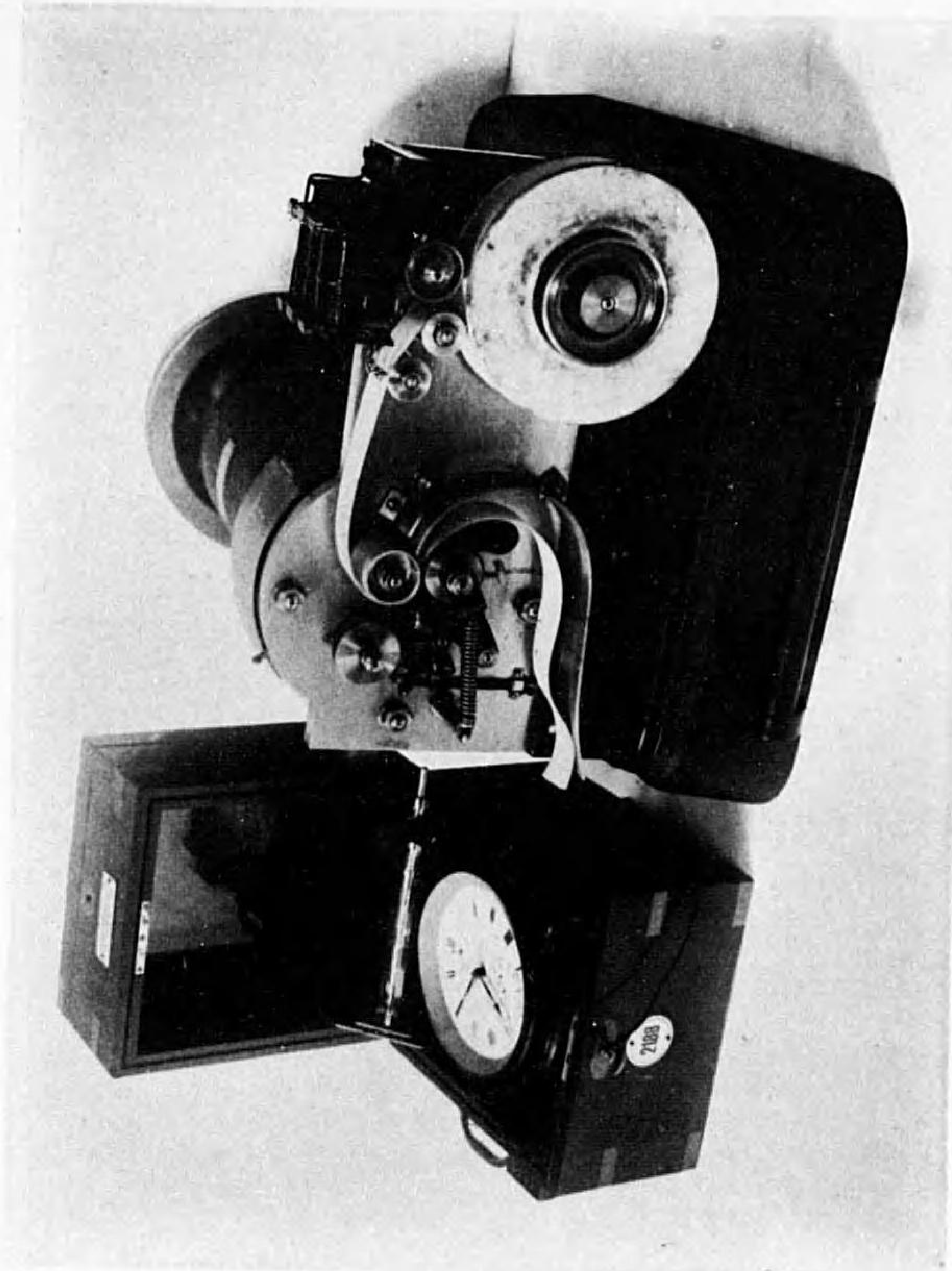

Fig. 1

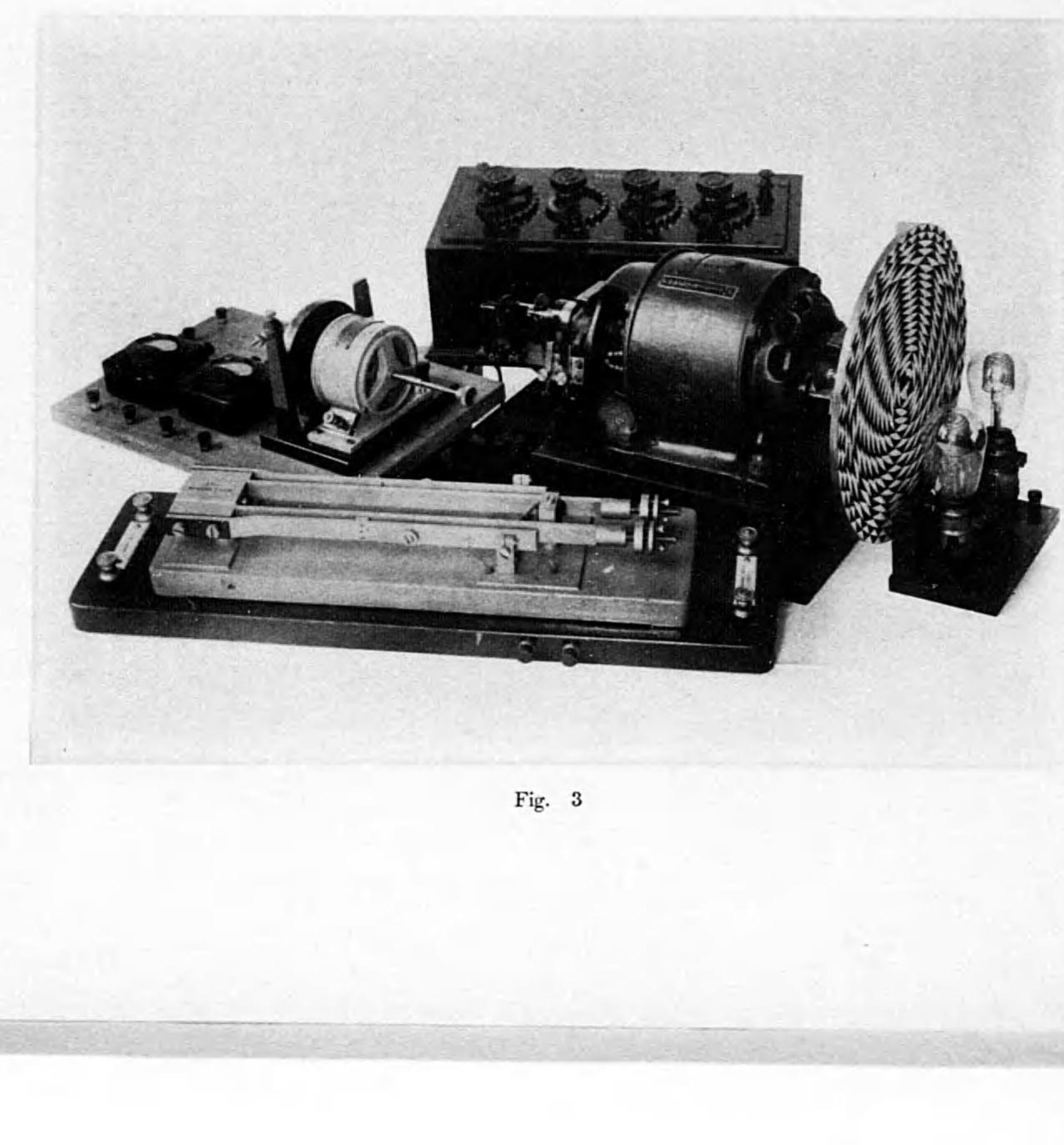

Fig. 3

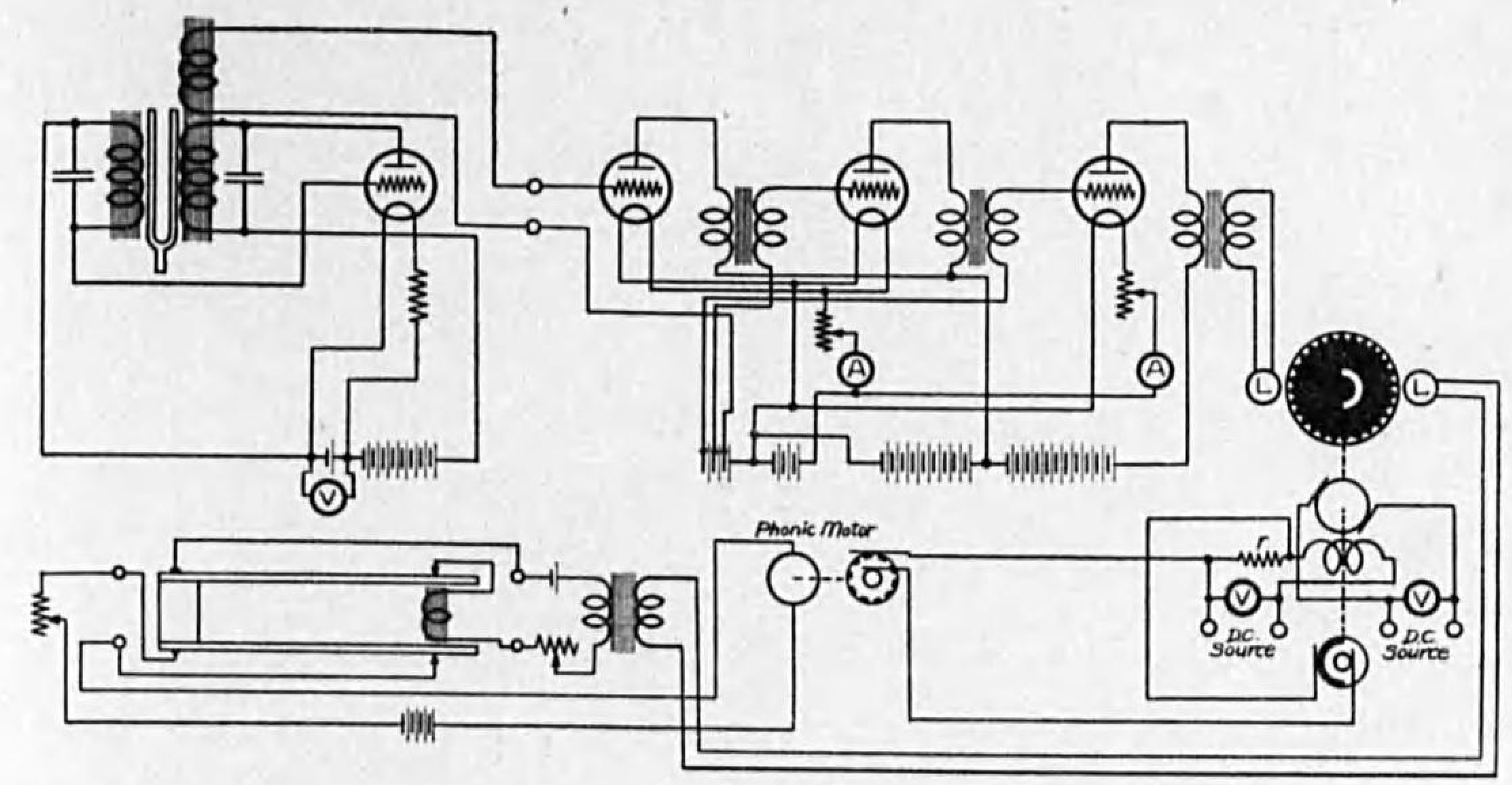

FIG. 2.

The latter commutator consists of ten segments and its diameter is 10 cm, and it will act as a fly-wheel to prevent the hunting of phonic motor. The phonic motor and the tuning fork of 25 cycles per sec. are of Tinsley-Wood type. (S. 11) (S. 21). Now if due to any cause the speed of motor is slightly decreased, the time interval short-circuiting the resistance *r* decreases and consequently the field current decreases until it is sufficient to keep the running of motor from falling below synchronism.

As in this device the commutators are used as the electrical contact, the time interval short-circuiting the resistance is reliable, consequently the performance of

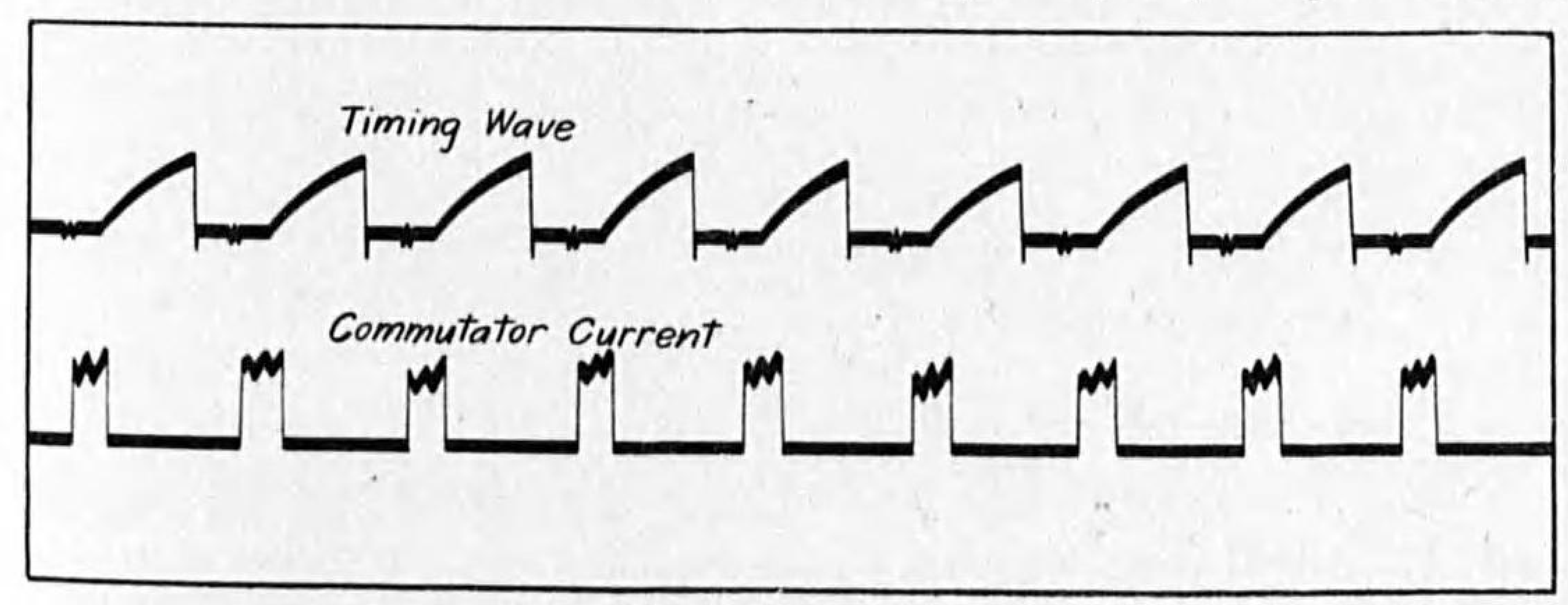

FIG. 4.

governor is sufficient. The motor is of 1/8 H.P. and made by Simens-schuckert. It is ascertained experimentally that the governor is most sensible when the time interval short-circuiting the resistance is 1/4 of the period corresponding to one complete revolution of motor, as shown in Fig. 4, and moreover the resistance r is 285 ohm and the exciting voltage 90 volt. The constancy of tuning fork shall be an important matter in this device. It is investigated by comparing two dots on the tape of the chronograph as shown in Fig. 1, one of which is made at the rate of once per second by an electric contact on the phonic motor operated by the tuning fork and the other by the chronometer. The experimental result during 20 minutes as shown in Fig. 5 shows the constancy of this fork to be sufficient. It will be noticeable that the wave form of the pressure striking the glim lamp must be steep to obtain a clear pattern.

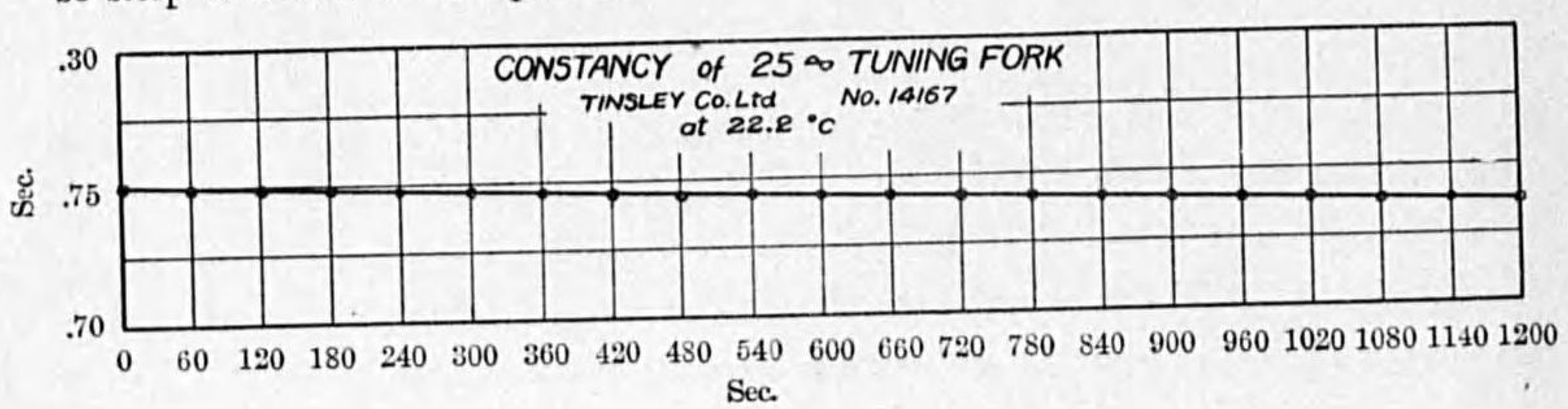

FIG. 5.

By this stroboscopic method with the above speed-governor, the author has succeeded to obtain the accuracy of one a hundred thousandth at the measurement of frequency of Sullivan standard tuning fork, as shown in the chapter III.

In this method, it will be a most excellent point that any multiple frequencies, such as 50, to 1025, can be easily measured. The author thinks that this governor will be available to miscellaneous applications, such as Maxwell bridge of measuring capacity and chronograph.

2 Phonic-Motor Method.

The phonic motor has been contrived by La Cour and Lord Rayleigh. The high frequency motor sufficiently operated by a small power valve has been presented by D. W. Dye (M. 13) and recently by J. W. Horton and W. A.

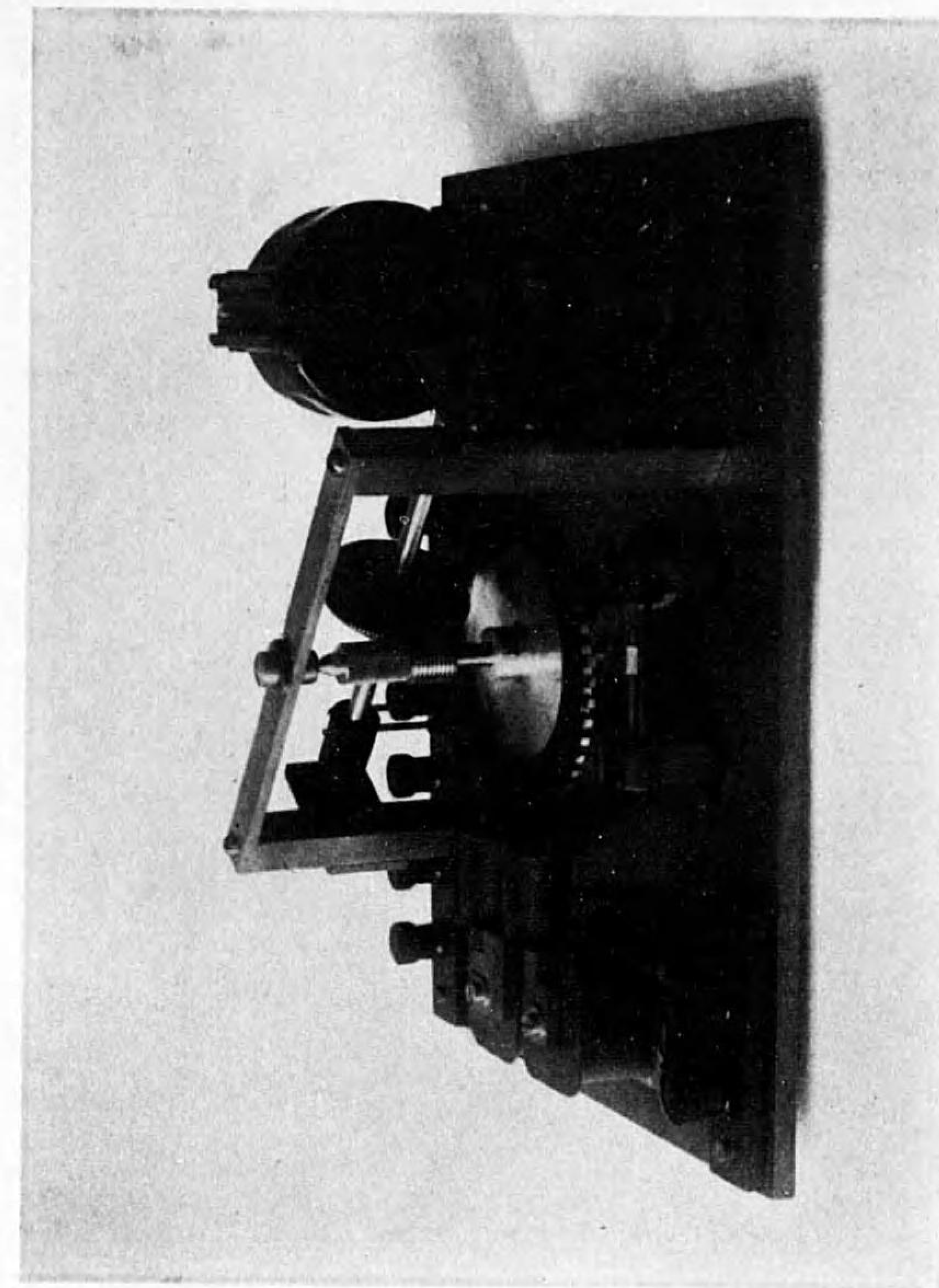

Fig. 6

Marrison (M. 27). The author has designed a phonic motor as shown in Fig. 6 which has 50 teeth and two pairs of poles. This motor can be sufficiently operated by a UX-171 valve from 100 to 700 cycles per second; for the frequency over 700 cycles, a synchronous motor made by General Radio Co. is used, until a high frequency motor now being designed is completed. In the phonic motor method, the hunting of motor will be noticeable. To prevent the hunting, the mercury is frequently used, while by the stroboscopic method it is ascertained that the mercury is not much sufficient to this purpose. In this point, it will be most important the pole arrangement to be as regular as possible. However perfection is not to be expected in this point, then the running of motor must be so long as to eliminate the effect of hunting from the experimental result.

