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On the Valve Method of Measuring Small Motion, with Special Reference to the Precise Recording of Sounds, Pressure-Variations and Vibrations.

By

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(with 4 plates).

Abstract.

The Paper contains the results of a series of experiments which were carried out with a view to apply the methods of measuring very small motion utilizing a generating circuit containing a triode to the precise recording of sounds, pressure-variations and vibrations.

A tuned grid circuit was employed and a small transformer was inserted in the plate circuit instead of balancing the plate current by means of the potentiometer method, an Einthoven string galvanometer or a high frequency oscillograph being used as the recording instrument.

To record sounds a condenser microphone was employed as the capacity in the generating circuit, and records of the sound of explosion, vowels and whistle were obtained. The microphone was slightly modified to record pressure-variations.

Finally, according to our experience a special instrument an "Ultramicrometer" has been constructed, which may be conveniently used for the same purposes and other problems requiring the measurement of very small displacement or motion. With this instrument the capacity method as well as the eddy current method may be carried out, the circuit being in all cases the "tuned grid." The plate current may be balanced or a transformer may be inserted according to the kind of problem.

Introduction.

During the past few years a number of papers has been published by Widdington,[1] Dowling[2] and Thomas[3] relating to the method of measuring very small displacement or motion utilizing one or several oscillating circuits containing the triode valve. It is shown by these authors, that the method is extremely sensitive, provided that a special care is taken in manipulating the apparatus, and hence it is sometimes called an "Ultramicrometer."

Although the methods used by these authors are all similar in utilizing the triode valve, yet in principle they are entirely different, so that each method has its special field of applications. The method devised by Widdington for the measurement of very small displacement utilizes the beat between two generating circuits and is so-called "heterodyne method." On the other hand, Dowling and Thomas work with only one generating circuit, and the displacement or motion to be measured is made to produce a corresponding change in the plate current of the valve. In the Dowling's method this change in the plate current is caused by the change in capacity in the circuit, while in the Thomas' method it is produced by the change in the eddy current loss.

The present paper contains the results of a series of experiments which were carried out with a view to apply these methods of measuring very small motion to the precise recording of sounds, pressure-variations and vibrations.

Any one who has had an experience in handling a generating circuit containing an electron tube is well aware of the fact that a minute change in the filament current as well as the plate voltage

(1) R. Widdington: Phil. Mag., **40** (1920), 634; **46** (1923), 607; **49** (1925), 113.
(2) J. J. Dowling: Engineering (1921), 395;
Proc. Roy. Dublin Soc., **15** (1921)
Nature, **107** (1921), 523.
Phil. Mag., **46** (1923), 81.
(3) H. A. Thomas: Engineer **135** (1923), 138;
Journ. Sci. Instr., **1** (1924), 22

cause a considerable change in the plate current, so that it is a matter of considerable difficulty to maintain the plate current absolutely constant in value during a long period of time.

The heterodyne method employed by Widdington is by far the best in this respect, if a single displacement is to be measured, because its operation has nothing to do with the value of the plate current itself, while in the other two methods the extreme constancy of the plate current is *a priori* looked for. On the other hand, the manipulation of an oscillating circuit containing an electron tube is a matter requiring some labour and skill, and the method using only one circuit is no doubt preferable for a practical use, so that in the experiment to be presently described only such a method was adopted.

1. Precise Recording of Sounds.

(*a*) *Sound of Explosion.* In measuring the change in the plate current, which is produced by the displacement or motion to be measured, Dowling and Thomas have both compensated the plate current itself by means of the potentiometer method as shown in Fig. 1.

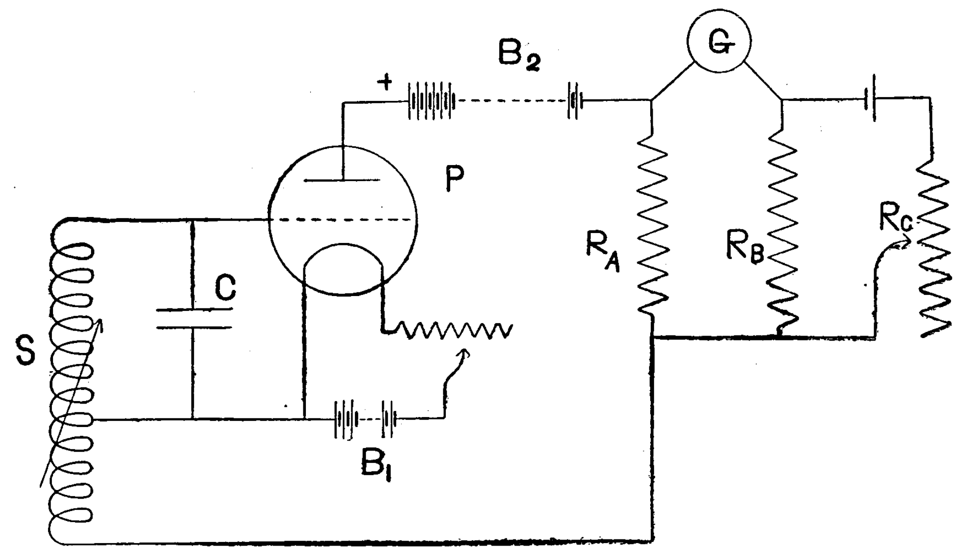


Fig. 1.