In this method, we can expect so great accuracy as one a hundred thousandth in frequency.

3. Harmonic Comparison Method.

As already known, the radio frequency can be measured by the harmonic comparison with a standard frequency. There are many methods regarding to this point, such as the multivibrator method and the cathode ray oscillograph method. (M. 3), (M. 12), (M. 13), (M. 14), (M. 16) and (M. 18).

The author has established a method of harmonic comparison as shown in Fig. 7 and Fig. 8. The measuring device consists of a multi-frequency oscillator, a selector circuit and a frequency bridge. The multi-frequency oscillator is somewhat similar to the timing device in Gabor's cathode ray oscillograph. (M. 3) By adjusting the resistance in the plate circuit so as the time constant of the plate circuit is nearly equal to the reciprocal of the circular frequency applied to the grid of valve, the sufficient result can be expected. The oscillating current contains amply the higher harmonics as shown in Fig. 9.

The selector circuit consists of a fixed air condenser, a variable air condenser and a Slektun coil, and its resonant sharpness is sufficiently large.

The resonant sharpness of the frequency bridge is so large as to give the balance within two tenth cycles per second from 100 to 1,500 cycles, and the bridge is calibrated by the phonic motor method. In this method, the frequency

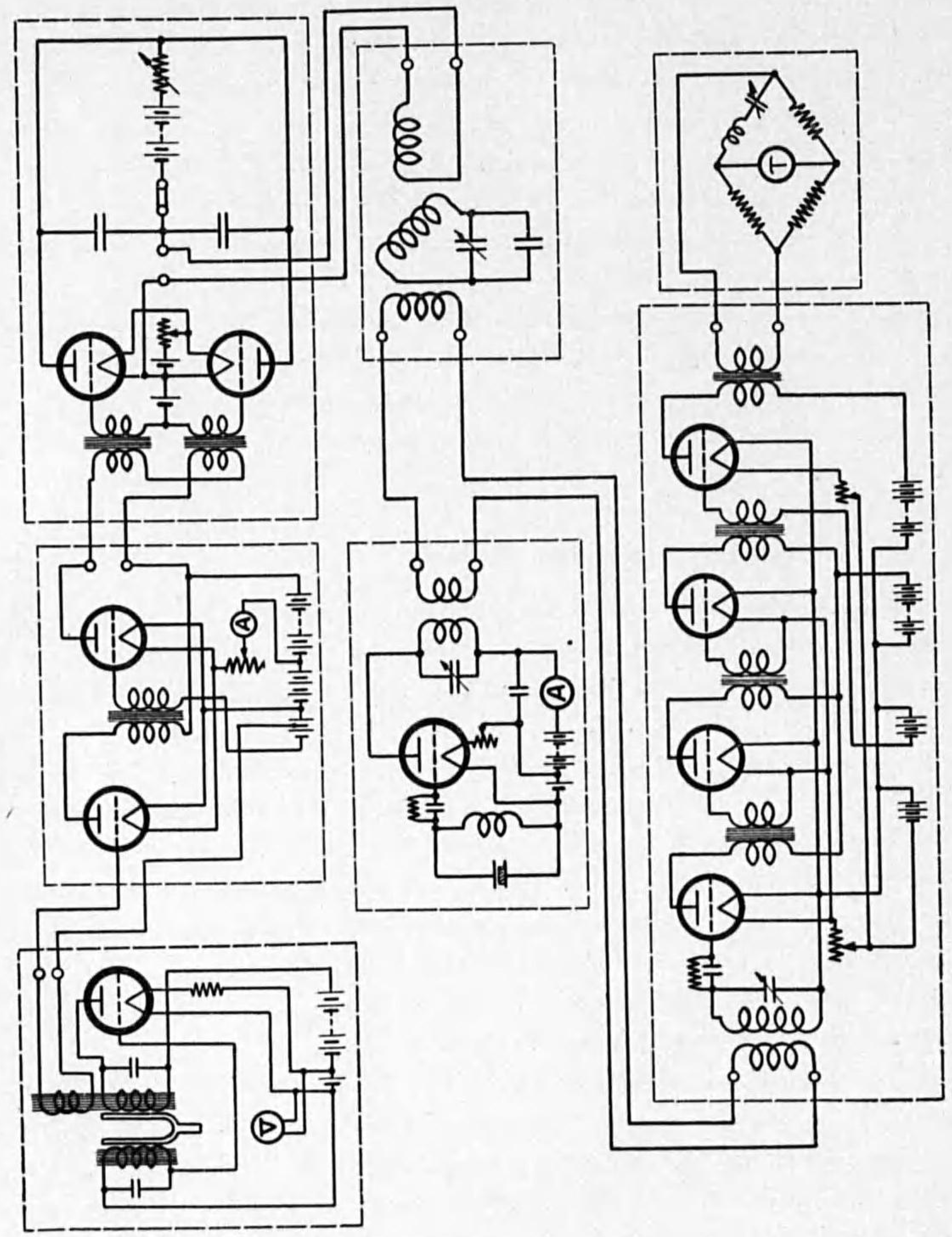

Fig. 7.

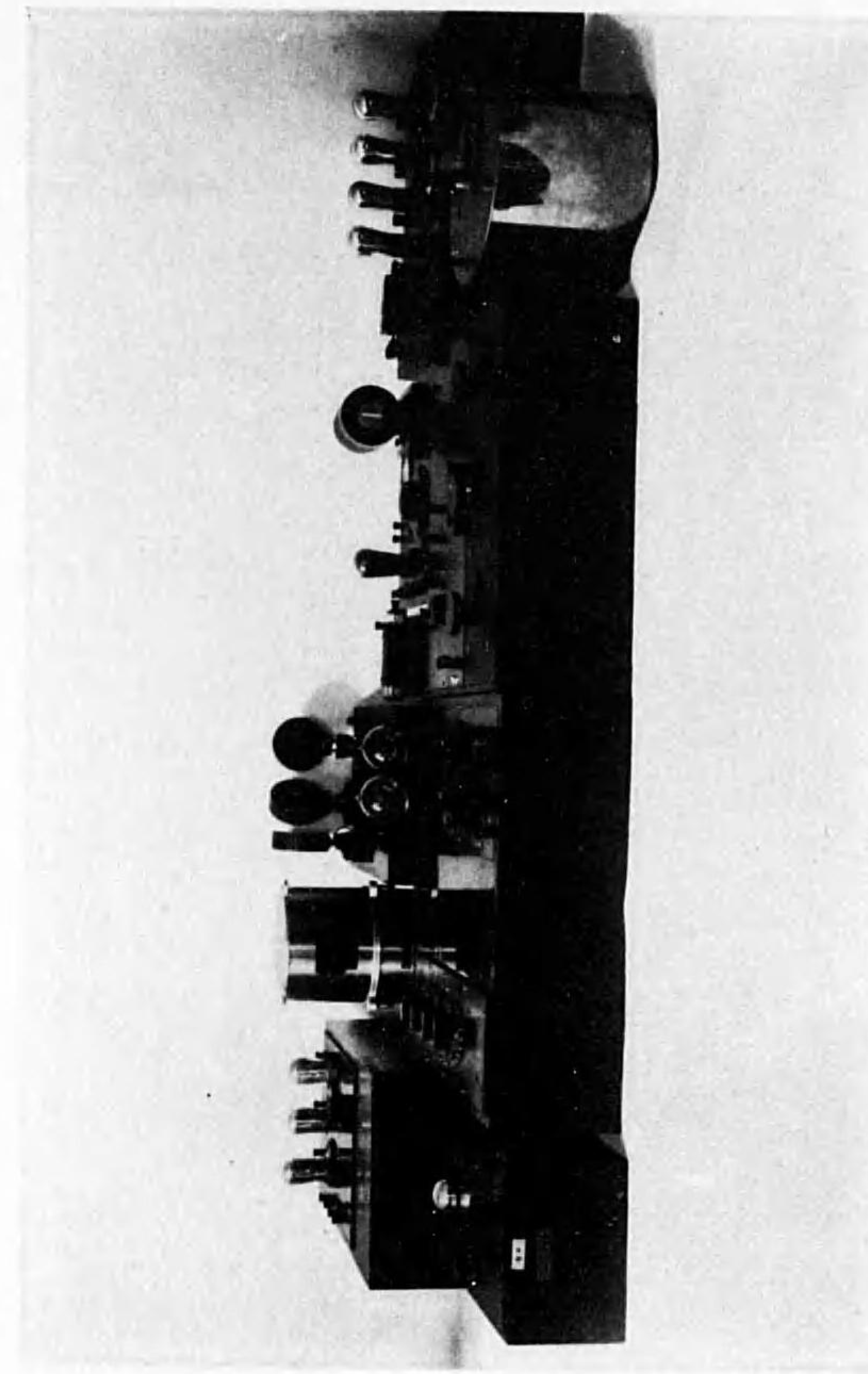

Fig. 8

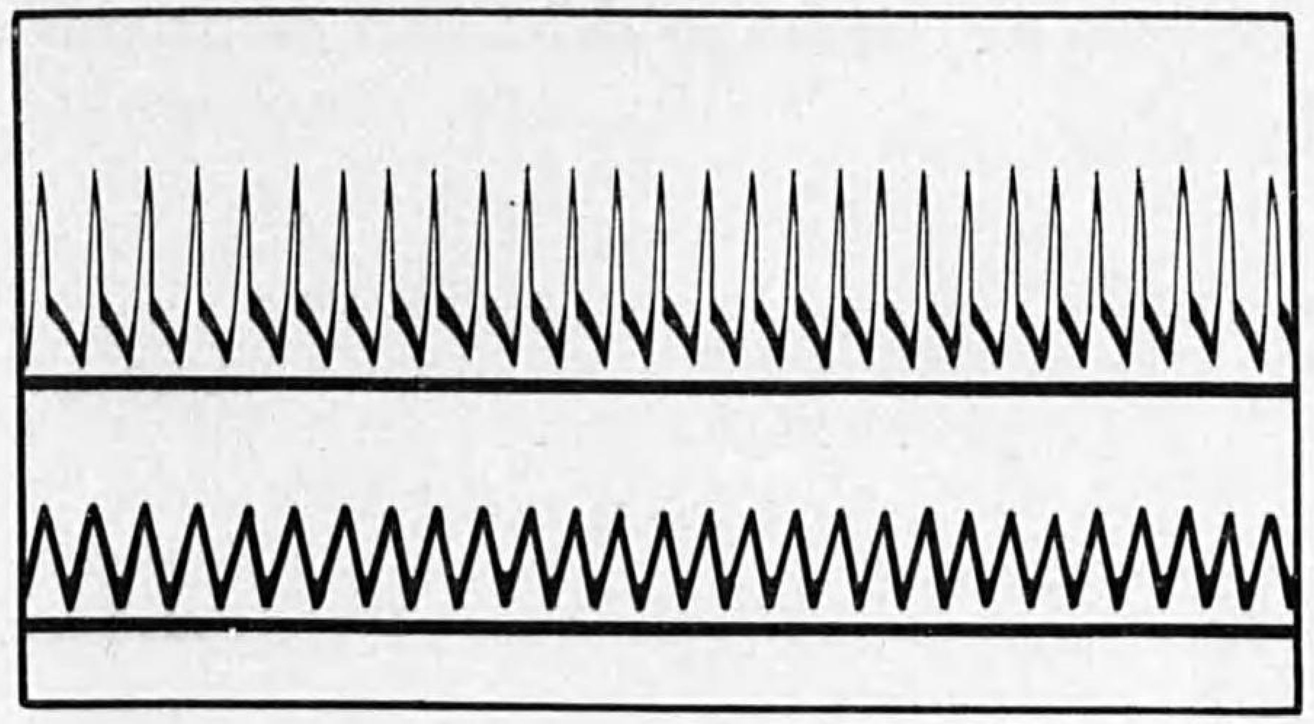

FIG. 9.

to be measured can be easily compared with the 50th harmonic of standard frequency, viz 1024 cycles per second.

The high frequency over 50 KC can be similarly compared with the multiple frequency of a quartz oscillator, the fundamental frequency of which can be determined by the above method, while in this case the multi-frequency oscillator is not necessarily needed. In the method above mentioned, we can expect the accuracy of one a hundred thousandth for any frequencies greater than 20 KC.

CHAPTER III. STANDARD FREQUENCY OSCILLATORS.

1. Introduction.

The absolute measurement of frequency is almost laborious, so that the standard frequency oscillator is needed to preserve the measured result. The standard frequency oscillator must be furnished with the following conditions,

(1) the frequency does not depend on the circumference, such as the ambient temperature,

(2) permanency of frequency.

The oscillators possessed the above conditions can be enumerated to chronometer and mechanical vibrator, namely

(1) Clock-controlled oscillator.

(2) Tuning-fork oscillator.

(3) Quartz oscillator.

Now we will consider of the performance of mechanical vibrator.

There are the longitudinal, lateral and torsional modes of vibration due to the elastic wave. Now we consider a thin bar with a rectangular cross section, and the thickness, length and breadth are x, y and z respectively, then the natural frequency of longitudinal vibration can be expressed by

$$f_{lx}=mv_e/2x, \quad f_{ly}=mv_e/2y, \quad f_{lz}=mv_e/2z \quad \cdots\cdots (2)$$

where m is any integer and v_e denotes the propagation velocity of wave.

Now we have

$$v_e=\sqrt{\frac{E}{\rho}}, \qquad v_t=\sqrt{\frac{T}{\rho}} \quad \cdots\cdots (3)$$

where E denotes the modulus of elasticity, T the torsional rigidity and ρ the density.

$$f_b=\frac{k^2 v_e}{4\pi\sqrt{3}}\frac{z}{y^2} \quad \cdots\cdots (4a)$$

and

$$k=\left(m+\frac{1}{2}\right)\pi$$

For the torsional vibration, we have

$$f_t=\frac{mv_t}{2y}\frac{2r}{\sqrt{1+r^2}}\sqrt{1-0.63\,r} \quad \cdots\cdots (5)$$

considering that r, or x/z is less than $1/3$.†

The propagation velocity of wave depends on the physical property of material. In our case, the mechanical vibrator is usually steel or quartz. The propagation velocities of these materials are shown in the following table.

Materials	v_e in cm/sec	v_t in cm/sec
Steel	$4.2-5.2\times10^5$	3.2×10^5
Quartz	5.4×10^5	* 3.5×10^5

* This value may not be corrected.

The tuning fork is a clamped free bar, and according to Load Rayleigh we have

$$f_b=845900\,\frac{z}{y^2} \quad \cdots\cdots (4b)$$

The vibration in the monochord whose length is y is not elastic wave, but its natural frequency will be similarly given by

$$f_c=\frac{v_c}{2y}$$

and

$$v_c=\sqrt{\frac{W}{\rho}} \quad \cdots\cdots (6)$$

where v_c denotes the propagation velocity of vibration, W the tension and ρ the mass of chord per cm. The above equations may not be applicable in practical case, because the actual vibration is too complicate to resolve its performance.

† J. Prescott: Applied Elasticity. (1924)

2. Clock-controlled Oscillator.

A. Dey and C. V. Raman have already shown that the vibration of a mechanical vibrator, whose frequency is f/m where m is any integer, can be maintained by the alternating current of f cycles. The present oscillator is somewhat similar to the above oscillator in its principle.

The similar oscillator has been designed in N. P. L. (S. 20), while in its oscillator the frequency of tuning fork must be adjusted to be within one or two parts in ten thousand of 50 cycles per second. It will be much troublesome and the running will be apt to step out.

The author has contrived a clock-controlled oscillator which consists of a chronometer and a valve maintained tuning fork oscillator, as shown in Fig. 10 and Fig. 11. (Public notice of patent). The principle of this oscillator stands on the automatic synchronization in mechanical vibrator. In the valve maintained mechanical vibrator, the condition to maintain its vibration is nothing but that the damping factor becomes zero. While the damping factor of mechanical vibrator, such as tuning fork, will increase in proportion as the amplitude of vibration increases.

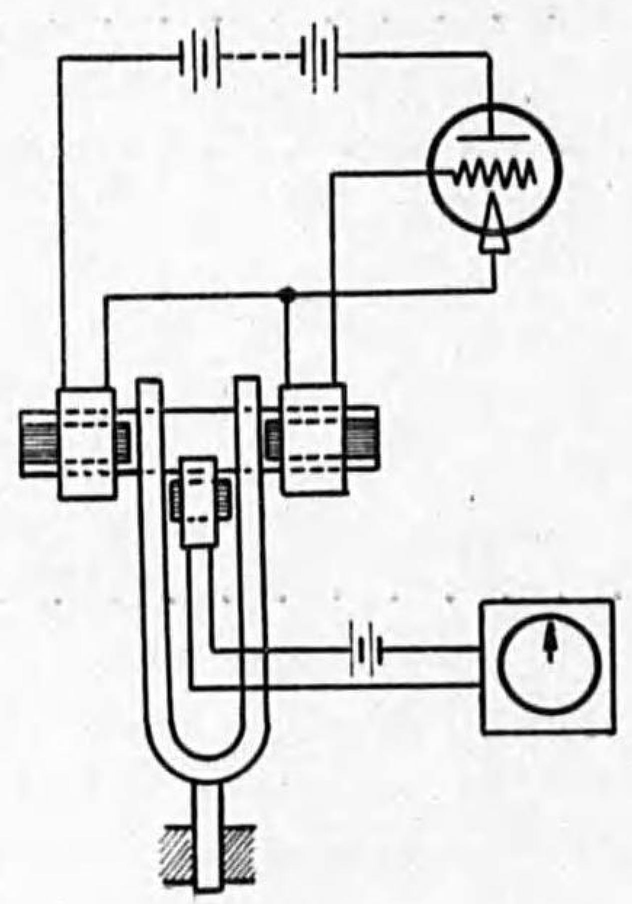

Fig. 10.

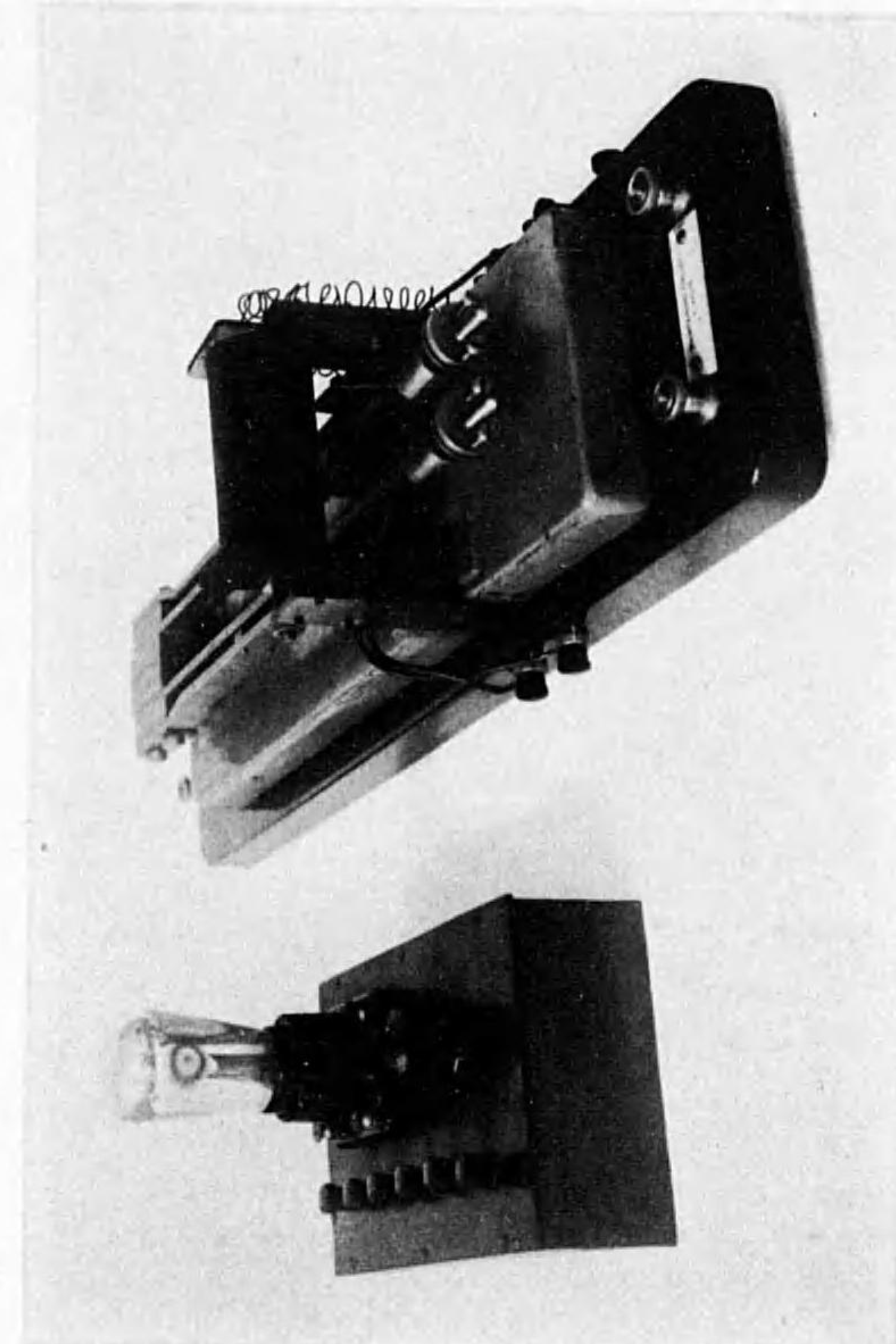

Fig. 11

Now we consider of a case where the free oscillation as well as the forced oscillation coexist. If the frequency of the latter be largely deviated from that of the former, the vibration due to the latter will be extremely small, so that the free oscillation only is remarkable; while if the frequency of the latter approaches with that of the former, the phenomena of resoncence will be remarkable, then the amplitude of vibration becomes large, and consequently the free oscillation comes no longer to be continued. In this case the forced oscillation only is remarkable. This is considered to be an important cause of the automatic synchronization in the valve maintained mechanical vibrator. In this vibrator, the damping is arisen from the mechanical and electromagnetical causes. According to the previous paper (S. 11), the damping constant in the tuning fork can be written

$$\beta=\beta_1+\beta_2 Y \qquad (7)$$

where Y is the amplitude of fork.

The equation of motion can be obviously given by

$$\left\{\alpha D^2+(\beta_1+\beta_2 Y)D+\gamma\right\}y=\frac{\partial T_e}{\partial y} \qquad (8)$$

where T_e denotes the electro kinetic energy in this system and y is the displacement of fork.

Now putting L_p, L_g, L_m the self inductance of plate coil, grid coil, magnetizing coil, and M_{pg}, M_{pm}, M_{gm} the mutual inductance between two of these coils, and I_0, I the exciting current and the induced current in the magnetizing coil, and I_p, I_g the plate current, the grid current, and supposing that L_p, L_g, M_{pg} are independent of y and I_g is zero and

$$\left.\begin{aligned} L_m&=l_0+l_1 y \\ M_{pm}&=-M_{gm}=m_0+my \end{aligned}\right\} \qquad (9\text{a})$$

then we have

$$\frac{\partial T_e}{\partial y} \doteqdot \frac{1}{2} l_1 I_0^2+l_1 I I_0+m_1 I_p I_0$$

On the other hand

$$I \doteqdot -G_m D(L_m I_0) = -G_m l_1 I_0 Dy$$

and

$$I_p \doteqdot G_v E_g = G_v m_1 I_0 Dy$$

where G_m denotes the conductance of the magnetizing coil and G_v the mutual conductance of valve.

Therefore we have

$$\left\{aD^2 + \beta_e D + \gamma\right\} y = \frac{1}{2} l_1 I_0^2 \quad \ldots\ldots\ldots\ldots \quad (10)$$

where

$$\beta_e = \beta_1 + \beta_2 Y + G_m l_1^2 I_0^2 - G_v m_1^2 I_0^2 \quad \ldots\ldots\ldots\ldots \quad (11)$$

β_e must be zero in order to that the free vibration is maintained.

Now put

$$Y_e = (G_v m_1^2 I_0^2 - G_m l_1^2 I_0^2 - \beta_1) / \beta_2 \quad \ldots\ldots\ldots\ldots \quad (12)$$

If suppose that there is no saturation of triode valve, then the amplitude of fork will gradually increase to the limiting value Y_e, although the amplitude is less than this limiting value. But if due to any causes the amplitude becomes greater than the limiting value, β_2 becomes positive and consequently the free vibration comes no longer to be continued.

On the other hand, the amplitude due to forced vibration can be written.

$$Y = \frac{\sqrt{2} A Y_0}{x\sqrt{1 + A^2\left(x - \frac{1}{x}\right)^2}} \quad \ldots\ldots\ldots\ldots \quad (13)$$

where A denotes the resonant sharpness and x is f/f_0, where f is the applied frequency, f_0 the natural frequency of fork.

In the tuning fork, the resonant sharpness is remarkable large; then the more the forced vibration approaches to the free vibration, the more the amplitude of

fork becomes large, and consequently the free vibration dies away, and the forced vibration only is recognized.

In this device, the tuning fork of 25 cycles per second whose frequency is adjustable is used. According to the experimental result as shown in Fig. 12,

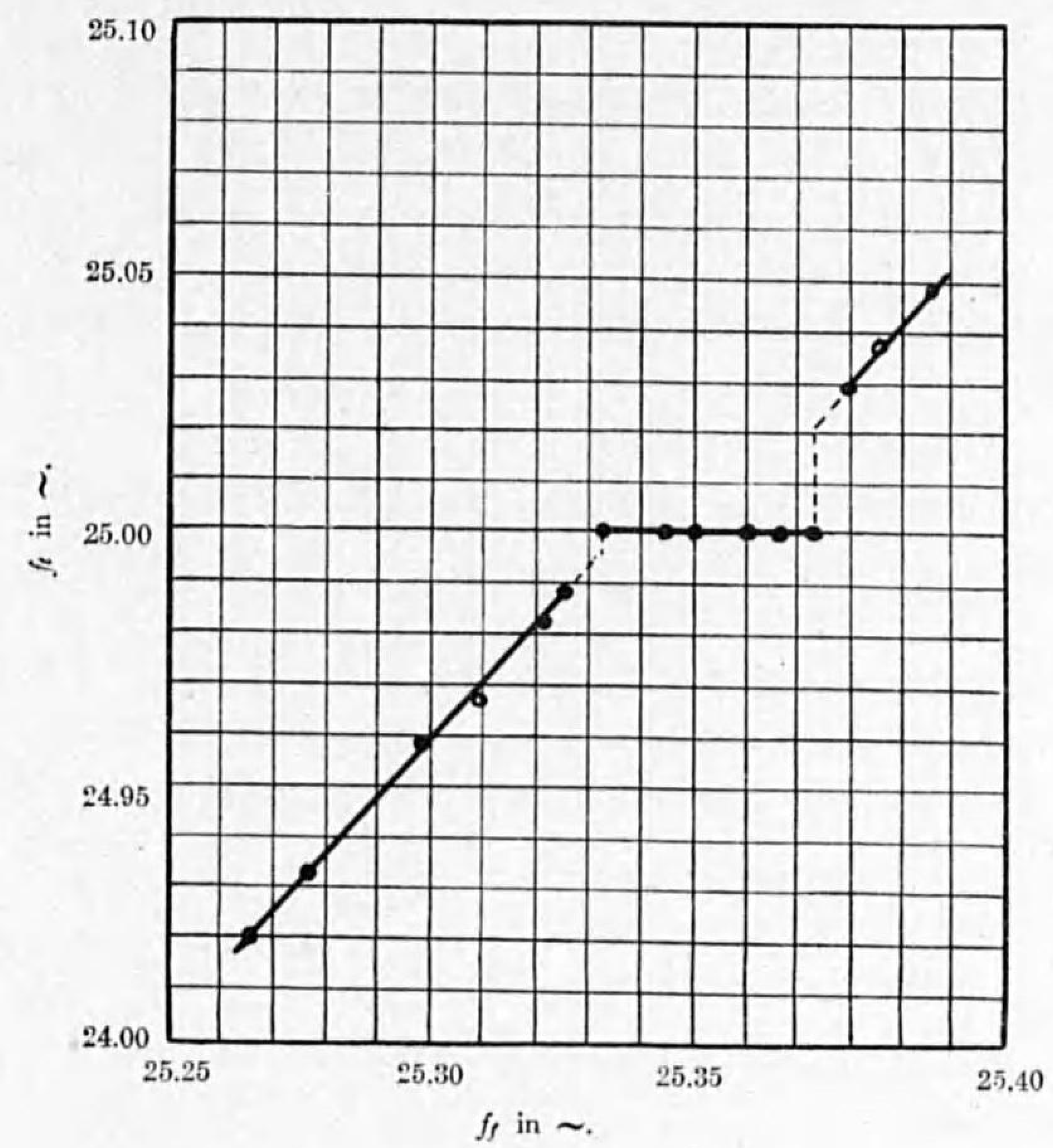

FIG. 12.

where f_c is the frequency of vibration with the chronometer and f_f that without the chronometer, we know that the automatic synchronization holds over a considerably wide range.

So that the synchronization can be easily obtained and it will not be disturbed by the circumference, such as the ambient temperature. In this point, the present oscillator can not be over-estimate against the usual type. The present oscillator will be most reliable in various standard frequency oscillators and miscellaneous applications will be considered.

3. Tuning-Fork Oscillator.

The principle of tuning fork oscillator has already been discovered by W. H. Eccles. (S. 4).

The performance has been studied by S. Butterworth and T. G. Hodgkinson theoretically, (S. 6) (S. 16) and by D. W. Dye experimentally. (S. 8).

However we cannot find any remarkable advances in this oscillator. The author thinks the important factors affecting on the oscillating frequency will be (1) the ambient temperature, (2) the magnetization of fork and (3) the clamping device of fork. These factors will be concerned as follows.

(1) The temperature coefficient.

The temperature coefficient of ordinary steel fork is about -10^{-4}; but if it be made of Elinvar (Ni 35%, Cr 12%, Fe 53%), this coefficient becomes so small as -10^{-5}.

The temperature coefficient of Elinvar fork, which is made by Sullivan Co., is measured by stroboscopic method and phonic motor method. The fork oscillator is kept at a constant temperature in a bath with a sensitive thermo-stat during six hours and then the frequency is measured. The experimental results are shown in the following table.

The two values are sufficient in close agreement with each other, and the

Correction of Riefler clock	temperature	humidity	measured frequency	
			by stroboscopic method	by phonic motor method
″ +0.49	30.4°C	66%	1023.08_7	1024.08_9
″ +0.53	20.2	72	1024.11_5	1024.11_0
″ +0.49	9.9	51	1024.18_6	1024.18_9
″ +0.52	0.0	30	1024.24_5	1024.24_0

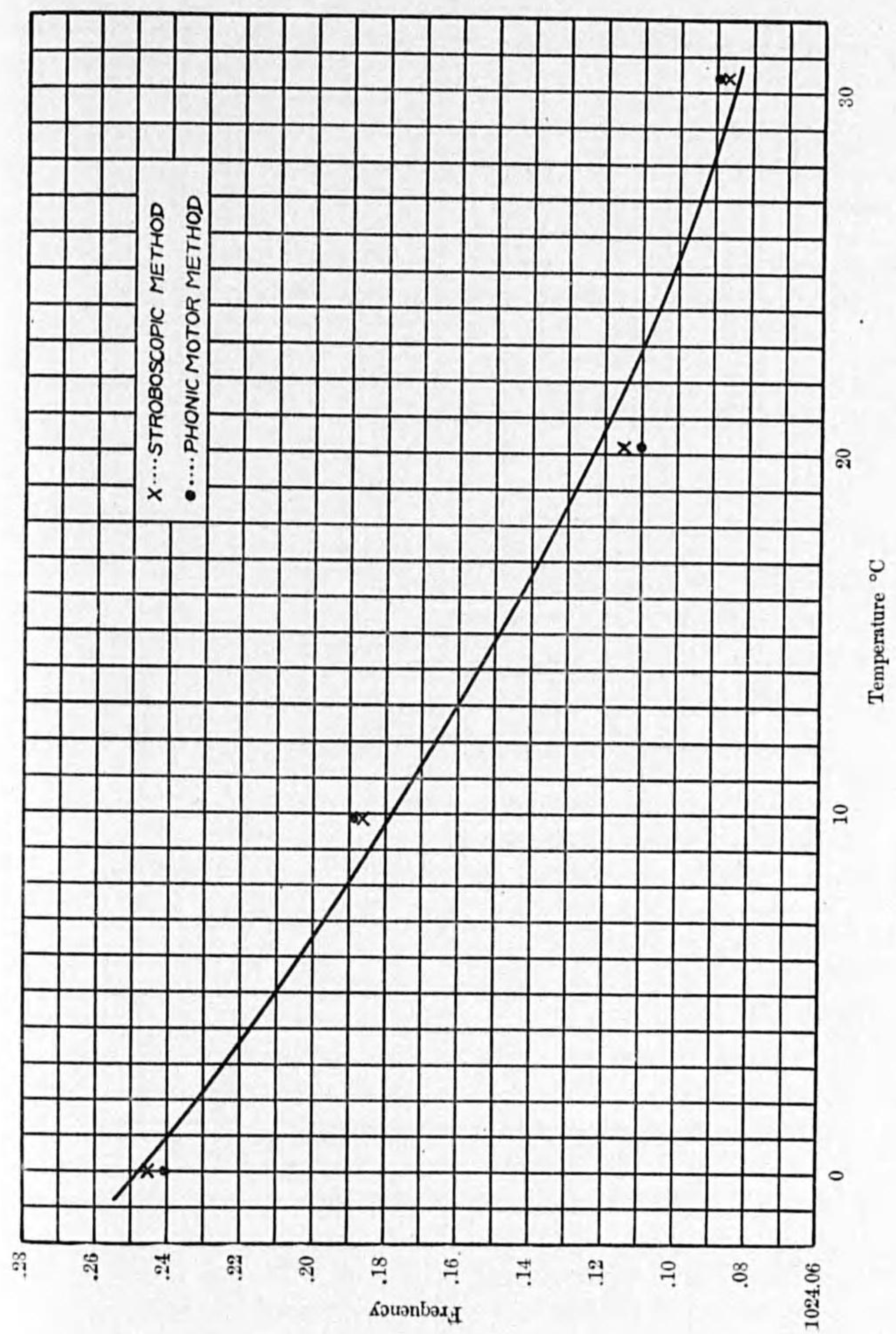

Fig. 15 A.

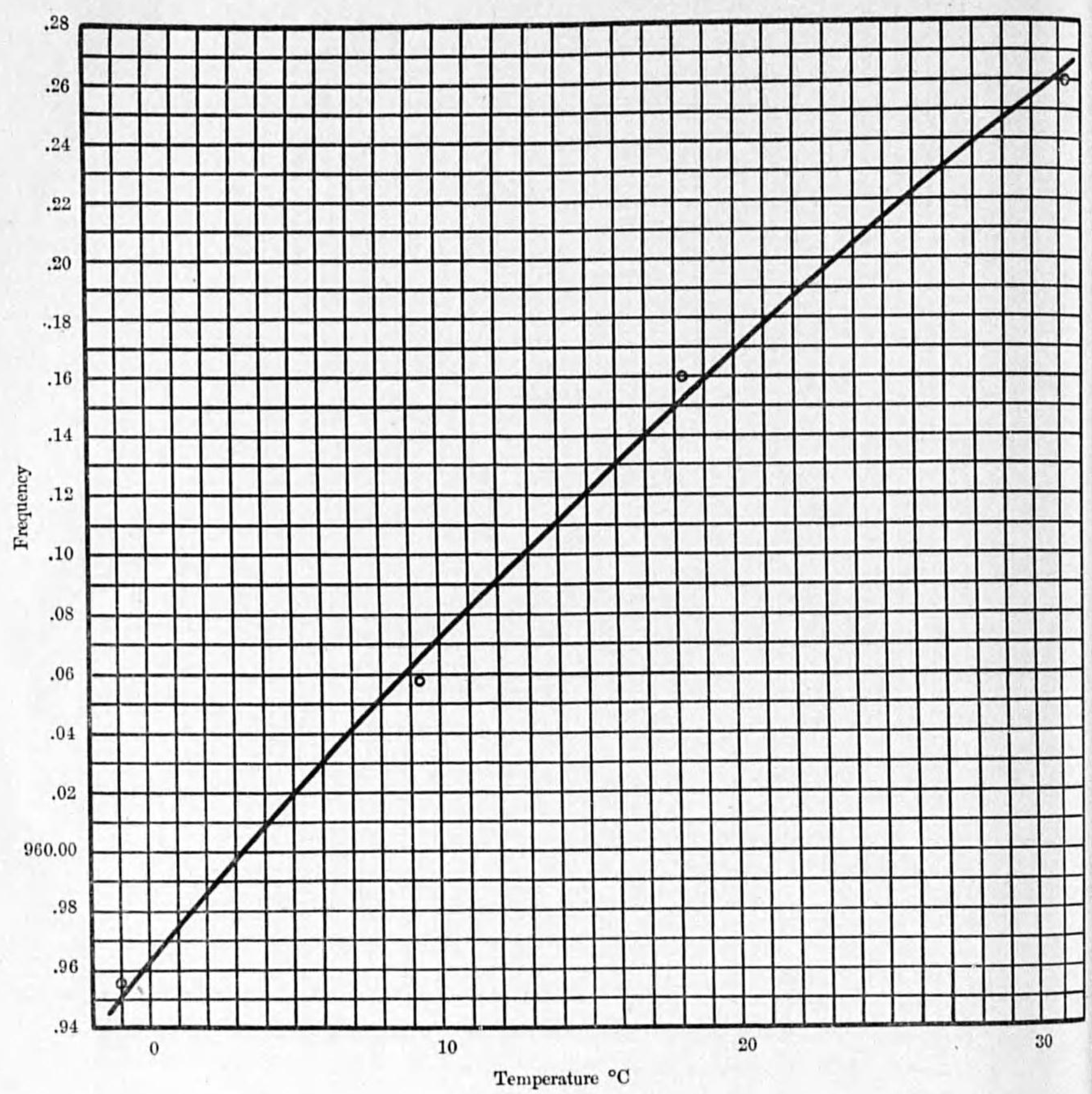

Fig. 15 B.

accuracy of measurement can be about one a hundred thousandth. The performance curves are shown in Fig. 15 A and Fig. 15 B, where the latter has the frequency of 960 cycles per second.

From these result, we have

$$\left.\begin{aligned} f&=1024.24_8\{1-7.6\times10^{-6}\times T+7.8\times10^{-8}\times T^2\} \\ \text{and}\quad f&=960.26_9\{1-12.8\times10^{-6}\times T+6.5\times10^{-8}\times T^2\} \end{aligned}\right\} \quad \cdots \quad (14)$$

Therefore, we know that the temperature coefficient of elinvar fork has always negative sign and it will be not greater than 10^{-5}.

(2) The magnetization of fork.

Now we consider of the theory of fork oscillator which is untuned type.

The motion of fork can be expressed by the following equation,

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{y}}\right)+\frac{\partial F}{\partial \dot{y}}+\frac{\partial V}{\partial y}=\frac{\partial T_e}{\partial y} \quad \cdots\cdots\cdots\cdots \quad (15)$$

where T denotes the kinetic energy, F the dissipation energy, V the potential energy, T_e the electro-kinetic energy and y the displacement of fork.

Now we will suppose that the fork is degree of one freedom and the mechanical restoring force of fork is not proportional to the displacement y, (Theory of Sound, Vol. 1, p. 77) and (S. 3) (S. 11) (S. 17) then we have

$$T=\frac{1}{2}\alpha\dot{y}^2, \qquad F=\frac{1}{2}\beta\dot{y}^2, \qquad V=\frac{1}{2}(\gamma-\tau y^2)y^2$$

Therefore we have

$$\left\{\alpha D^2+\beta D+(\gamma-2\tau y^2)\right\}y=\frac{\partial T_e}{\partial y}$$

As shown in Fig. 13, let L_p, L_g, L_m be the self-inductance of plate coil, grid coil and magnetizing coil respectively.

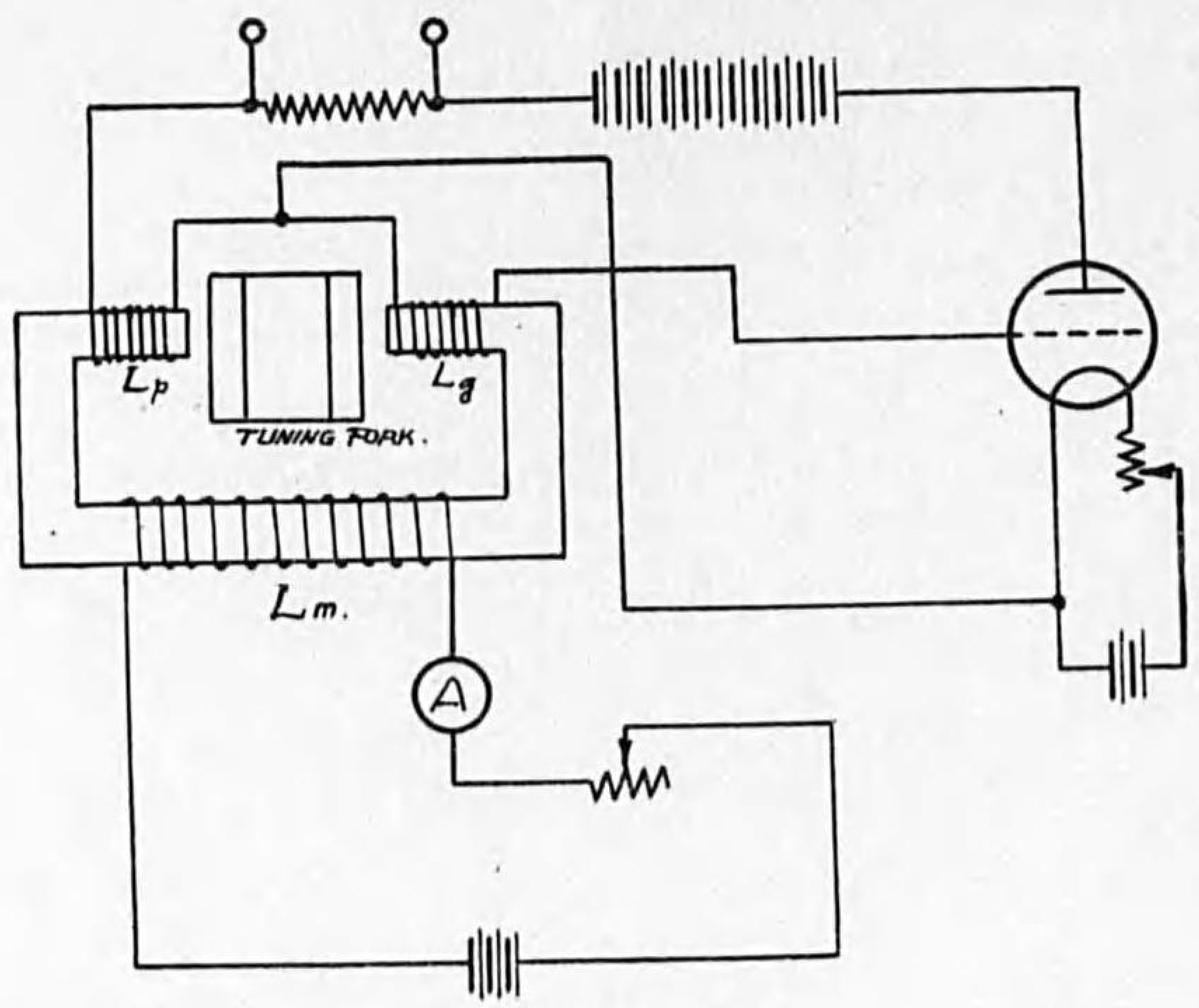

FIG. 13.