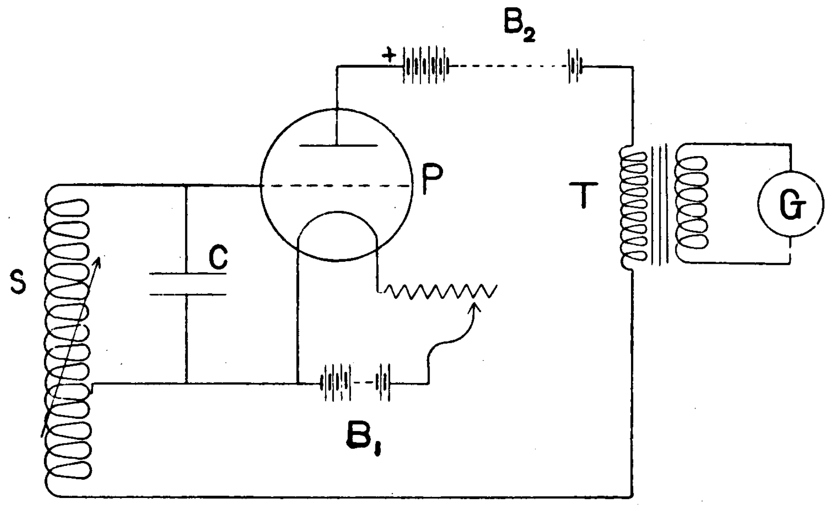


Fig 2.

It is, however, convenient to insert a small transformer in the oscillating circuit as shown in Fig. 2, if only the quick variation of the plate current is to be measured as in the case of taking a record of sound or pressure-variation. By inserting a transformer not only the trouble of compensating the plate current is avoided, but at the same time the adjustment of the generating circuit is made exceedingly easy on account of the separation of the oscillating circuit from the recording arrangement.

In making a precise record of a complex sound the great difficulty always met with is that the record is inevitably complicated by the resonant character of the receiver or other part of the recording arrangement,[1] and a special care should therefore be taken to avoid the distortion of the wave form.

Of all transmitters usually employed the condenser microphone devised by Wente[2] has a remarkable merit in this respect, because

(1) The Low-Hilger Audiometer recently put on the market is an excellent apparatus for recording sound; but the natural frequency of the membrane is rather low, being usually 300 per sec. and 1500 per sec. at the max, so that it is not suited for recording complex sounds.

(2) E. C. Wente: Phys. Rev. **10** (1917), 39; **19** (1922), 498.

its natural frequency can be made so high as several thousands per second or more and be made to exceed the highest possible frequency, which would be contained in the sound to be recorded. The microphone consists essentially of a thin metal diaphragm under strong tension placed at a very small distance from a metal plate, the plate and the diaphragm forming two electrodes of a parallel plate air condenser. Although the condenser microphone is sometimes employed as the transmitter in broadcasting, yet it is not sensitive enough for practical use. However, it may be justly used as a convenient apparatus for taking a precise record of sound, if it is employed as the capacity in the ultramicrometer circuit here dealt with.

The microphone constructed by us is essentially the same as that devised by Wente (See Fig. 5). As the vibrating membrane a thin sheet of German Silver (brass silver) of thickness 0·05 mm. was employed instead of steel, because it was difficult to obtain steel sheet of sufficient thinness, and ebonite was replaced by a marble plate of the highest quality, by which much more stiffness and superior constancy in adjustment could be secured. The vibrating membrane being of non-magnetic material, the plate which forms an air condenser with it was made of steel, instead of brass, which made it easier to ground the surface of the plate perfectly in the same plane with the edge of the metal part which supports the membrane in strong tension. The electron tube employed was supplied by the Tôkyô Electric Co. and was a large sending valve, requiring 600 volts for the normal plate voltage, so that a very thin sheet of mica having uniform thickness was sticked with shellac on the surface of the plate so as to increase the insulating power of the narrow air gap.

Since the vibrating membrane consists of metal, the microphone can safely be employed to receive a sudden and violent sound such as produced in explosion, so that first of all we have employed it for that purpose.

The electrical connexion is shown in Fig. 2, a transformer being inserted so as to step down the voltage. As the oscillating coils a pair of coils mounted in same manner as in a variometer was used, and the oscillation[1] was started by changing the coupling. Both coils consisted of a single layer coil, having a diameter 16 and 12 cm. respectively, wound with about 55 turns of B. S. No. 20 double-silk covered copper wire. A high frequency oscillograph made by Cambridge Paul Instrument Co., England, was employed as the recording instrument. The vibrating element of the oscillograph had a natural frequency of about 10,000 per second and very good damping, so that no error could be imposed on the record by the sympathetic vibration of the element. A wave of an alternating current of 50 cycle was recorded simultaneously on the film in order to show the lapse of time.

To avoid any electromagnetic disturbance from outside all the apparatus belonging to the oscillating circuit, except the microphone, were enclosed in a large wooden case, the inner side of which was covered with a sheet metal and was perfectly earthed. The microphone was encased similarly in a separate case.

Pl. 19 *A* and *B* are the records thus obtained of the sound of explosion of a small rubber balloon, containing a suitable mixture of oxygen and hydrogen, and exploded by an electric spark produced at the centre.

A is the record of sound produced in a laboratory room, placing the rubber balloon one metre apart from the microphone. There existed in the room several desks, furnitures and many instruments, and the record shows clearly the reverberation of the room, the air being set in violent vibration for some time by a single impulse of explosion.

B is the similar record of sound of an explosion produced in the open air. The microphone was placed at a distance seven metres

(1) Throughout this paper the word "oscillation" denotes an electrical but not mechanical one.

from a concrete wall and the balloon was exploded at a position one metre farther away. Of course, no resonance is shown in this case and the reflection from the building is clearly observed after the lapse of about 1/25 second. The minute wavy motion appeared on the record is the natural vibration of the membrane, which was not stretched quite enough.