Now we suppose that L_p, L_g, M_{pg} are independent of y and

$$\left.\begin{aligned} L_m &= l_0 + l_1 y + l_2 y^2 \\ M_{pm} &= -M_{gm} = m_0 + m_1 y + m_2 y^2 \end{aligned}\right\} \quad \cdots\cdots\cdots \quad (9\,\text{b})$$

Then we have

$$\frac{\partial T_e}{\partial y} = \frac{1}{2}(l_1 + 2l_2 y) I_0^2 + (l_1 + 2l_2 y) I I_0 + (m_1 + 2m_2 y) I_0 I_p$$

Considering the saturation of valve, we have

$$\mathrm{I}_p = G_v E_g (1 - g E_g^2)$$

where I_p, E_g denote the alternating component of current, and G_v the mutual conductance of valve.

Then we have

$$I_p = G_v(m_1 + 2m_2 y)(1 - g m_1^2 I_0^2 (Dy)^2) I_0 Dy$$

and

$$I = -G_m(l_1 + 2l_2 y) I_0 Dy$$

Therefore, the equation of motion can be written

$$\{\alpha D^2 + \beta_e D + \gamma_e\} y = \frac{1}{2} l_1 I_0^2 \quad \cdots\cdots\cdots \quad (16)$$

where $\beta_e = \beta + \beta_m - \beta_v$.

$$\beta_m = G_m (l_1 + 2l_2 y)^2 I_0^2, \qquad \beta_v = G_v (m_1 + 2m_2 y)^2 \{1 - g m_1^2 I_0^2 (Dy)^2\} I_0^2,$$

$$\gamma_e = \gamma - l_2 I_0^2 - 2\tau y^2$$

The above differential equation can not be completely solved, because β_e, γ_e are the complicate function with respect to y. Now we will consider that actually the mean values of β_e, γ_e during one complete vibration act on the fork supposing $y = Y\cos\omega t$, in order to obtain an approximate solution, then we have

$$\omega \doteqdot \omega_0 \left\{1 - \frac{l_2 I_0^2}{2\gamma} - \frac{\tau}{2\gamma} Y^2\right\} \quad \cdots\cdots\cdots \quad (17)$$

$$Y \doteqdot \frac{\sqrt{2}}{\omega_0 m_1 I_0 \sqrt{g}} \left\{1 - \frac{\beta}{G_v m_1^2 I_0^2} - \frac{G_m}{G_v}\left(\frac{l_1}{m_1}\right)^2\right\}^{\frac{1}{2}} \quad \cdots \quad (18)$$

supposing l_2/m_1, m_2/m_1 are very small.

We denotes 2π times of the natural frequency of fork, viz $\sqrt{\frac{\gamma}{\alpha}}$. From the above theory, we have

i. The oscillating frequency depends on the magnetizing current; namely the frequency increases with the decrease of magnetization of fork, because the electromagnetic controlling force, besides the mechanical restoring force, acts on the fork.

ii. The amplitude of vibration is small when the natural frequency of fork is large.

iii. The existence of magnetizing coil has the damping increased.

The first point will be most noticeable. According to the author's theory, the electromagnetic controlling force can be eliminated by means of the coefficient l_2 becomes zero. The author has contrived a new device of fork oscillator as shown in the left hand side of Fig. 14, while that in the right hand side is an ordinary type.

In this new oscillator, the four poles are arranged against the fork and the pole-shapes are made in such a manner as the above coefficient l_2 becomes zero. (Public notice of patent). The relations between the magnetizing current and the amplitude of fork or the frequency are investigated experimentally. In this experiment, the tuning fork of 1000 cycles made by Cambridge instrument Co. is used and it is installed in a bath with a thermostat and the temperature is always kept at constant. The amplitude of fork is measured by a cathetometer with a microscope and the frequency of oscillation is measured by phonic motor, chronometer and chronograph, already mentioned. These experimental results are shown in Fig. 16. Fig. 16 A is corresponding to the untuned type of ordinary device, and Fig. 16 B the tuned type of that. Fig. 16 C is corresponding to the untuned type of new device, and Fig. 16 D the tuned type of that. In the ordinary device, there is a considerably large variation of frequency due to the change of exciting current, while in the new device, this variation is extremely small.

The author thinks that this new device will be appreciate as the standard frequency oscillator, because the permanet magnet in the oscillator may be largely demagnetized after the long running of the fork.

The oscillators will be classified into tuned type and untuned type. The author proposes that the former is suitable for high frequency fork, while the latter for low frequency fork. The monochord oscillator designed by the author (Patent No. 72948 and 73757) may be also available as the standard frequency oscillator, but the reliability is not so large as that of chronometer, fork and quartz.

(3) The clamping device of fork.

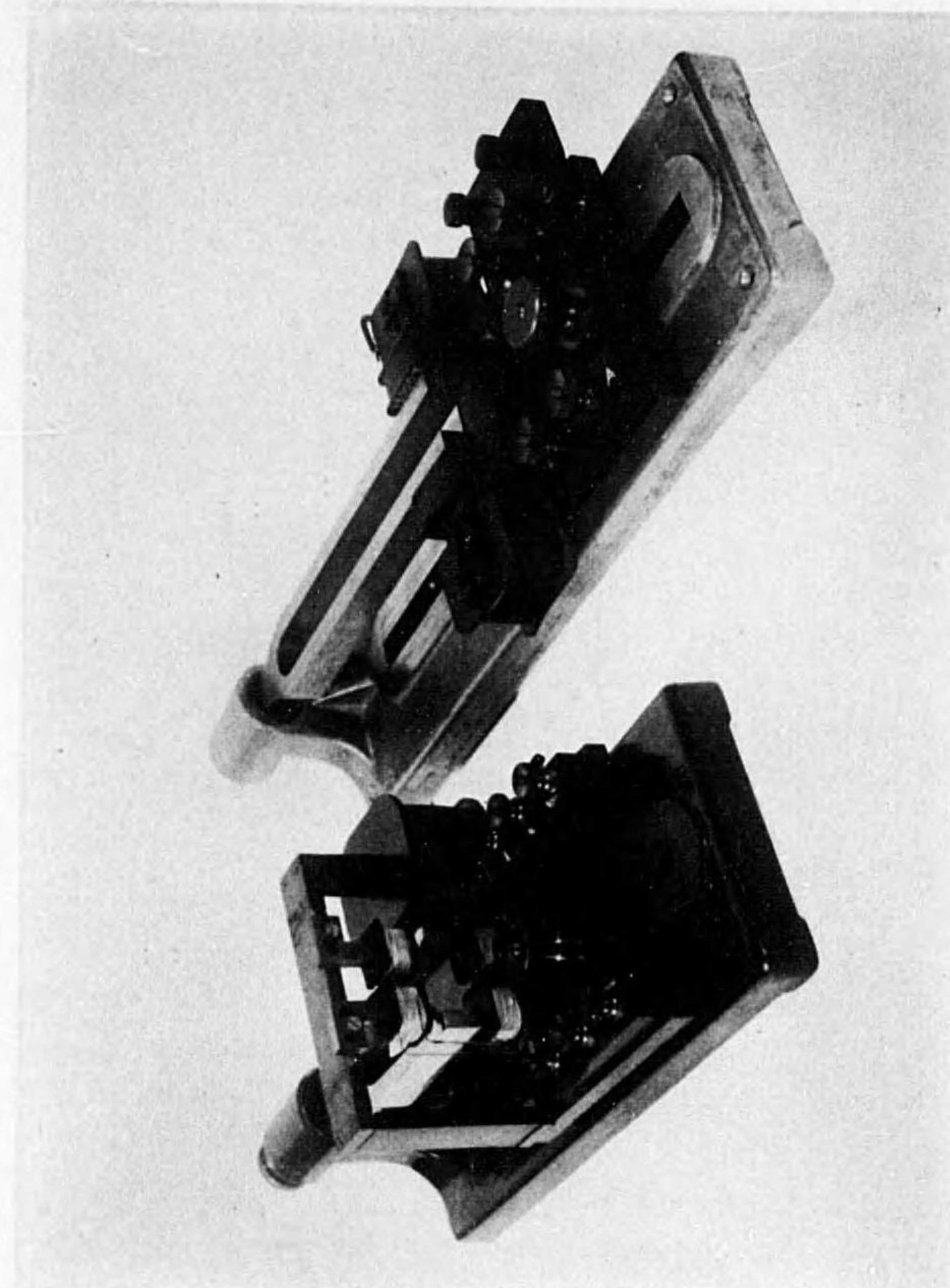

Fig. 14

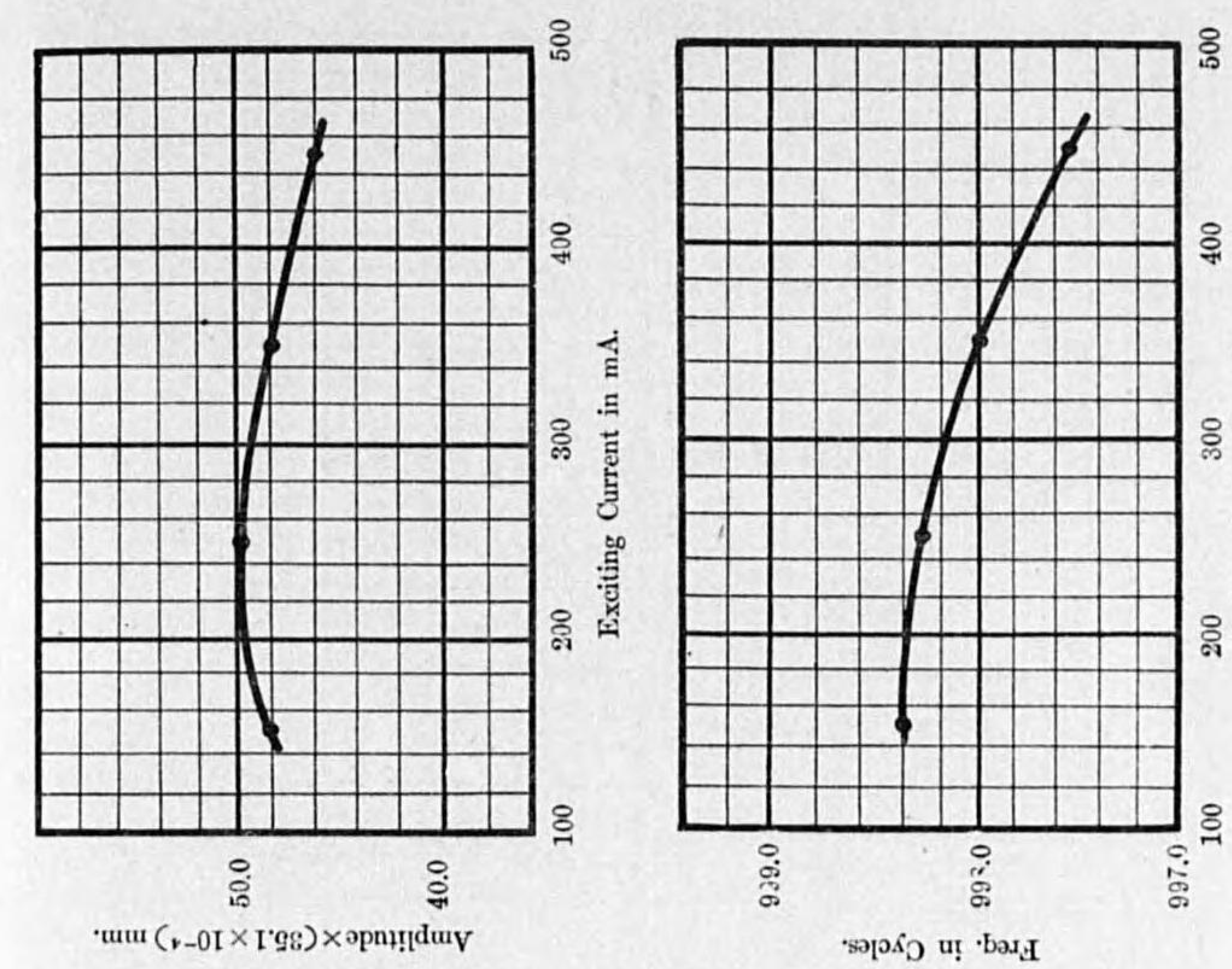

Fig. 16 B.

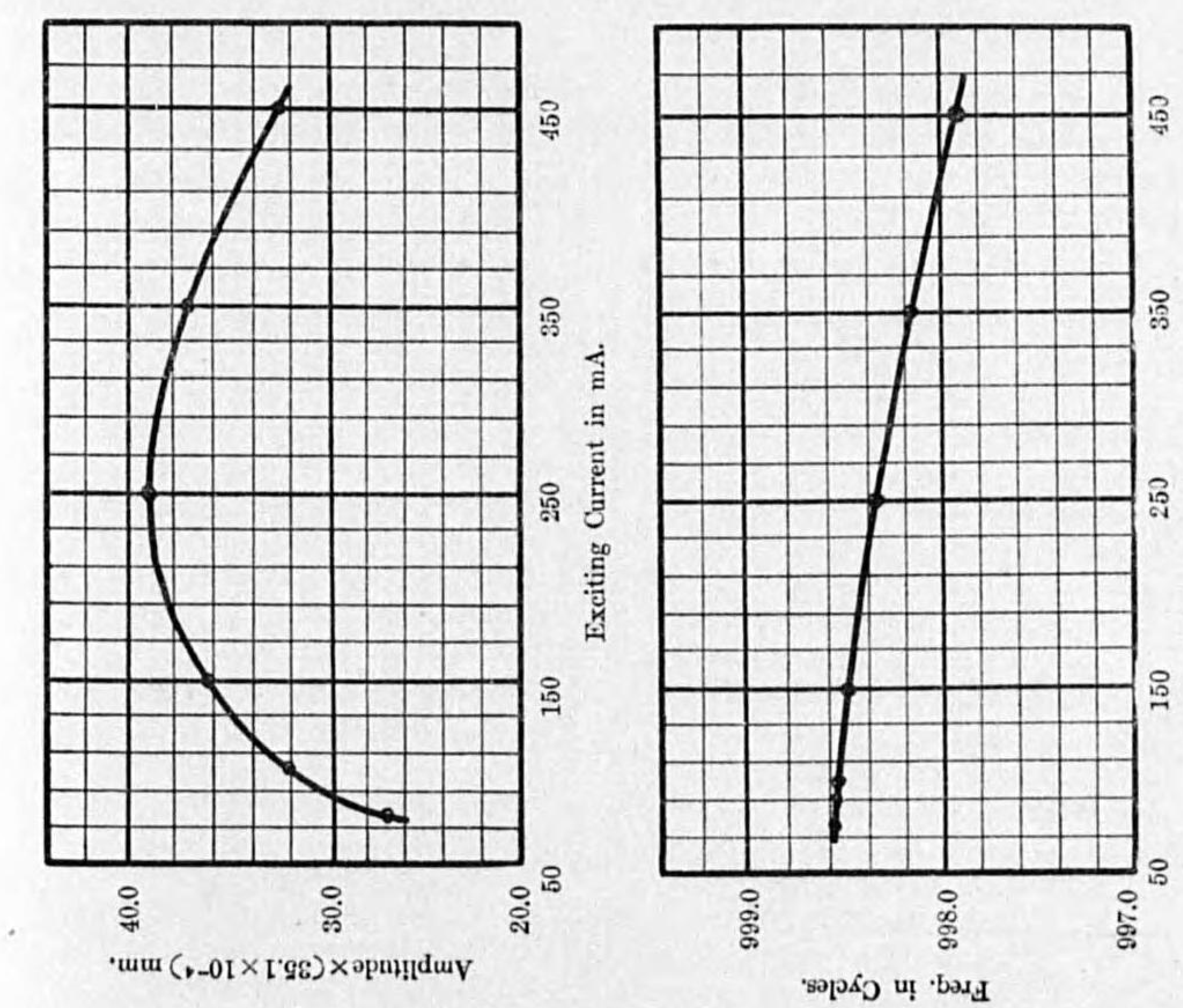

Fig. 16 A.

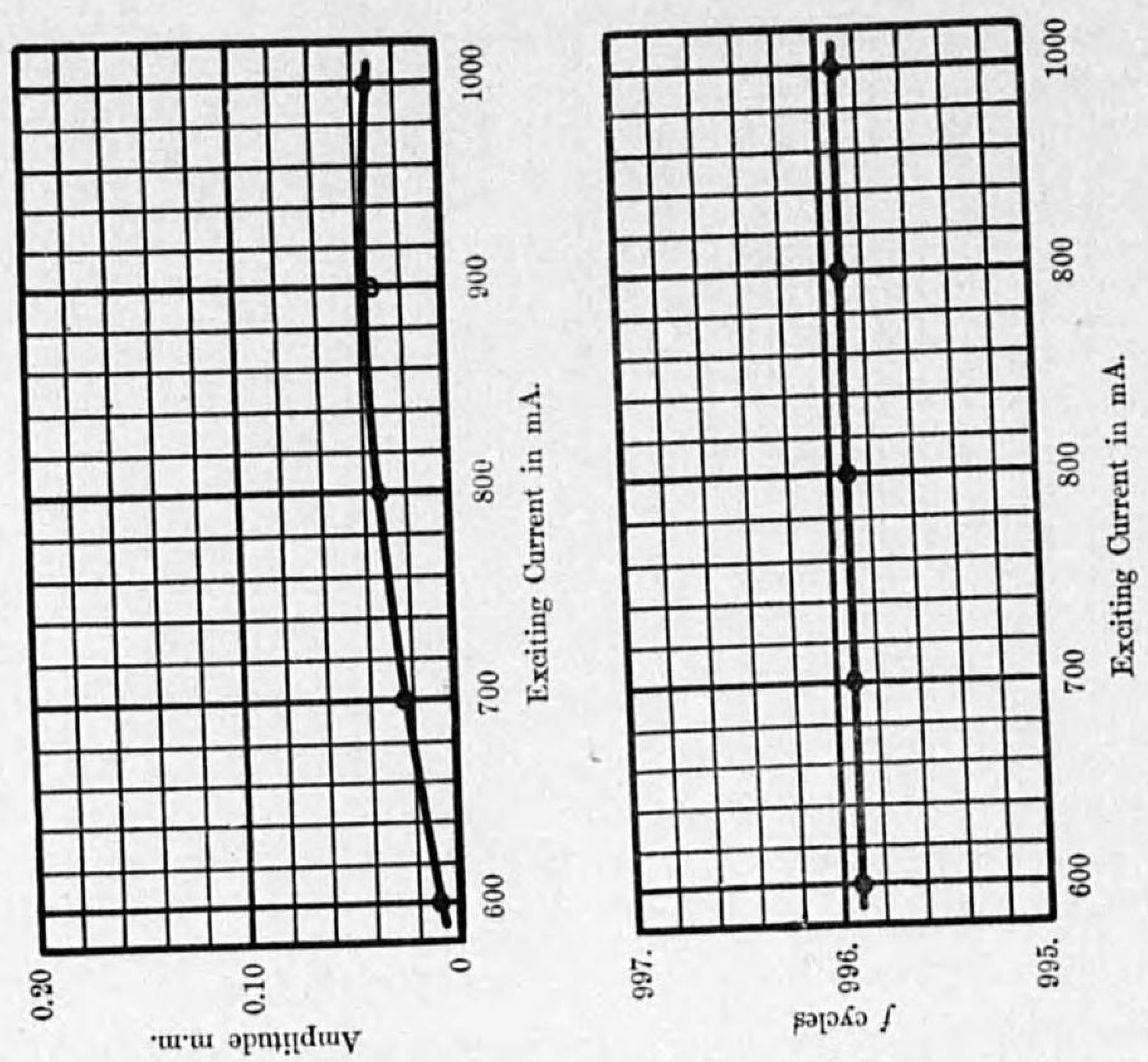

Fig. 16 D.