A sudden and violent sound can thus be faithfully recorded by the present devise, it may well be employed for recording sounds produced by a gun or a bullet, and also for investigating objectively the acoustic properties of a lecture hall, auditorium etc.

(*b*) *Record of Simple Tone.* As an example of recording a simple tone, a record of whistle is shown in Pl. 21 *D*. To take this record an Einthoven string galvanometer made by Cambridge Paul Instrument Co. was employed as the recording instrument. A platinum wire, 0·01 mm. in diameter (Wollaston wire supplied by Hartmann & Braun, Germany) was employed as the vibrating element, its tension being so adjusted that the natural frequency was 50 cycles per second. In recording a simple sound such as whistle no distortion of the wave form can be established by the low natural frequency of the vibrating system.

(*c*) *Record of Vowels.* The characteristics of vowels have long been made the subject of investigations by many physicists, physiologists as well as psychologists, and a long list of previous investigations lies before us, and indeed while the present work has been in progress two very interesting papers have appeared giving precise records of vowels and discussing their characteristics. The one[1] is the results obtained at the Research Laboratory of the Siemens & Co., Berlin. An extremely delicate condenser microphone was constructed for that purpose and the electrical connexion is the so called super-heterodyne method utilizing frequency modulation. No doubt the method as used is very ingeneous but it is too elaborate for many purposes which do not aim

(1) F. Trendelenberg: Zs. f. techn. Phys., **5** (1924), 236.

at utmost degree of precision. It requires the simultaneous use of several circuits containing electron tube and a powerful amplifier using eight electron tubes.

The other(2) is the results of a series of extended investigations carried out at the Research Laboratory of the American Telephone & Telegraph Co., New York. No detailed description of the experimental arrangement is given, except that the recording apparatus were consisted of a Wente condenser microphone, an amplifier, and an oscillograph, and the combined amplitude-response for the whole system is fairly uniform over a wide range from 100 to 5000 cycles.

Though it is beyond the scope of the present experiment to attempt to give records of vowels with utmost degree of precision, yet it may be shown that with a comparatively simple arrangement a complex sound such as vowel can be recorded with sufficient fidelity.

For this purpose similar oscillating circuit and microphone were employed as above; no horn being employed and the membrane being stretched so as to make its natural frequency about 3000 per sec. Owing to the low natural frequency the Einthoven string galvanometer, though very sensitive, is not suitable for recording a complex sound such as vowel, so that the high frequency oscillograph was employed. On account of the smallness of the sensitivity of the condenser, microphone having such a high natural frequency, it is not possible to record a human voice of usual intensity by using simply the oscillograph as the recording instrument; an amplifier should inevitably be employed in this case.

Amplification of a current, easy as it may appear, is, however, a matter of considerable difficulty, if the distortion of the wave form is taken into account.

The resistance coupled amplifier is no doubt the best in this respect, and at first we have tried to amplify the current by this method. However, it was soon found that it was not possible to use

(1) J. B. Crandall and C. F. Sacia: Bell System Techn. J., **3** (1924), 232.

this method in our oscillating circuit. By connecting the amplifier circuit across a resistance directly to the oscillating circuit two kinds of troubles are brought in. Firstly, the distribution of potential being considerably changed, the sensitivity of the arrangement is much reduced. Secondly, minute adjustment of the initial circuit gives rise to an influence, moreover in amplified amount, at all the stages up to the final stage of the amplifier, and much time and labour are therefore required to adjust the whole system to its maximum sensitiveness.

The method was therefore abandoned, and a small inter-valve transformer was inserted in the first stage as shown in Fig. 3. By inserting here a transformer both troubles described above were avoided.

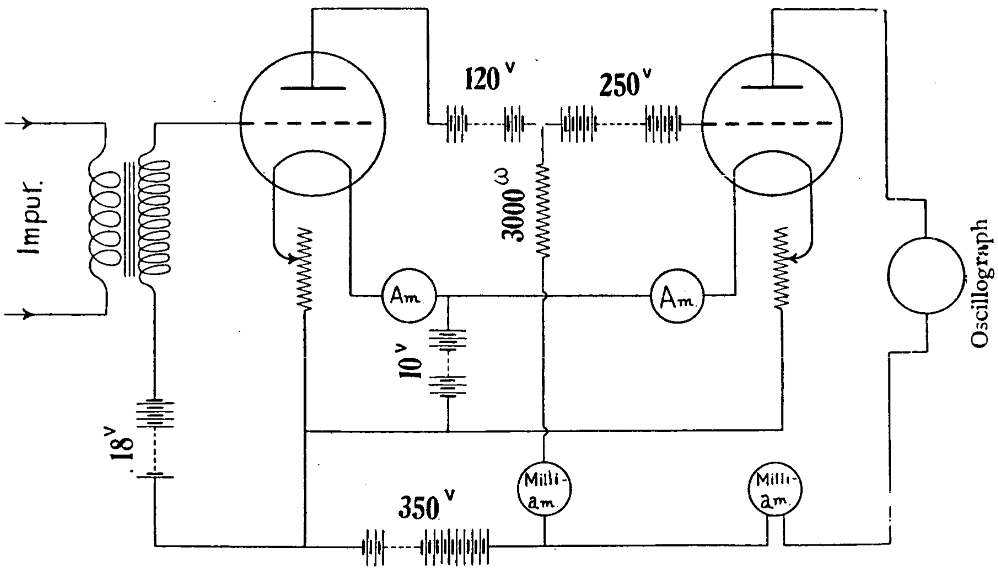
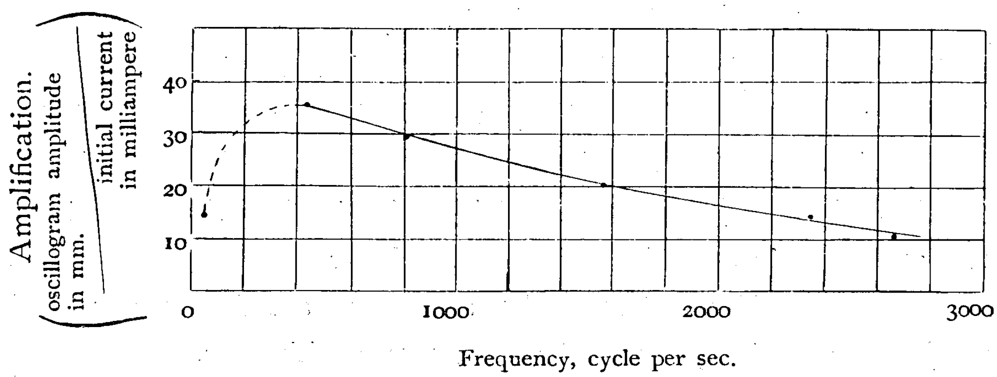


Fig. 3.

Pl. 20 *C* and 21 *C* contain some of the records of vowels obtained by this method, as intoned by two different male voices (J. O. and Y.Y.).

Obviously, the sensitivity of the system containing a transformer is not uniform over a wide range of frequency, the degree of amplification being no doubt less for higher frequencies. To determine the amplitude-response of the system a feeble current was amplified and recorded, the initial current being measured by means of a Duddell thermogalvanometer made by Cambridge Paul Instrument Co., England



Amplitude-response of the system combining the amplifier and oscillograph.

Fig. 4.

and the amplified current estimated on the oscillogram. The results are plotted in Fig. 4. Evidently the characteristic of the oscillograph is also included in the ordinates. As shown in Fig. 4. the amplitude-response of the system, combining the amplifier and the oscillograph is not uniform, its response for a frequency 200 being about three times that for a frequency 2500 cycles per sec. However, the natural frequency of the microphone being 3000 cycles, its response to higher note is much greater than that to lower note, so that the amplitude response of the whole system is somewhat better than that shown by the curve.

In order to reveal the fine characteristic of vowel the oscillogram should be made as fine as possible, by using the finest slit before the arc lamp and by falling the dry plate at the highest speed, i. e. 4 metres per sec., and in consequence of insufficient illumination it was made extremely difficult to obtain a good oscillogram. Therefore to increase the intensity of light the tiny mirror of the oscillograph was replaced by a mirror, same in weight but somewhat larger in size, and tolerably fine records were obtained at last.

It will be noticed in the records, that while the lower characteristic regions of each vowel is clearly shown, the characteristic region having higher pitch is not distinct. Though this defect may be perhaps due to the non-uniformity of the sensitiveness of our recording system, some part of it may be accounted for by the lack of any musical training of the voice.

2. Record of Pressure-Variations.

The condenser microphone can be employed as a sensitive differential manometer, if a slight modification be made as shown in Fig. 5.

The difference in pressure on both sides of the membrane will thus produce a change in the capacity.

As an example of the application of the manometer thus constructed we have recorded the fluctuation of the speed of wind of an electric fan using a Pitot tube. The electric fan employed was one having a diameter of 12 inches, and the end of the Pitot tube was placed at a distance 15 centimetres from the plane of the blades. In the manometer thus simply modified, one side of the membrane being faced to a very narrow air gap, there might exist some time-lag in the effect of the variation of pressure on this side, so that the static pressure of the Pitot tube was introduced to this side.

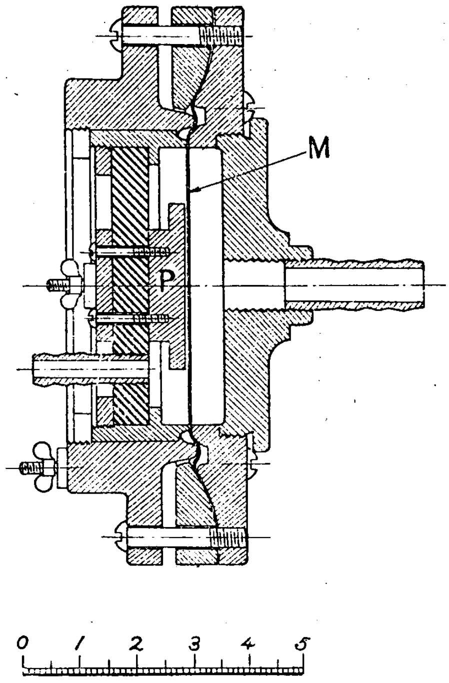


Fig. 5.

In Pl. 21 *E* the fluctuations of the pressure difference at two different numbers of revolution are given. At the maximum revolution, i. e. 1,270 revolutions per minute, the fluctuation caused by each blade is very clearly shown. The fluctuation recorded corresponds the number of revolution multiplied by the number of blades (4).

In taking these records the same electrical connexion as used in recording a simple tone was employed, an Einthoven string glavanometer being the recording instrument.

3. Record of Vibration.

Thomas[1] employed the Colpitts Hartley circuit to record a small motion. The change in the plate current is produced by the change of the loss due to eddy current. The novel feature of this method is that it needs no contact with the body whose motion is to be recorded still, its sensitivity is exceedingly high.