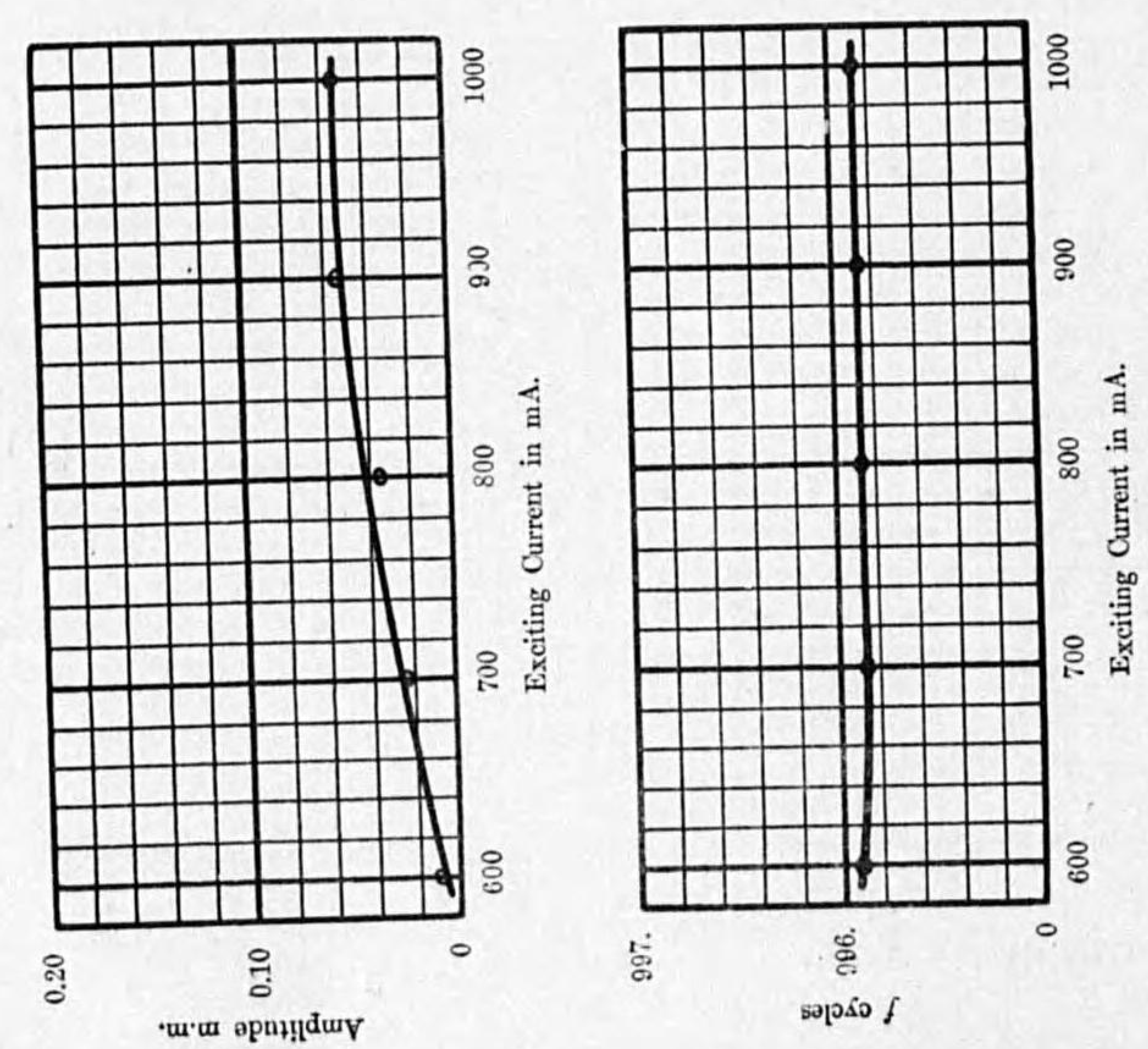

Fig. 16 C.

The relaxation in clamping of fork will introduce a remarkablly change of frequency. However, it will be easily removed by means of sfficiently clamping the fork to the base.

Besides the above factors, there are several factors, such as the weight of base and the electric circuit, etc., but these factors will not introduce any noticeable influences on the frequency. The standard frequency oscillator must be always kept at a state being as constant as possible.

4. Quartz Oscillator.

Recently, the quarts oscillator becomes more and more noticeable.

There are few data pertaining the performance as the standard frequency oscillator. There are two modes of cutting a crystal, and at the normal cutting x is small compared with y, while at the other cutting y is small compared with x, where x is the length along the electric axis, z that along the optical axis and y that along the other axis.

In this paper, the crystal cut by the normal mode is used. The frequencies corresponding to the longitudinal, lateral and torsional vibrations of quartz are measured by the harmonic comparison with the tuning fork oscillator, as shown in the third paragraph of chapter II. The experimental results are assembled in the following table.

No. of Crystal	dimension in mm.			f_l in KC		f_b in KC	f_t in KC
	x	y	z	f_{lx}	f_{ly}		
B_1	4.96	19.87	15.00	572.7	129.5	21989.8	54958.3
D_2	3.00	50.00	20.00	951.8	53517.1	—	—

The longitudinal vibration can be easily obtained by the well-known method as shown in Fig. 17, while it has been considered hitherto that it is much troublesome to realize the lateral and torsional vibration in the quartz oscillator.

However, the author has succeeded to easily obtain these vibration by means of the automatic synchronization in the valve oscillator. As shown in Fig. 18 B, a quartz is connected to the grid coil in a usual triode valve oscillator, where the grid coil is somewhat loosely coupled to the plate coil and the four electrodes covering a portion of surface of quartz are used. When the free oscillation in the valve oscillator approaches to that of the quartz, the deflection of ammeter in the plate circuit suddenly decreases, and the synchronization will be clearly recognized. The important factors affecting on the frequency will be (1) the ambient temperature, (2) the air gap in the mounting vessel and (3) the electric circuit.

These factors are investigated experimentally by a beat-note method as shown in Fig. 17. The experimental results are assembled in Fig. 18 A, Fig. 18 B and Fig. 19.

The temperature coefficient, measured about the quartz A_2, is as follows:

Temp. Coeff. in cycles per second per degree centigrade			
f_{lx}	f_{ly}	f_b	f_t
-1.6×10^{-5}	-3.8×10^{-5}	-4×10^{-5}	-2×10^{-5}

From these results, we know that the temperature coefficient of quartz is always from $4\cdot10^{-5}$ to $1\cdot10^{-5}$.

It will be note-worthy that in the temperature characteristic of the torsional vibration there is a abrupt change. The relation between the air gap-length and the frequency, measured about the quartz A_2, is shown in Fig. 19.

According to these results, we know that the frequency always increases with the increase of air-gap length, and it is remarkable that f_{lx} cannot be realized at some peculiar air gap-length. It will be caused from the resonance of the region of air between the quartz and the electrode, to increase the damping of vibration.

It will be prevented by using the mesh-electrode instead of the plane electrode.

The other factors, such as the electric circuit, will not introduce any remarkable influences, so as above-mentioned.

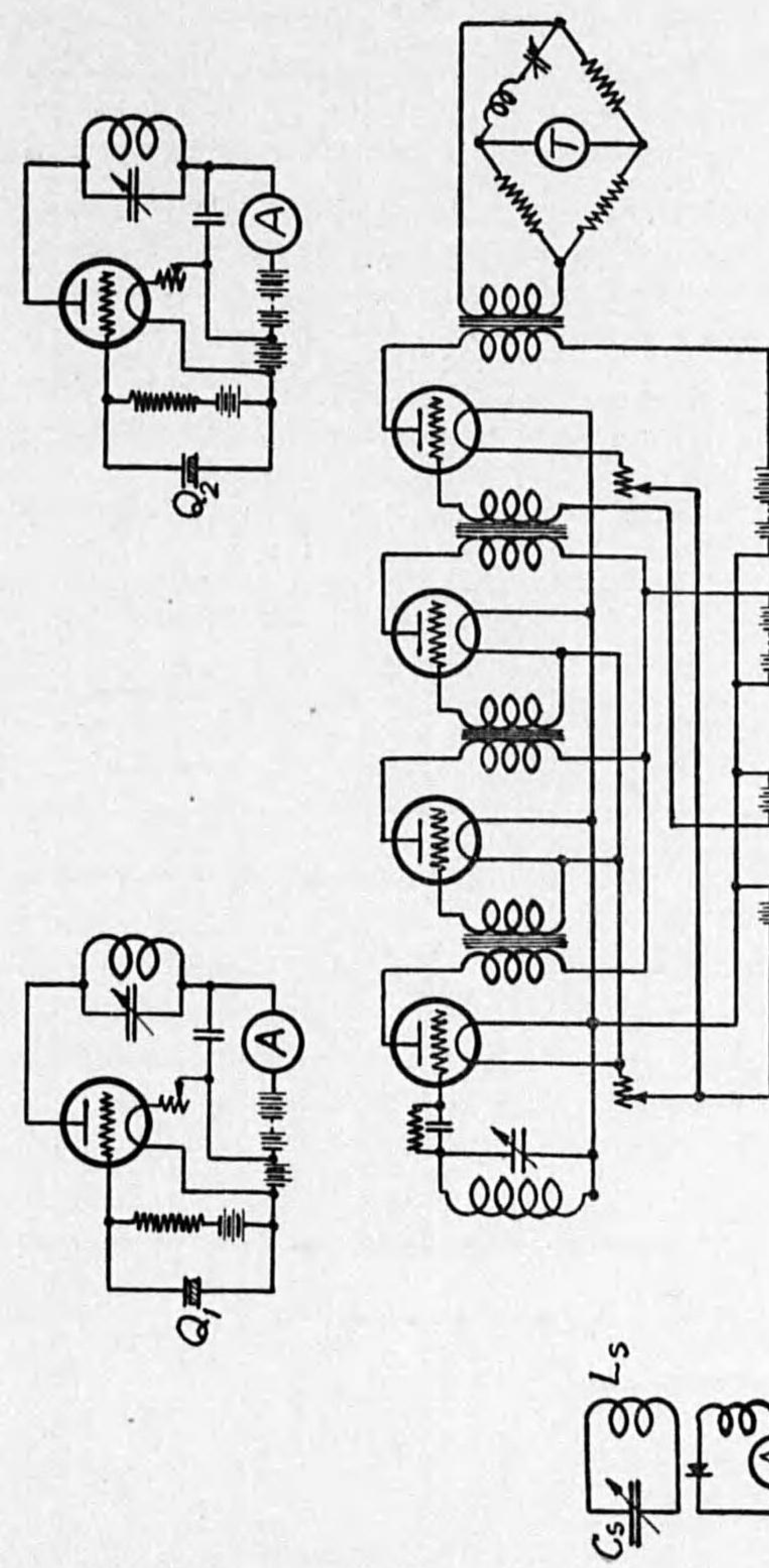

Fig. 17.

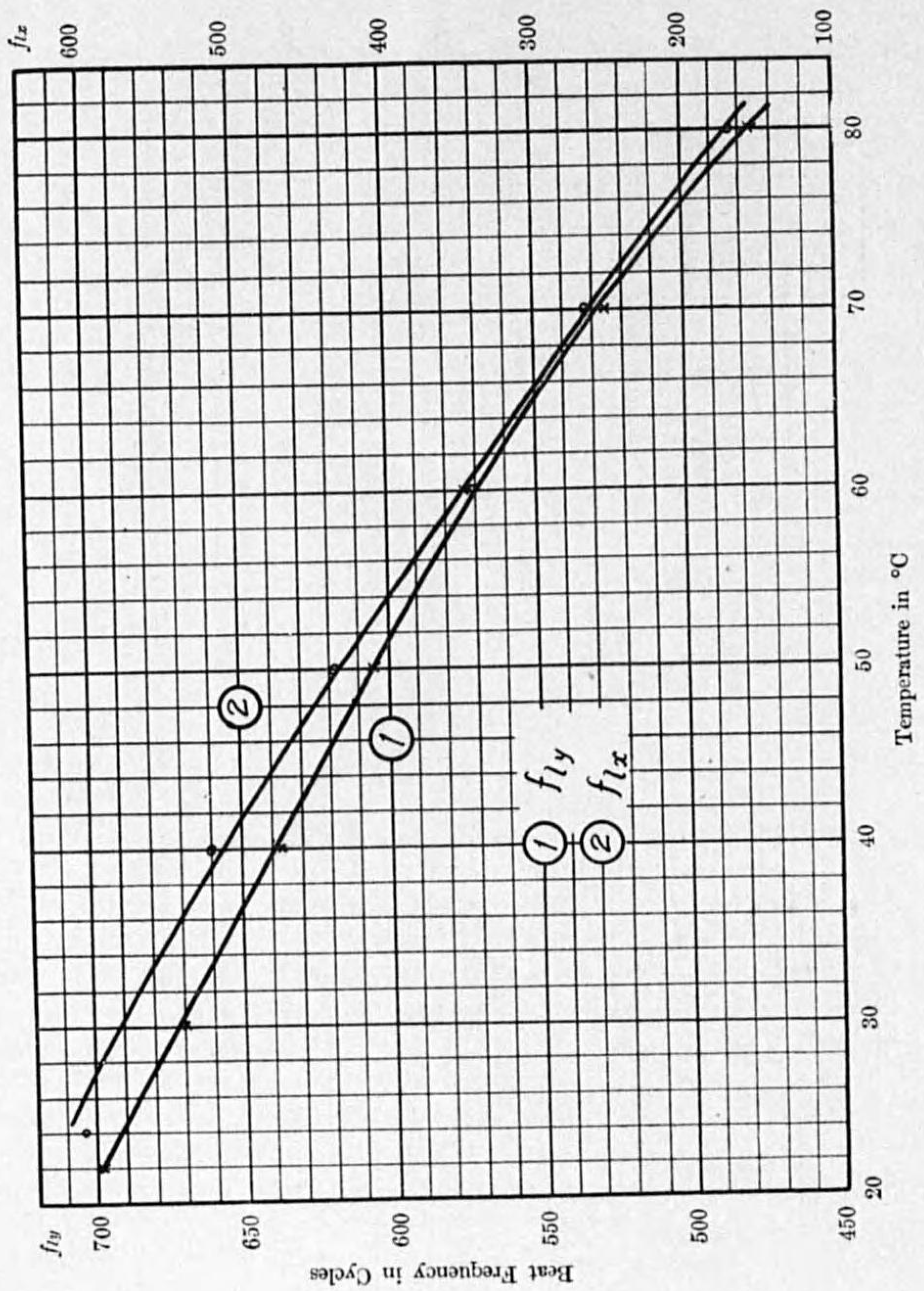

Fig. 18 A.

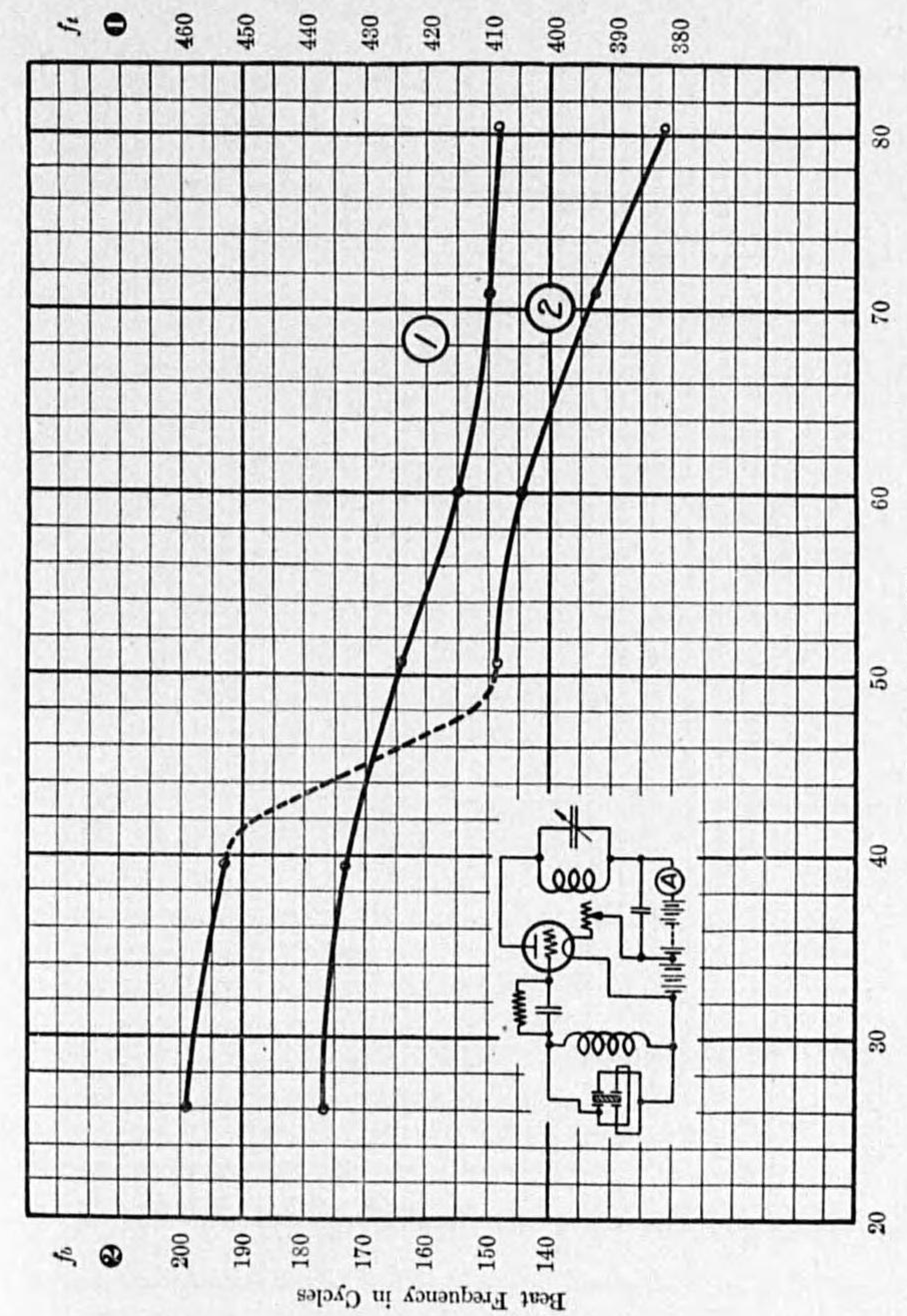

Fig. 18 B.

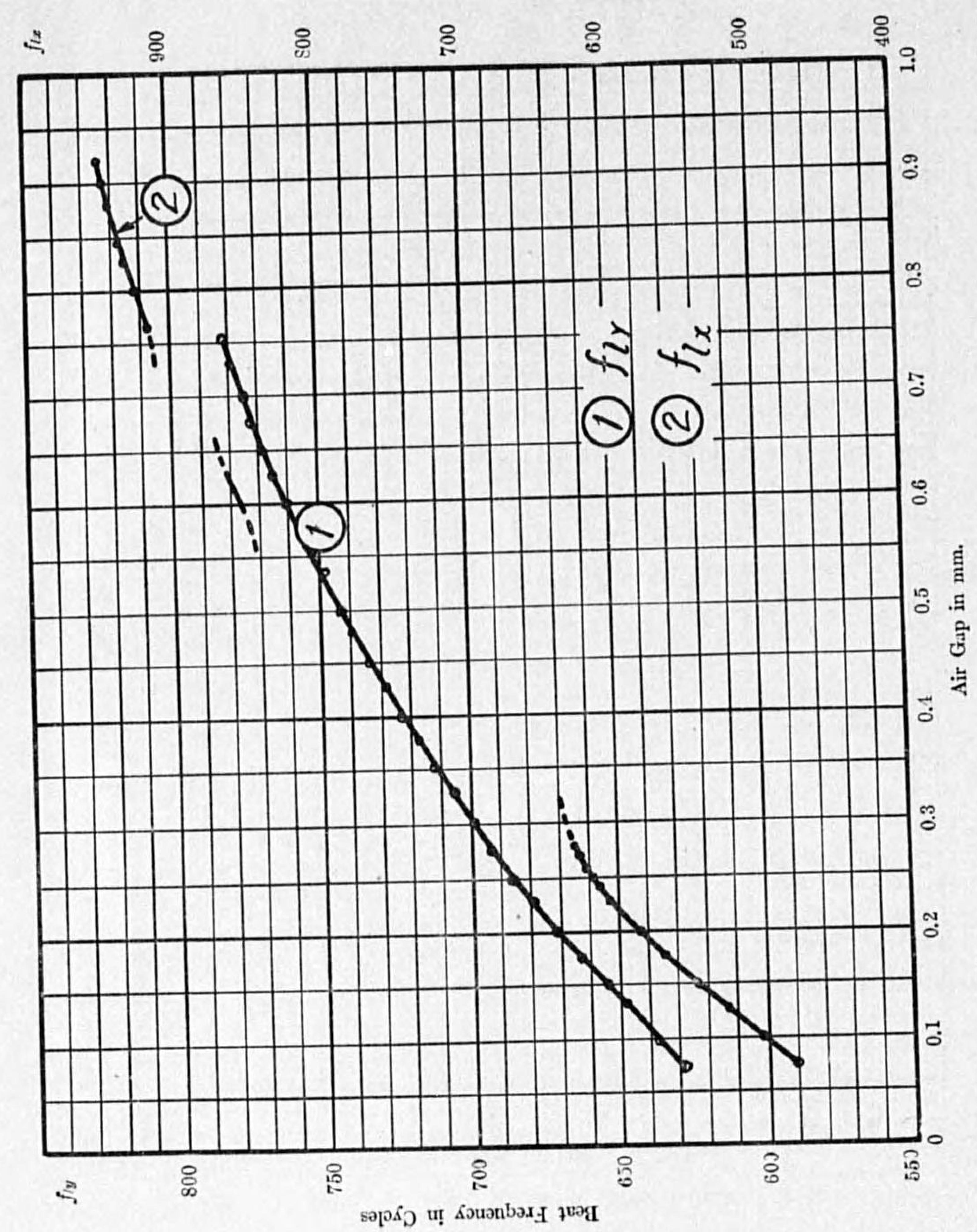

Fig. 19.

CHAPTER IV. RESONATORS.

1. Theory of resonator.

Various resonator will be appreciate as the working standard of frequency.

The resonator must be furnished with the following conditions,

(1) the frequency slightly depends on the circumference, such as the ambient temperature.

(2) the resonant sharpness must be as large as possible.

The resonators are classified into two classes, the one being the electrical type and the other the mechanical type. Frequency bridge and wave meter belong to the former, while sonometer type resonator and quartz resonator belong to the latter.

Now the resonant sharpness Λ can be defined by the following equation,

$$\Lambda=\omega_0/2\delta \quad \text{. . . . .} \quad (19)$$

where ω_0 is $2\pi f_0$, f_0 the resonant frequency and δ the damping factor. Now let Δ, S, R be logarithmic decrement, selectivity, resonance range respectively, then we have

$$\Delta=\pi/\Lambda \quad \text{. . . . .} \quad (20a)$$

$$S=\sqrt{1+4\cdot10^4\Lambda} \quad \text{. . . . .} \quad (20b)$$

$$R=\frac{\sqrt{3}}{2}\,\frac{100}{\Lambda} \text{ in } \% \quad \text{. . . . .} \quad (20c)$$

The last equation holds when Λ is greater than 100. The numerical relations between them are shown in the following table.

Λ	1	50	100	300	600	1000	3000	6000	10000
Δ	314	6.3×10^{-2}	3.1×10^{-2}	11×10^{-2}	5.2×10^{-3}	3.1×10^{-3}	11×10^{-4}	5.2×10^{-4}	3.1×10^{-4}
S	200	1400	2000	3500	4900	6300	11000	15000	20000
R %	—	—	0.87	0.29	0.15	0.087	0.029	0.015	0.009

It will be clearly understood how convenient Λ is to express the sharpness of resonance.

Now we will consider of the resonant sharpness of resonator. The electrical type resonator can be classified into wave meter type and bridge type.