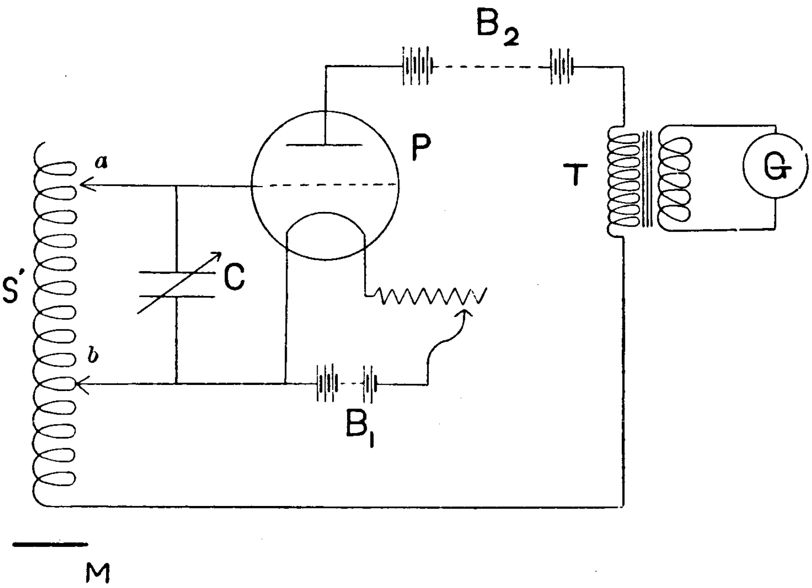


Fig. 6.

Obviously the "tuned grid circuit" here employed for recording sounds etc. may also be employed for the same purpose. The electrical connexion is shown in Fig. 6, where M is the moving body and C is a variable air condenser. The change in the relative position between the body M and the oscillating-coil S gives rise to a change in the eddy current loss and hence a change in the plate current. The oscillating-coil S consists of a single layer coil of double silk-covered copper wire B. S. No. 24, wound on a glass tube 4 cms. in

(1) loc. cit.

diameter, the total number of turns being about 90.

Several taps have been taken off from the coil and the number of turns in the grid circuit was varied so as to set the circuit in oscillation. Changing the capacity of the air condenser and observing the corresponding change in the plate current by means of a milliammeter inserted in the circuit, the characteristic of the circuit, i. e. the relation between the change in reactance and the corresponding change in the plate current, could be easily estimated, and the point of suitable sensitiveness could be easily found.

Pl. 22 *F* and *G* are records of vibration thus obtained. Small triode valve was employed in this case. It required 100 volts as the normal plate voltage and 1 ampere as the filament current. *F* is a record of vibration of a tuning fork, and *G* is that of vibration of a circular brass disc supported at the centre and set in vibration by bowing the edge with a violin bow. The vibrating body was placed about 10 mm. below the coil *S*.

4. A New Instrument "Ultra-micrometer."

As stated in the beginning of this paper, it is already shown by many authors that the method here dealt with is a very convenient means for measuring very small displacement. It will be seen from the results obtained by the present authors that the method may also be applied for taking precise records of souuds, pressure-variations and vibrations.

The method utilizing capacity change and that working with the change in eddy current loss each has its own field of applications. Although the capacity method is no doubt more sensitive than the eddy current method, yet for recording vibrations of a body the latter method is much more convenient than the former, because no special arrangement except the oscillating coil is needed and moreover no fine adjustment is required in the eddy current method.

Further, in both these methods, if only the quick variations of the plate current is to be recorded, it is preferable to insert a transformer in the plate circuit than to balance the plate current by potentiometer method.

Since these methods of measuring very small displacement or motion may have many other fields of application in engineering as well as in purely scientific works, it would be desirable to make all the necessary apparatus in a complete set, with which any of the circuits described above, Figs. 1, 2, 3 and also Fig. 7. can readily be made.

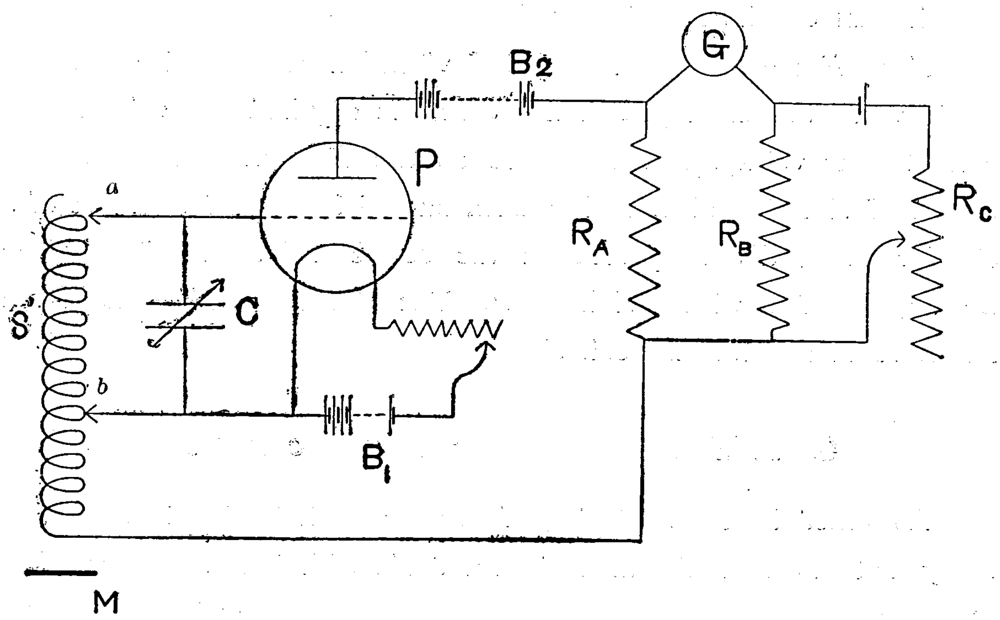


Fig. 7.

We have had therefore an instrument "Ultra-micrometer" constructed by Messrs. Andow & Co., Tôkyô, the general view of the instrument being shown in Pl. 22 *H*.

With this instrument the capacity method as well as the eddy current method may be carried out, the circuit being in all cases the "tuned grid." The plate current may be balanced or a transformer may be inserted according to the kind of problem. To carry out the eddy current method a special oscillating coil is provided. The oscillating coil is mounted on a micrometer screw so as to be able to move it axially in order to calibrate the instrument in measuring a displacement. The oscillating coil consists of a single layer of wire wound on a glass bobbin and the change in reactance to start oscillation in the circuit is accomplished by means of a sliding contact. The use of such a variable reactance instead of fixed coil is necessary in using different kind of valves.

Tôkyô, April 1925.

第十一號
大正十四年八月發行

抄錄

三極眞空管を應用して微細な變位や運動を測定する方法に就て

所員 理學博士 小幡重一
技手 吉田彌平

三極眞空管を含む電氣振動回路を利用して微細な變位や運動を測定する方法は「ウイデイントン」「ドーリング」及「トーマス」等によつて研究され極めて感度鋭敏なものである事が證明された。

「ウィデイントン」の方法は三極眞空管を含む二つの電氣振動回路の間の「ビート」を利用する所謂「ヘテロダイン」法であつて變位の絶對の値を極めて精密に測定する樣な場合には最も適當して居るが少くも二つの振動回路を必要とし取扱上かなりの不便を免れない。

これに反し「ドーリング」及「トーマス」の方法は夫々全然違つた考を基とした方法であるが何れも唯一つの振動回路を必要とする點に於て實用上甚だ好都合である。

著者等は此等唯一つの振動回路を使用する方法を研究し色々の應用を試みた。先づ「ドーリング」の方法即ち「チユーンド、グリッド」回路內の蓄電器の電氣容量の變化を利用する方法に「コンデンサー、マイクロフォン」を應用して爆發の音響、母音等種々なる音響を精密に記錄する事を試みた。

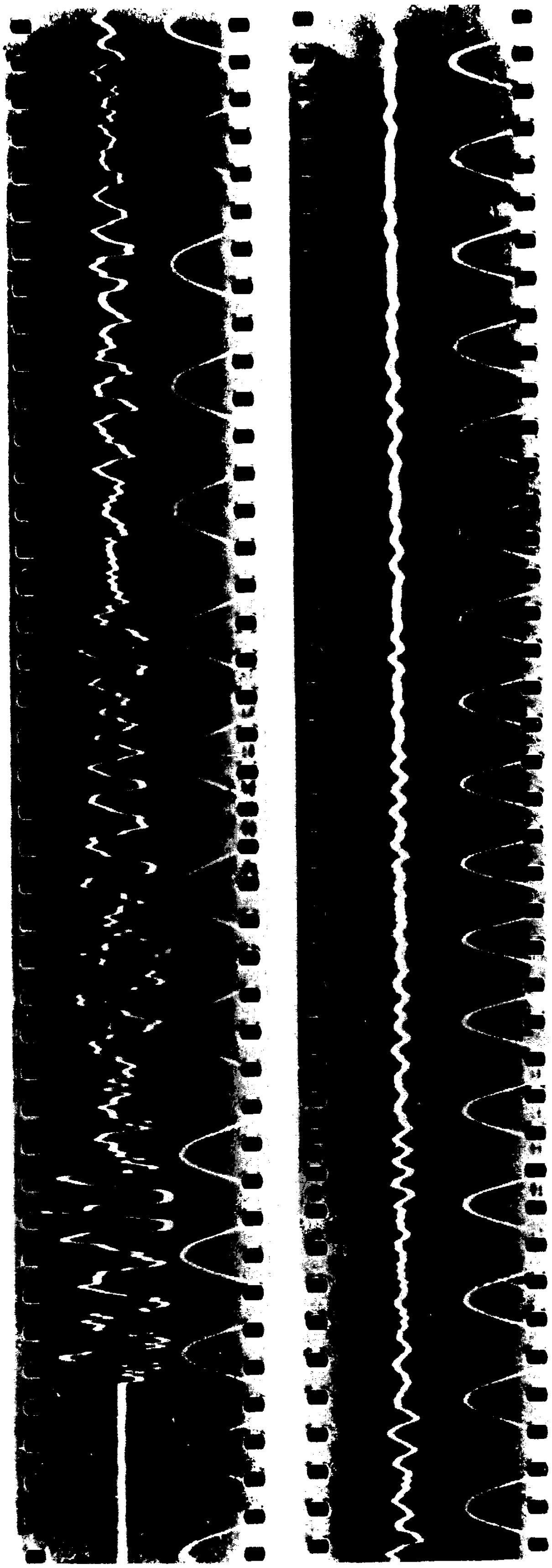
次に此「コンデンサー、マイクロフオン」を壓力計に改造して壓力變化の精密なる記錄をとる事を試み其應用の一例として「ピトー」管に此壓力計をつないで扇風器の風速の變動を記錄してみた。

物體の振動等を記錄するには非常な精密を要する場合以外は「トーマス」の方法が便利である。此方法では物體と「コイル」との關係的位地の變化によつて「エッディーカーレント」損失の變化を惹き起すのを利用するもので振動體に何物をも觸れさせずに其振動を記錄する事が出來る。「トーマス」は「ハートレー」回路を使用したが著者等は音響や壓力變化の記錄をとる場合と同じく「チユーンド、グリッド」回路を使用して全く同樣の成績が得られる事を示した。

是等の方法は猶色々な方面に應用の途があると考へられるから種々な用途に適應する樣な裝置を一と纏めにした器械を造つたら甚便利であらうと考へられる。因つて著者等は以上の經驗に基いて「アルトラ、マイクロメター」即三極眞空管を應用して微細な變位や運動を測定する器械を東京市麴町區有樂町報知ビルデイング內安藤商店をして製作させた。

(A) Explosion of a Small Rubber Balloon.