Campbell's frequency bridge and ordinary wave meter belong to the former.

Let I be the current in a L-C-R circuit, and I_0 that at the resonance, then we have

$$I=\frac{I_0}{1+j\,\Lambda\left(x-\frac{1}{x}\right)} \qquad \ldots\ldots\ldots\ldots \quad (21)$$

where $I_0=E/R,\quad x=\omega/\omega_0,\quad \Lambda=1/\omega_0 CR=\omega_0 L/R.$

If the resistance R is nothing but that of the inductance coil, Λ is equal to $\tau\omega_0$, where τ denotes the time constant of coil. Therefore, the time constant of coil must be as large as possible, in order to get the great sharpness, but there is a limit in the time constant of coil, then this type resonator, viz wave meter, will be available for only the radio frequency.

From the above equation, we have

$$\Lambda=\frac{\sqrt{\left(\frac{I_0}{I}\right)^2-1}}{x-\frac{1}{x}} \qquad \ldots\ldots\ldots\ldots \quad (22)$$

By this equation, we can obtain the resonant sharpness. At the Campbell's bridge as shown in Fig. 20, let E and E_0 be the potential difference in the detector and that at the resonance, and supposing that the current at the primary side I is constant, we have

$$E=E_0\left\{1+j\,\Lambda\left(x-\frac{1}{x}\right)\right\} \qquad \ldots\ldots\ldots\ldots \quad (23)$$

where $E_0=rI$ and $\Lambda=\omega_0 M/r.$

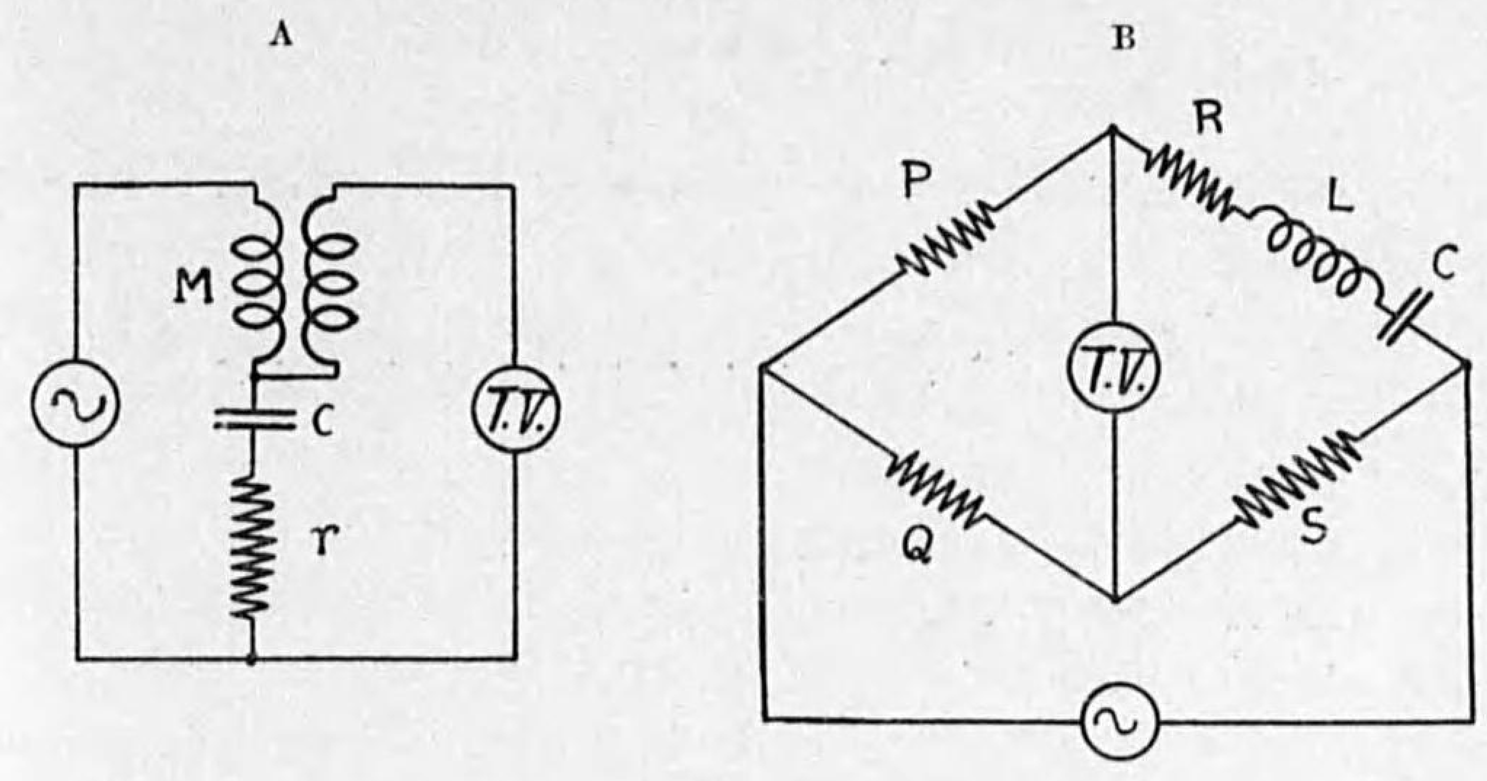

FIG. 20.

The resistance r is caused from the impurity of mutual inductance and the dielectric loss of condenser. If the low loss apparatus can be used, the sharpness will be considerably large at the audio frequency.

From the above equation, it follows

$$\Lambda=\frac{\sqrt{\left(\frac{E}{E_0}\right)^2-1}}{x-\frac{1}{x}} \qquad \ldots\ldots\ldots\ldots \quad (24)$$

By this equation, we can know the resonant sharpness using a tube voltmeter.

At the bridge type resonator as shown in Fig. 20, supposing that the applied voltage E_0 is always kept at constant, we have

$$\zeta=\frac{E}{E_0}\left(1+\frac{S}{Q}\right)=\frac{j\,\Lambda\left(x-\frac{1}{x}\right)}{1+j\,\Lambda\left(x-\frac{1}{x}\right)} \qquad \ldots\ldots \quad (25)$$

where E is the potential difference at the detector circuit measured by a tube voltmeter, and

$$A=A_0\frac{R}{P+R}$$

A_0 denotes the intrinsic resonant sharpness of resonance arm. From this equation, it follows

$$A=\frac{\zeta}{\sqrt{1-\zeta^2}}\Big/\left(x-\frac{1}{x}\right) \quad \ldots\ldots\ldots\ldots (26)$$

So that A can be found experimentally.

Now we will consider of the mechanical resonator.

There are two kinds in this resonator, and the one is the electromagnetic type and the other the electrostatic type. The fork type frequency meter and the magnetic sonometer type resonator belong to the former, while the static sonometer type resonator and the quartz resononator belong to the latter.

In the case of the electromagnetic type resonator, the equation of motion can be written

$$(aD^2+\beta D+\gamma)y=\psi I \quad \ldots\ldots\ldots\ldots (27)$$

The intrinsic sharpness A_0 is given by

$$A_0=\sqrt{a\gamma}/\beta \quad \ldots\ldots\ldots\ldots (28)$$

This resonator can be represented by an equivalent electric circuit as shown in Fig. 21, and

$$C_v=a/\psi^2, \quad L_v=\psi^2/\gamma, \quad R_v=\psi^2/\beta$$

It will be noticeable that the working resonant sharpness is different from the intrinsic one.

At the case as shown in Fig. 25 H, supposing that the current I_0 is always kept constant, we have

$$\zeta=\frac{I}{I_0}\left(1+\frac{R}{R_v}\right)=\frac{1}{1+j\,A\left(x-\frac{1}{x}\right)} \quad \ldots\ldots (29)$$

where R is the resistance of ammeter A_2, and

$$A=A_0\frac{R}{R+R_v} \quad \ldots\ldots\ldots\ldots (30)$$

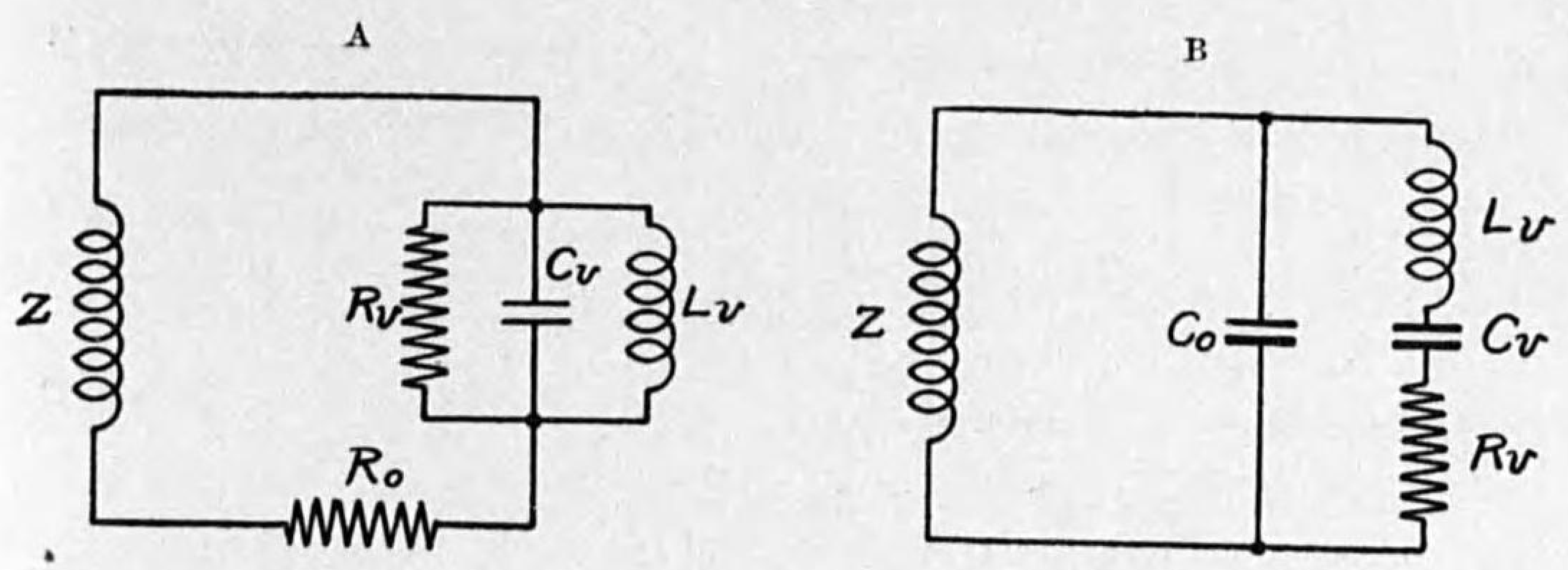

Fig. 21.

At the static type mechanical resonator, the equation of motion can be written

$$(aD^2+\beta D+\gamma)y=\phi E \quad \ldots\ldots\ldots\ldots (31)$$

The intrinsic sharpness is also given by the equation (28).

It can be represented by an equivalent electric circuit as shown in Fig. 21, and

$$C_v=\phi^2/\gamma, \quad L_v=a/\phi^2 \quad R_v=\beta/\phi^2.$$

The working sharpness at the case as shown in Fig. 25 G, can be written

$$\zeta=\frac{I}{I_0}=\frac{1}{1+j\,A\left(x-\frac{1}{x}\right)} \quad \ldots\ldots\ldots (32)$$

and

$$A=A_0\frac{R}{R+R_v} \quad \ldots\ldots\ldots\ldots (33)$$

The working sharpness of the quartz resonator, as shown in Fig. 25 I and Fig. 25 J, is also given by the above equation, supposing that the shunt capacity C_0 is extremely small.

2. Experimental Results.

There are two methods of measuring the resonant sharpness, the one is the optical method in which the decay motion of vibrator is automatically recorded, and the other is the resonance-curve method using a tube voltmeter or a thermo-ammeter.

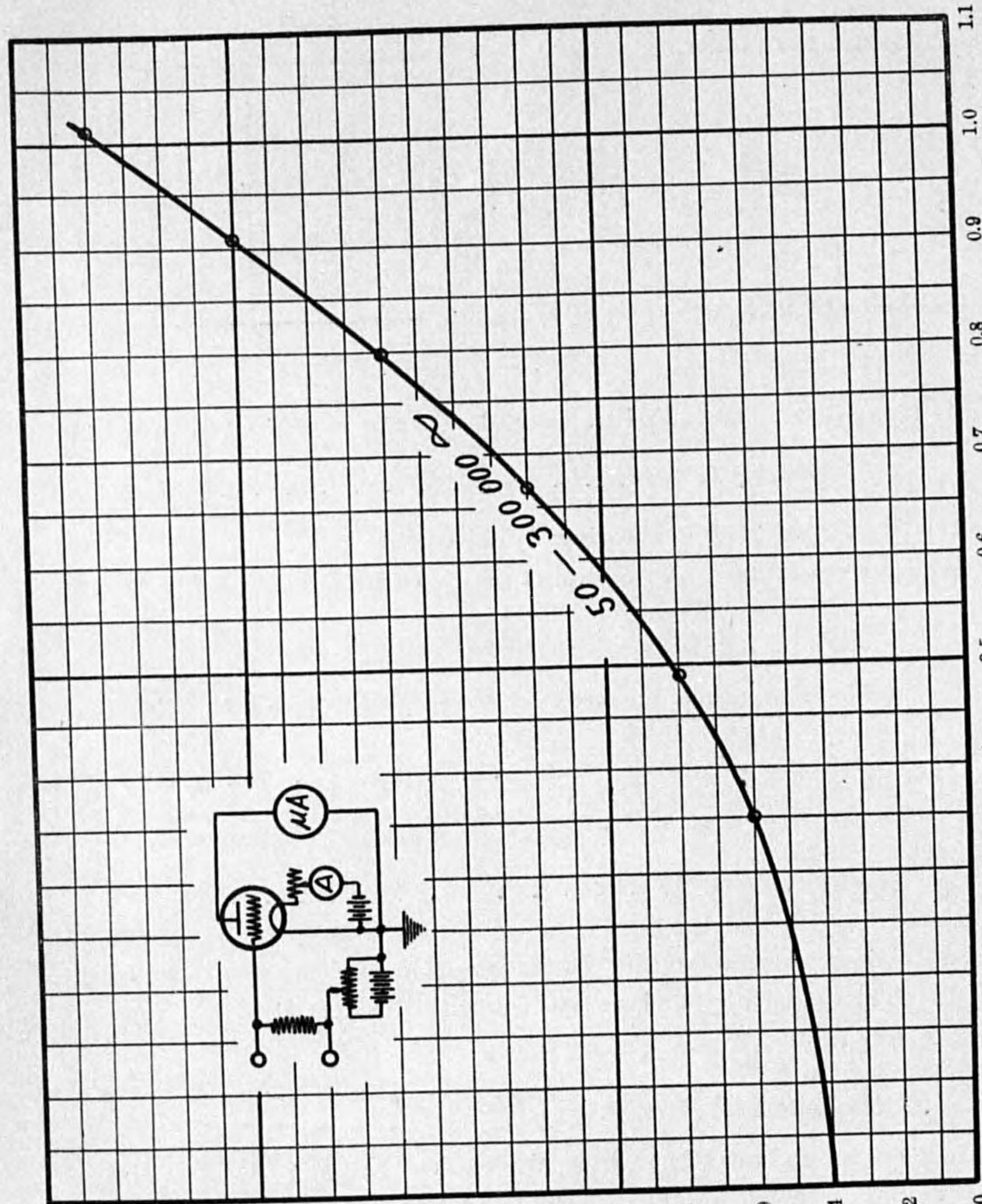
E. M. F. in Volt
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
Deflection in μA
0 2 4 6 8 10 12 14 16 18 20 22 24 26
50 — 300 000 ∞
μA
A

Fig. 24.

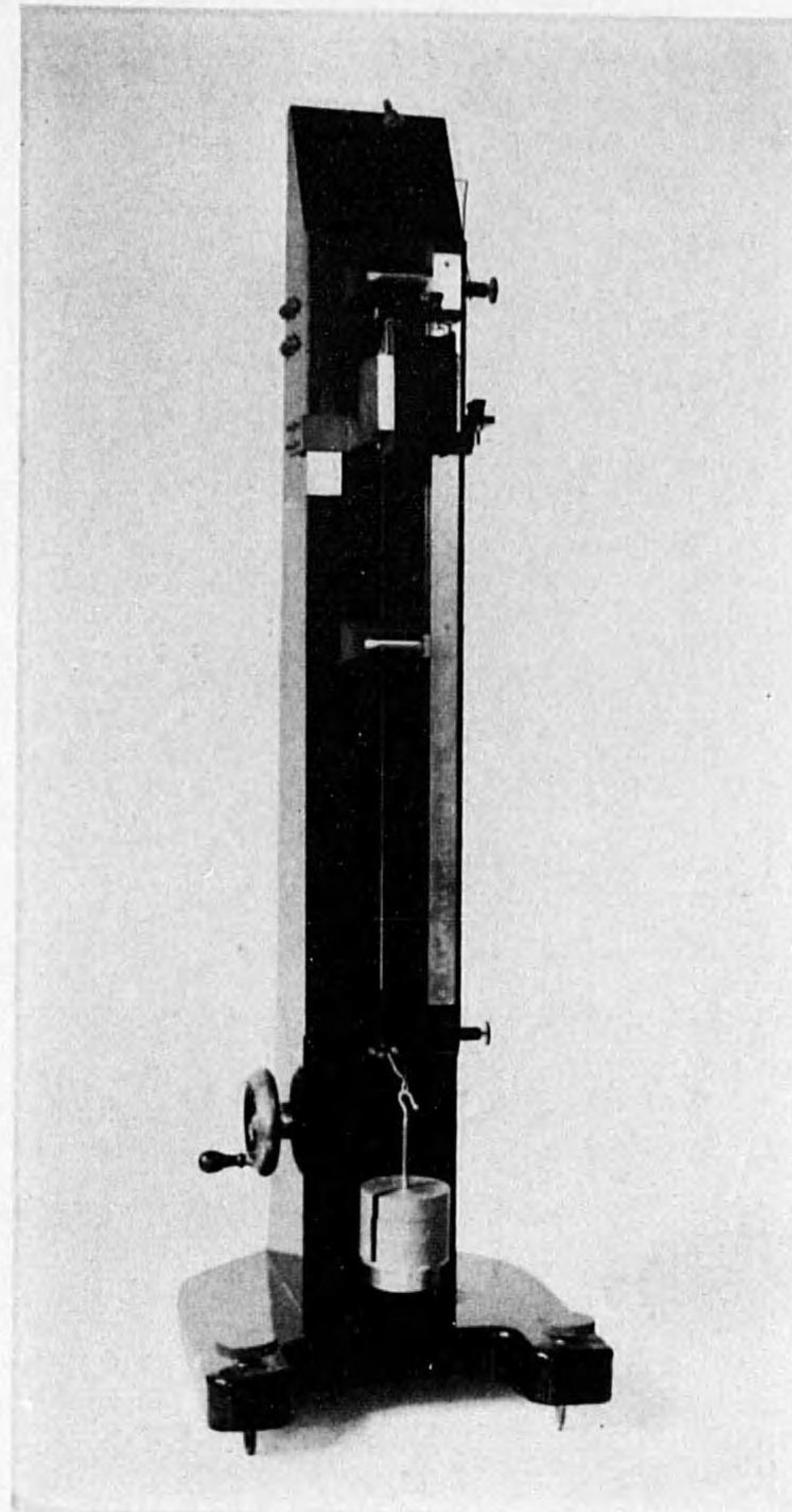

Fig. 22

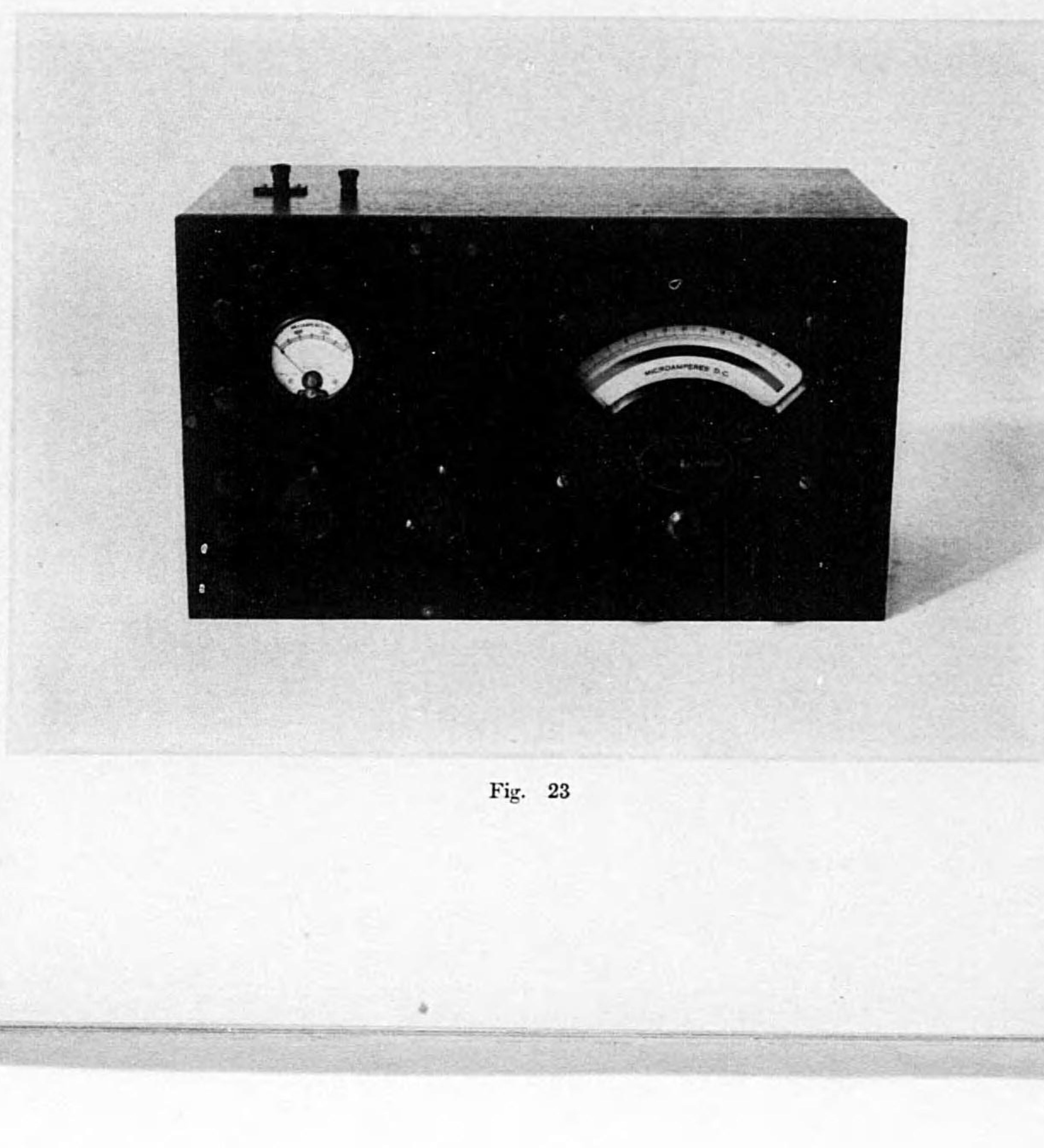

Fig. 23

The author uses almost the latter method in this experiment, and a new type tube voltmeter as shown in Fig. 23 and Fig. 24 is used. (R. 7) The author's voltmeter has the following merits; (1) the calibration slightly depends on the frequency, (2) the input power is extremely small and (3) the calibration does not effected by the outside circuit.