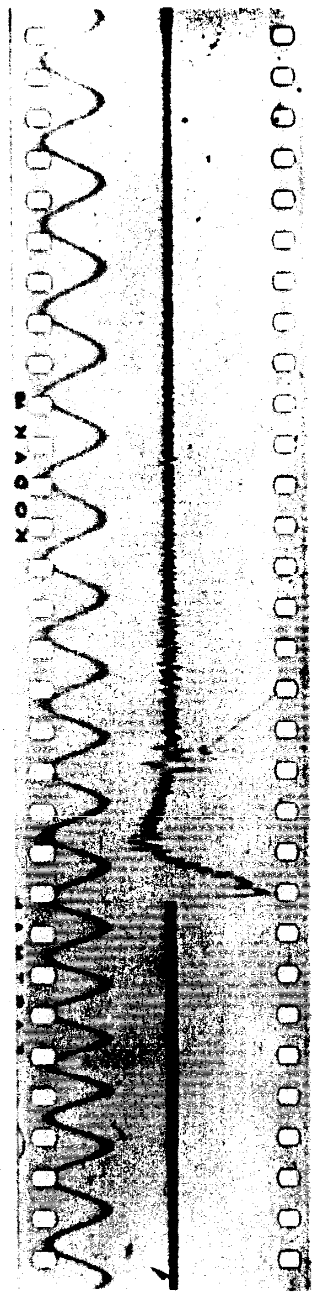
(in a laboratory room)



50~A.C.

(B) Explosion of a Small Rubber Balloon.

(in the open air)

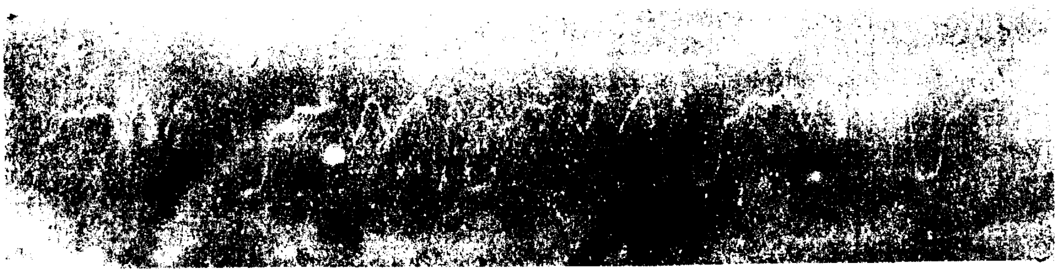


Reflection from the building

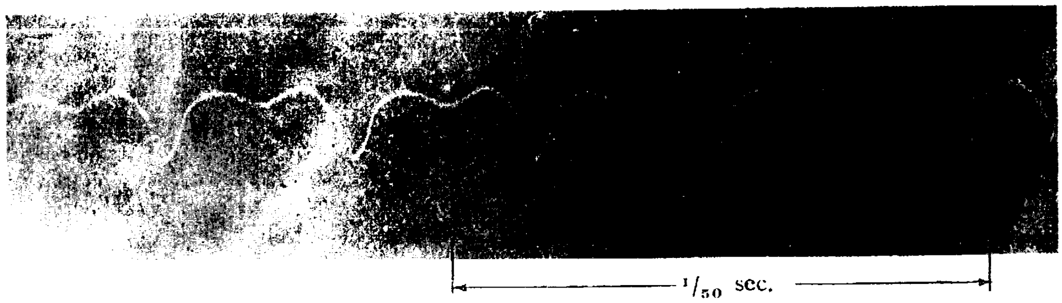
50~A.C.

(C) Vowels.

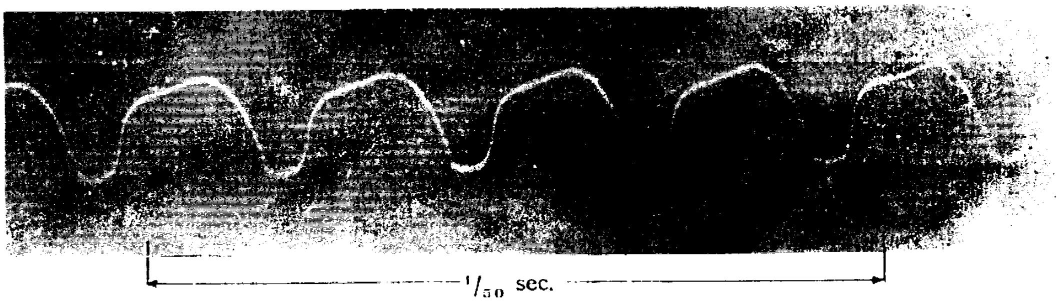
"a" as in *fa*ther. $n = 151$ per sec. J.O.



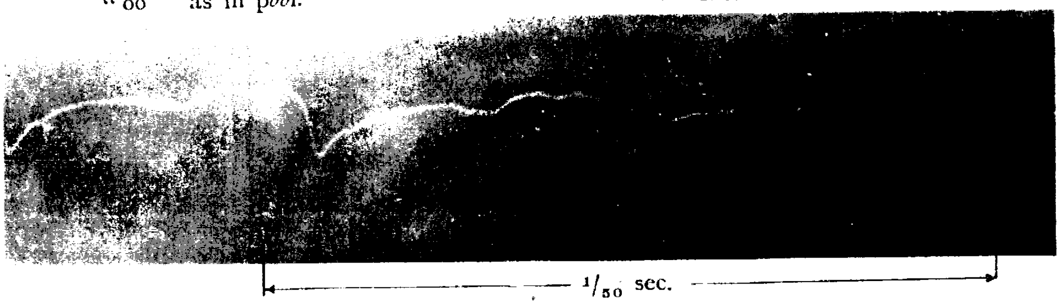
"ee" as in m*ee*t. $n = 150$ J.O.