We can accurately measure a voltage so small as from 0.1 to 1 volt by this voltmeter. The thermo-ammeter, used in this experiment, consists of a Western thermovacuo junction and a Weston milli voltmeter. The sonometer type resonator is shown in Fig. 22. (Patent. No. 75431), and it will be much appreciate as a working standard of frequency.

Many resonance curves, obtained by the method above mentioned, are illustrated from Fig. 25 A to Fig. 25 J, and the resonant sharpness obtained by the equations already mentioned are assembled in the following table.

Kinds of Resonator		Resonant Frequency	Λ
Hartmann Kempf Frequency Meter		22.5 32.0 46.5 52.5	1100 900 900 610
Tuning Fork		260 490 760	2800 7300 3300
A Freq. Meter Made in Japan		920	6.3
Campbell Frequency Meter		850 640	6.3 2.6
Campbell's Bridge		950 570	11 7.5
L. C. Bridge		970 550	17 11
Wave Meter		127000 570000	54 69
G. R. Co. Wave Meter		140000	19
Sonometer	Magnetic	310 730 1010	360— 660 630— 1400 1000— 1600
	Static	990	1600— 2000
Piezo Resonator		128000 570000	18000—22000 22000—34000

The resonant sharpness of the fork type frequency meter and the tuning fork are measured by the optical method.

It will be note worthy that the resonant sharpness is extremely small at some finished frequency bridges, and it is greatest at the quartz resonator. There are some aperiodic types of frequency bridge, and in this type the calibration curve will be linear, but it will be a drawback that its sharpness of resonance is considerably small. According to the results as shown in Fig. 25 I and Fig. 25 J, we know that the resonant sharpness of quartz resonator decreases regularly with the increase of air gap length for the frequency f_{ly} while for the frequency f_{lz} it is not regular, and it will be remarkable that the resonancy for the frequency f_{lz} can not be obtained at some peculiar length of air gap and at the case near this peculiar state the resonant sharpness is considerably small.

This peculiar phenomenon is considered to be arisen from the damping in the region of air between the quartz and the electrode. (R 12).

In conclusion, the author wishes to render many thanks to Mr. R. Kojima and Mr. K. Inagaki who have shown many splendid assistances to carry out the precise measurement.

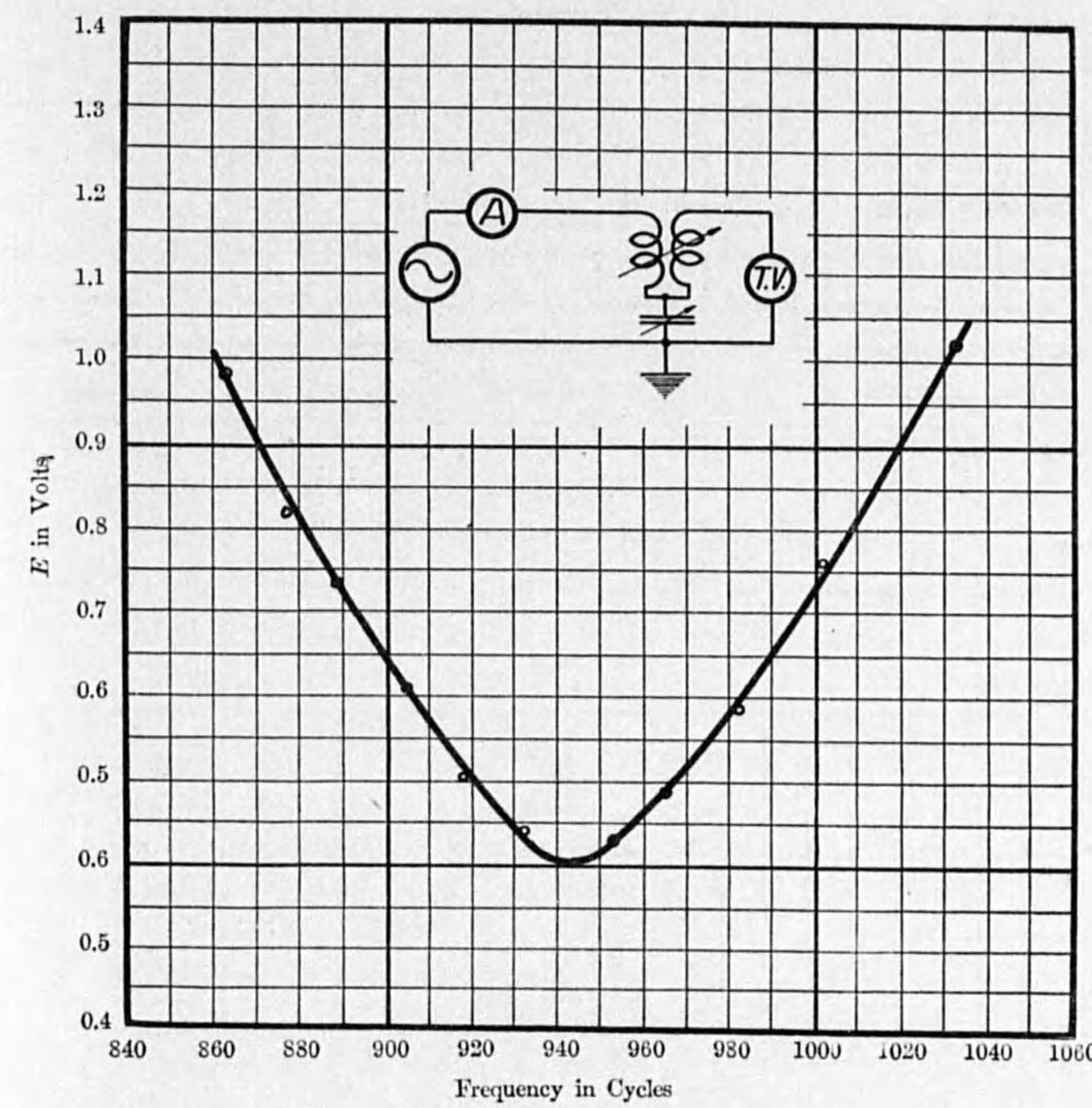

Fig. 25 A.

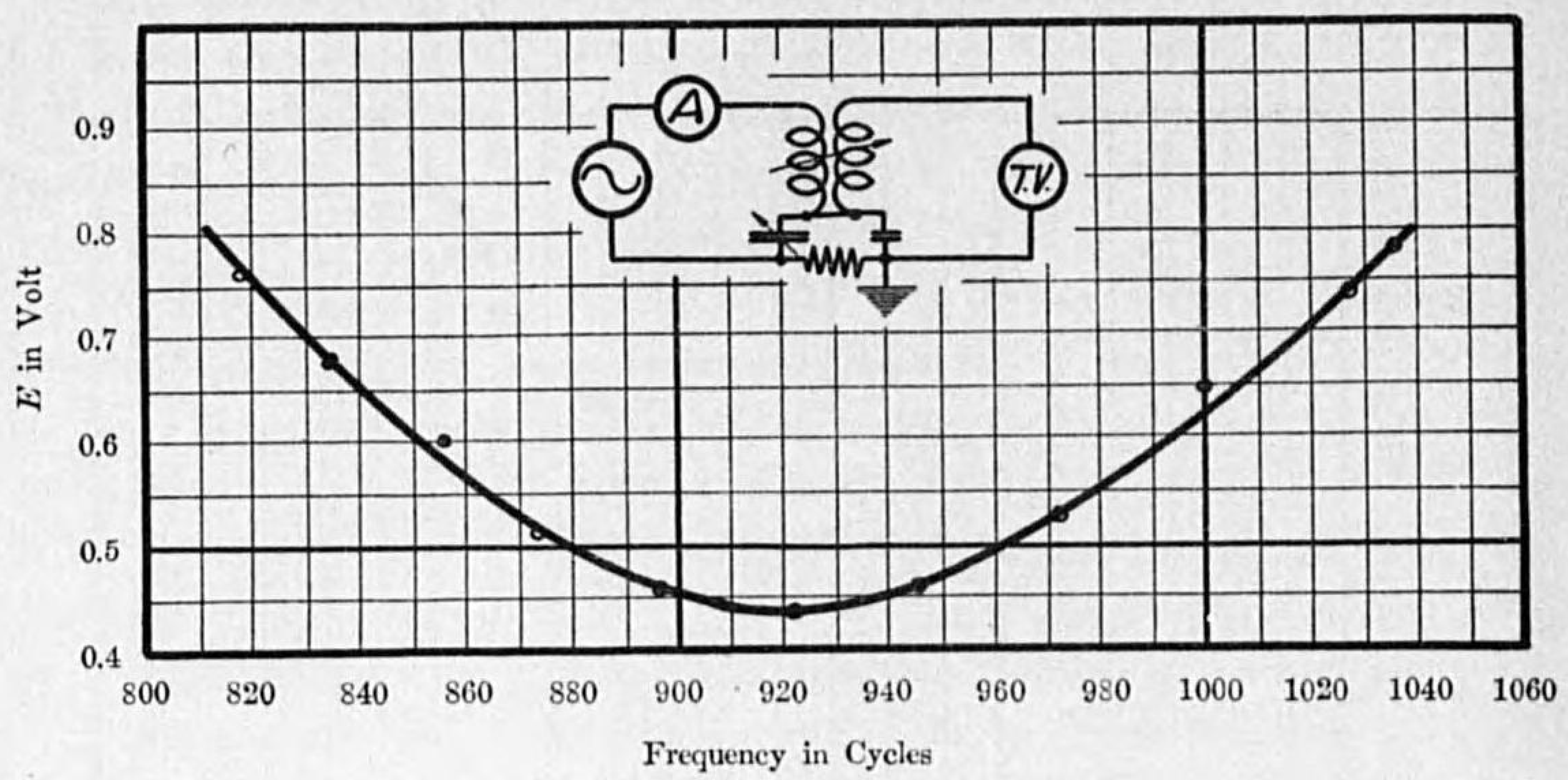

FIG. 25 B

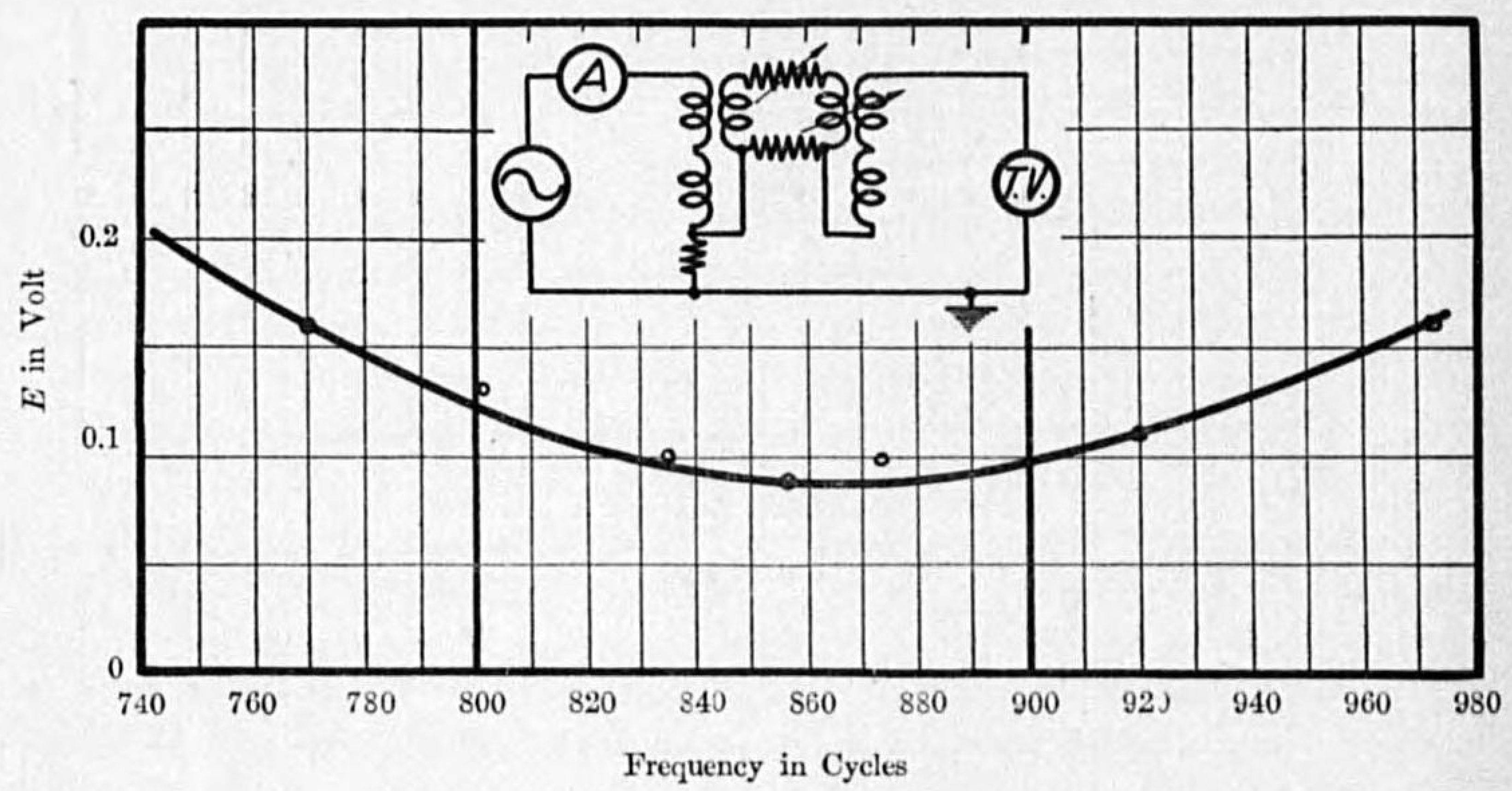

FIG. 25 C

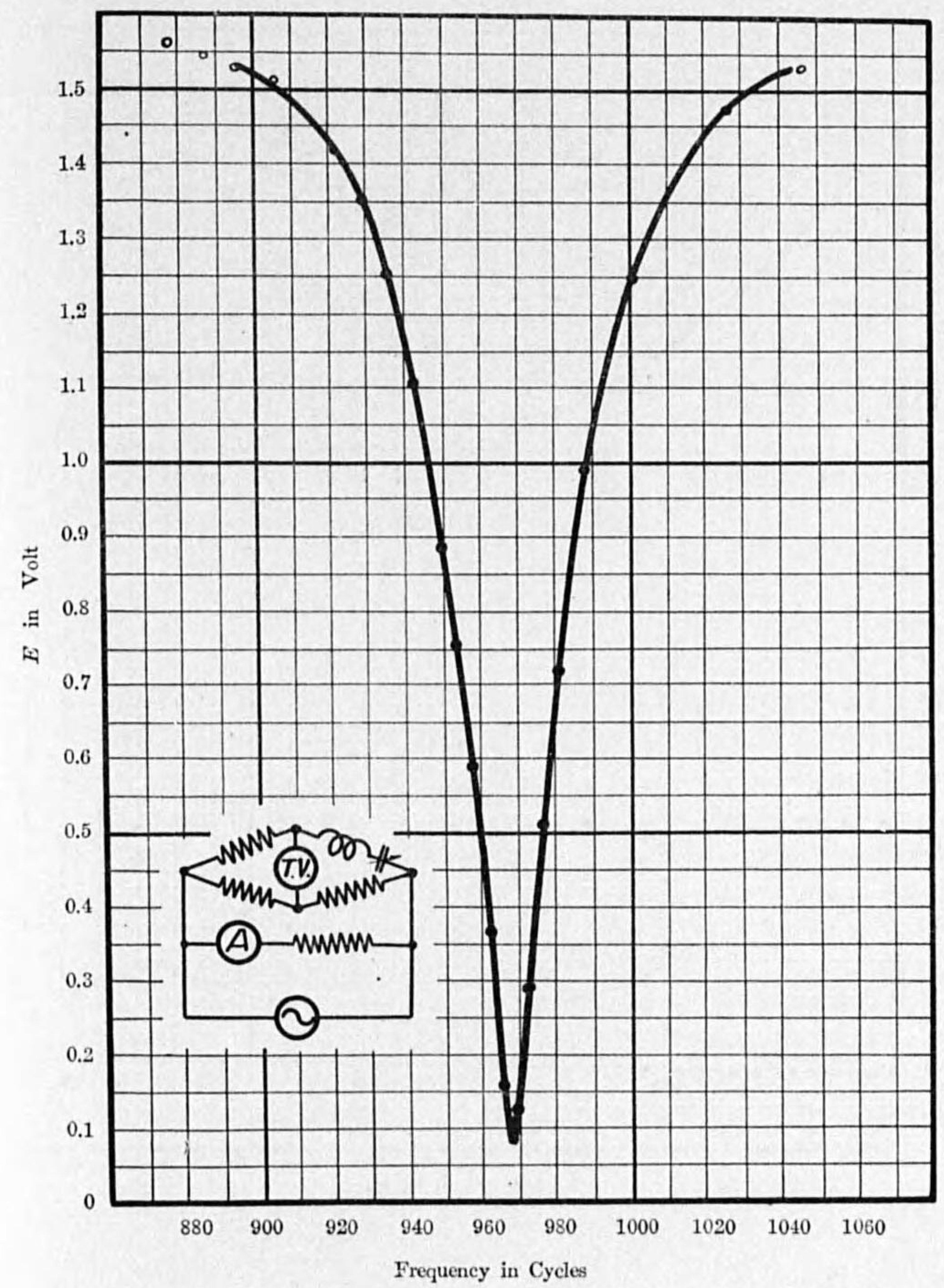

FIG. 25 D

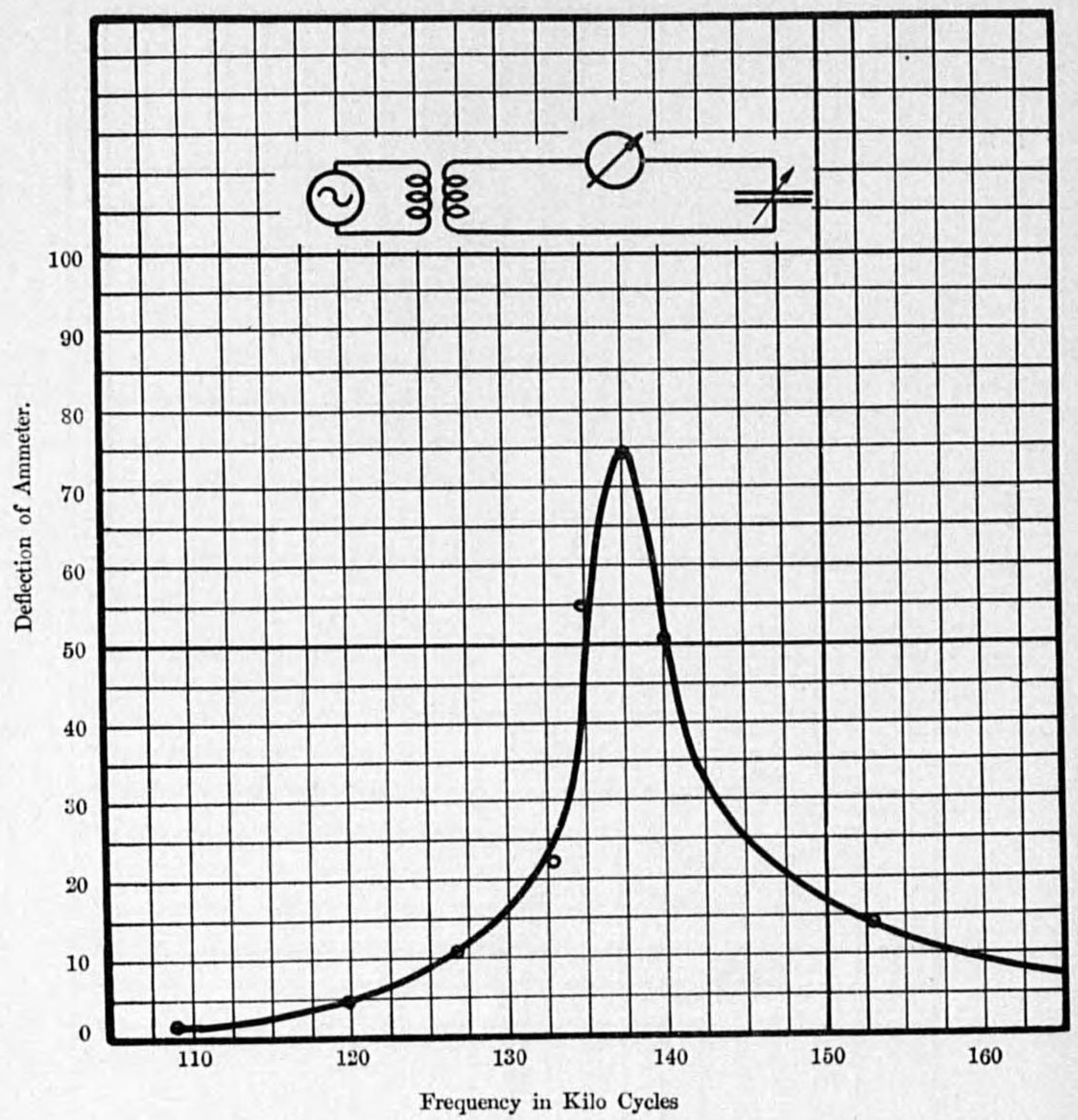

FIG. 25 E.

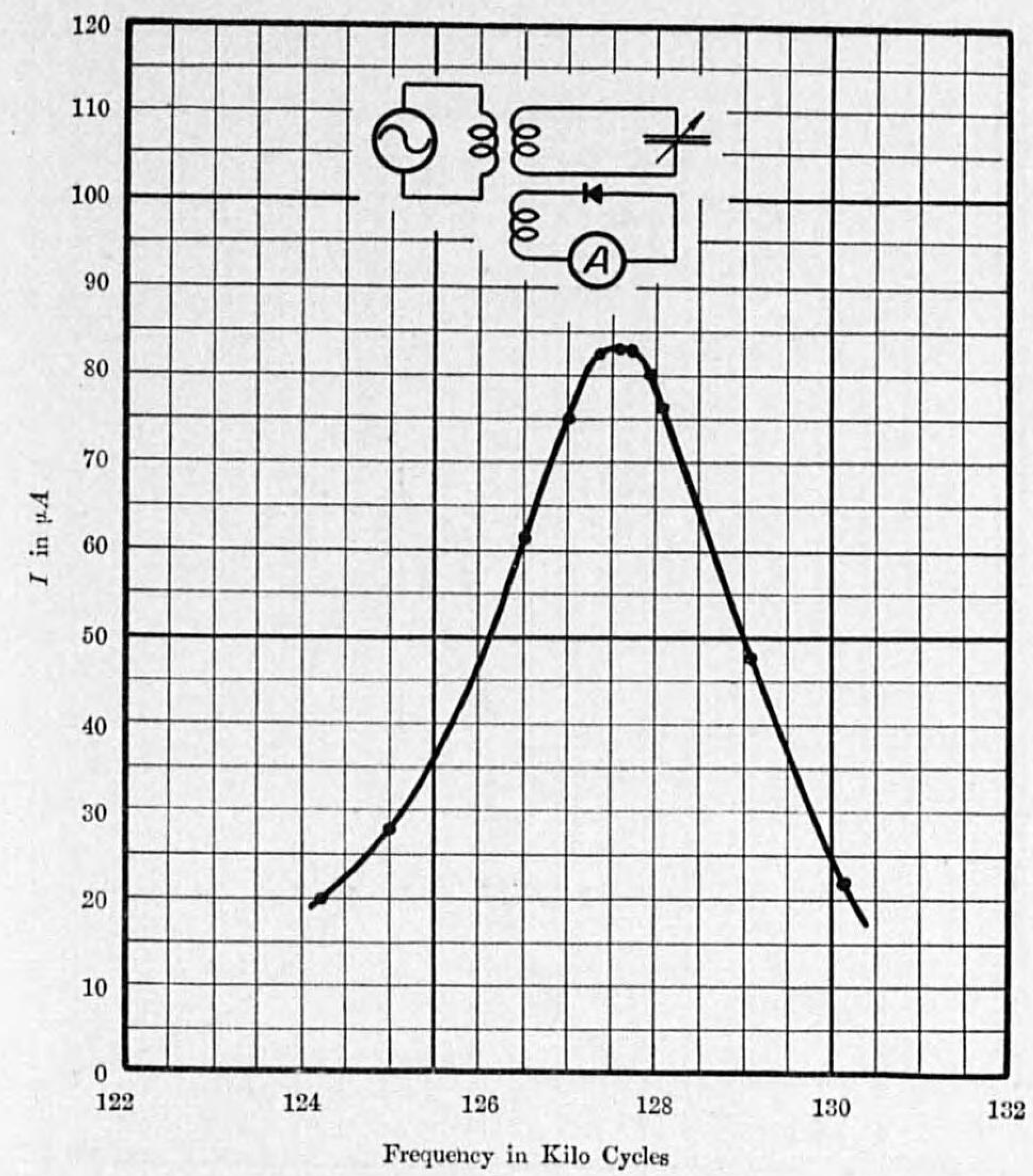

FIG. 25 F.

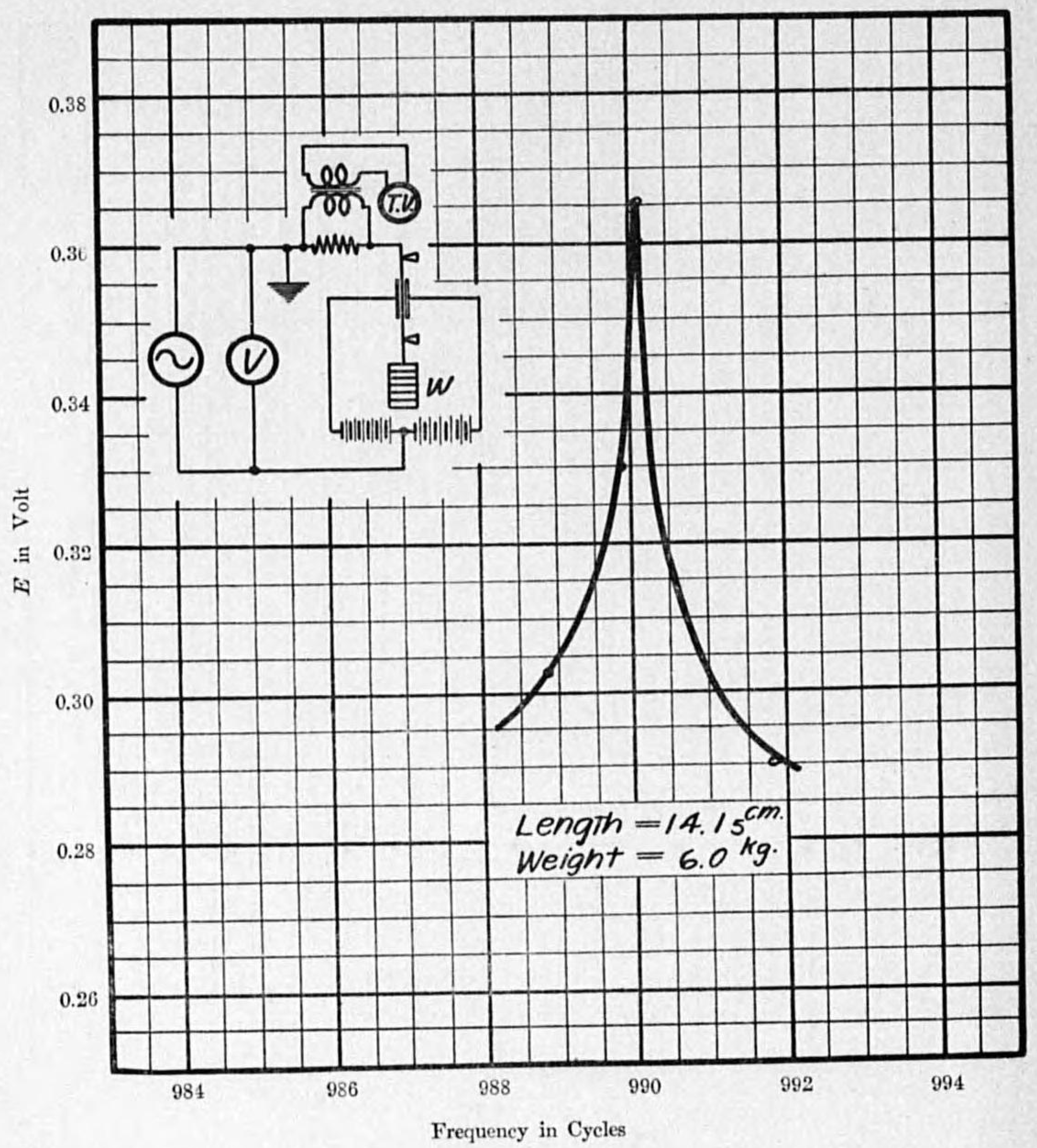

FIG. 25 G.

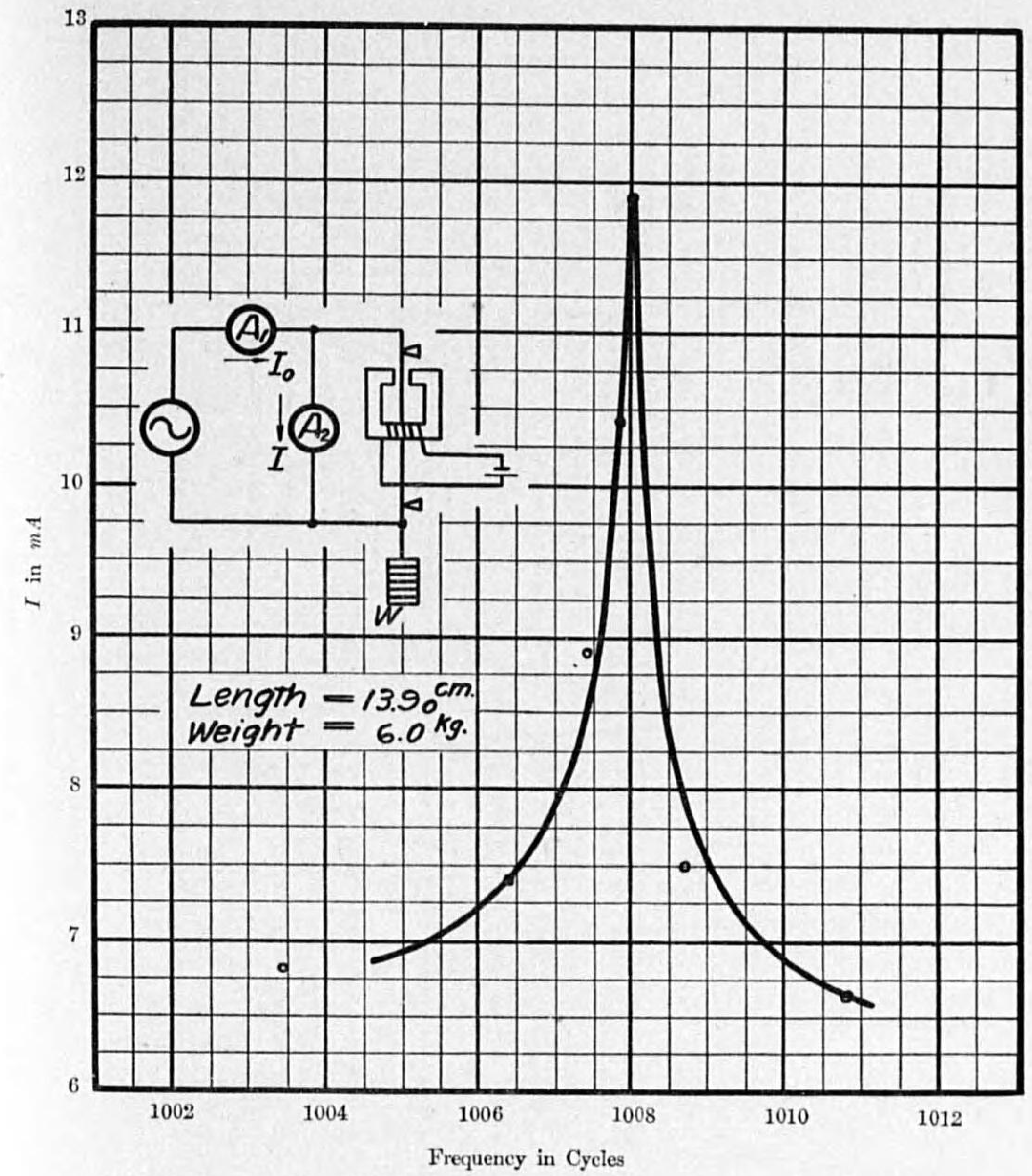

FIG. 25 H.

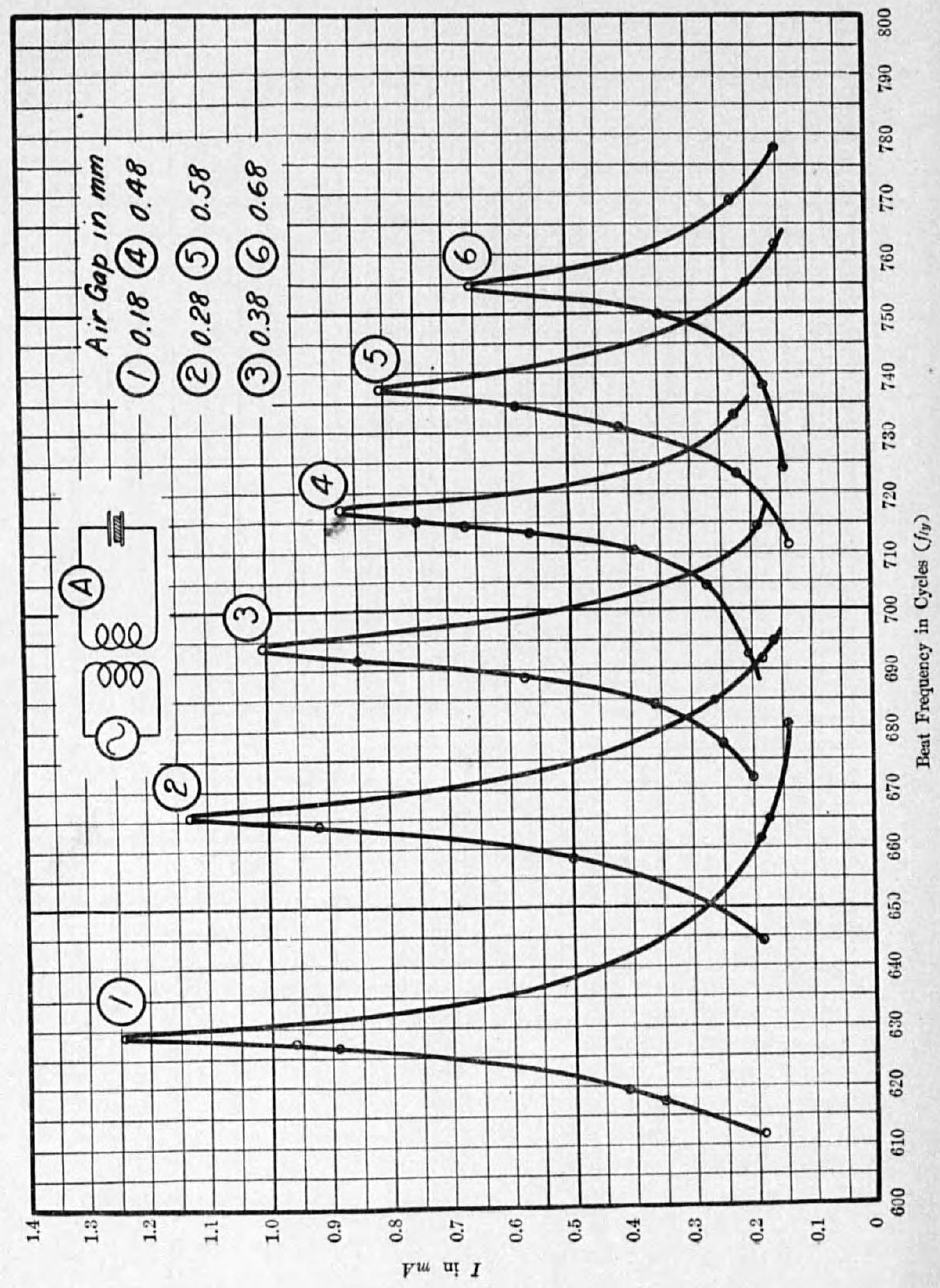
Air Gap in mm
1 0.18
2 0.28
3 0.38
4 0.48
5 0.58
6 0.68
A
I in mA
Beat Frequency in Cycles (f_y)
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
600
610
620
630
640
650
660
670
680
690
700
710
720
730
740
750
760
770
780
790
800

FIG. 25 I.

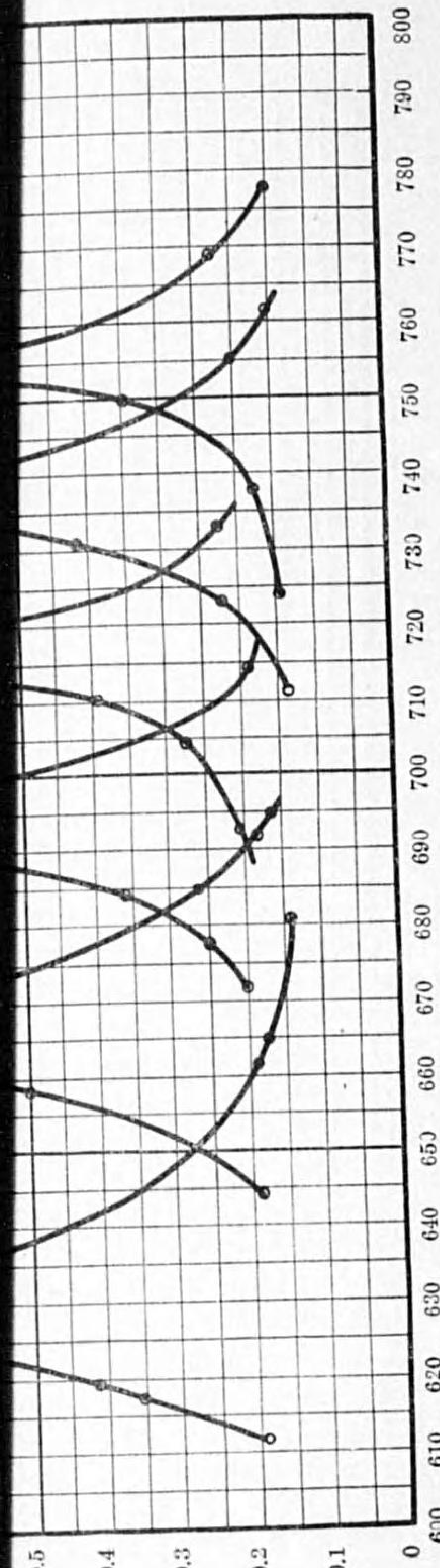

Fig. 25 I.

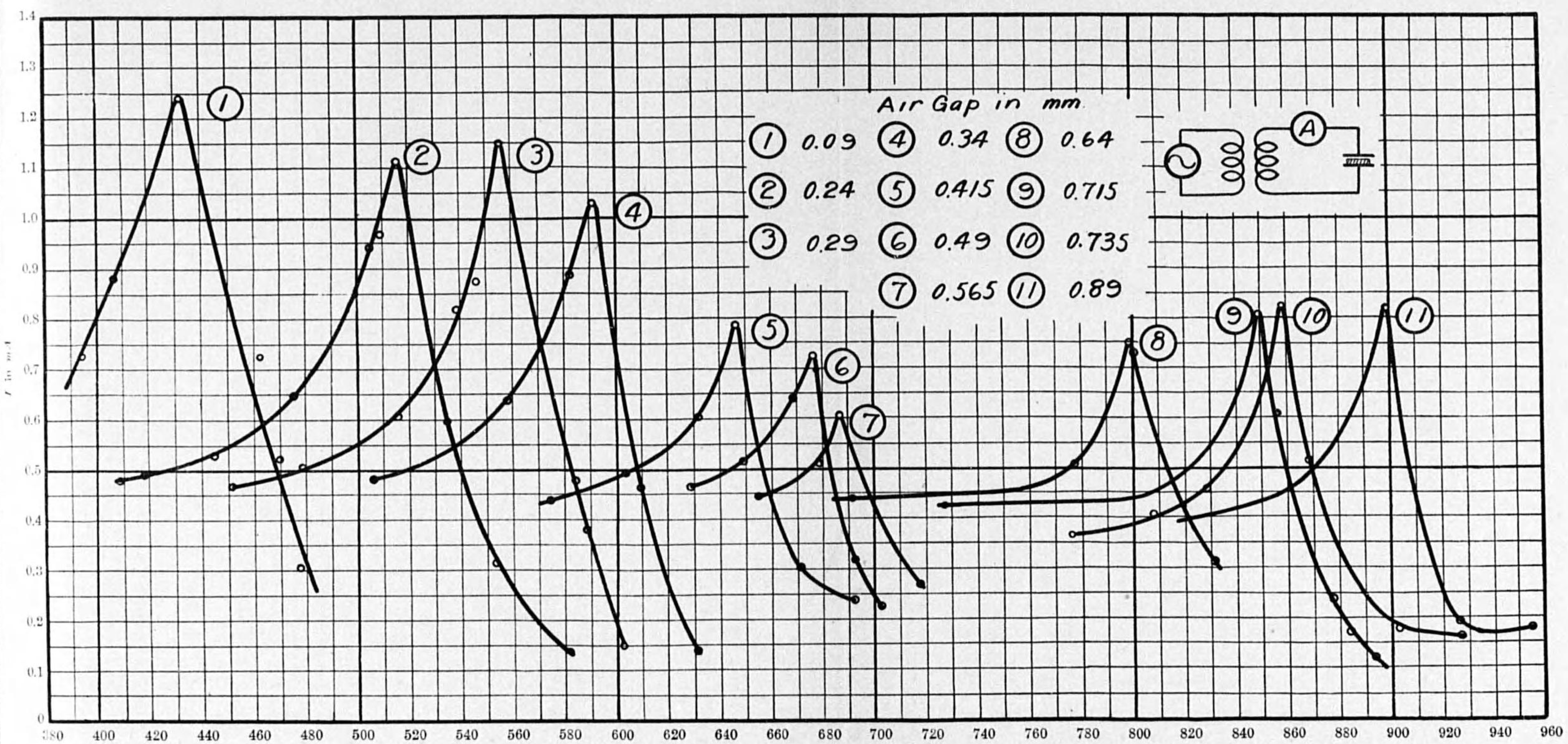

Fig. 25 J.

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