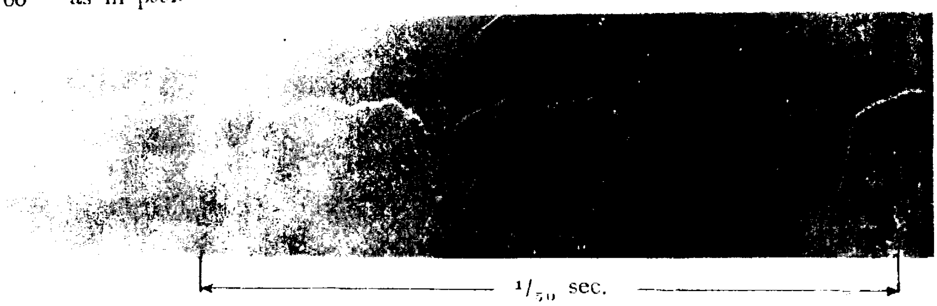
"ee" as in m*ee*t. $n = 200$ Y.Y.



"oo" as in p*oo*l. $n = 120.$ J.O.

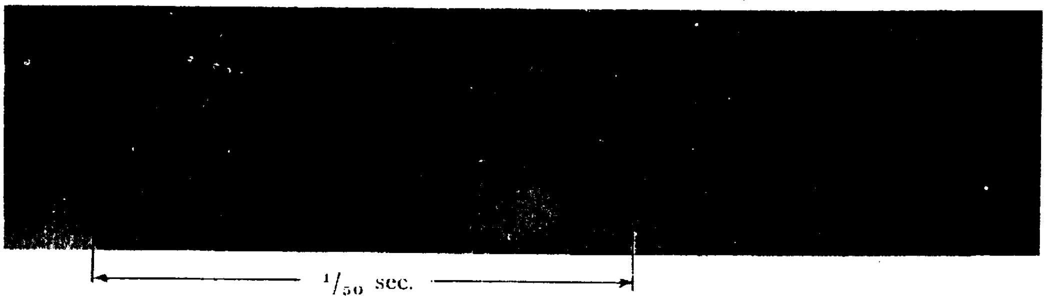


"oo" as in p*oo*l. $n = 166.$ Y.Y.

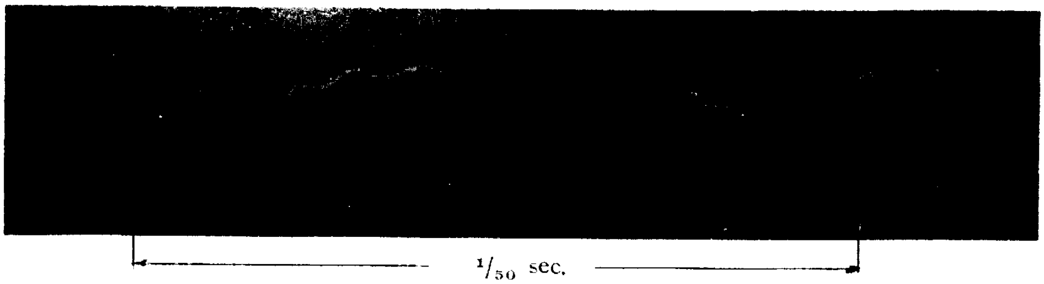


(C) Vowels *(continued)*.

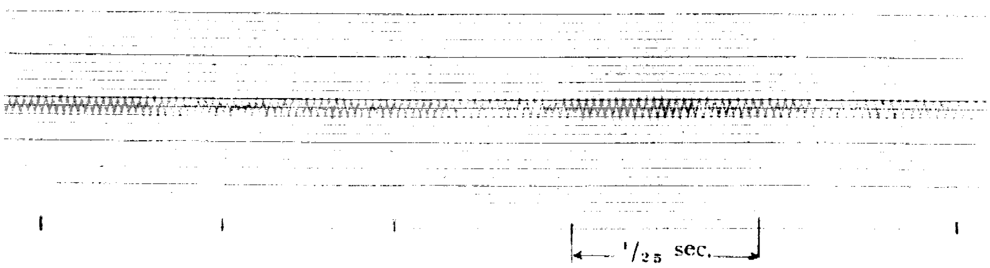
"e" as in *they*. $n = 127$ per sec. Y.Y.



"o" as in *ho*. $n = 138$. J.O.

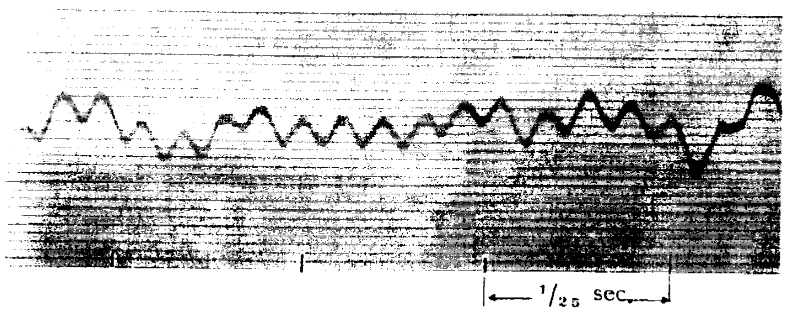


(D) Whistle



(E) Fluctuation of the Speed of Wind of an Electric Fan

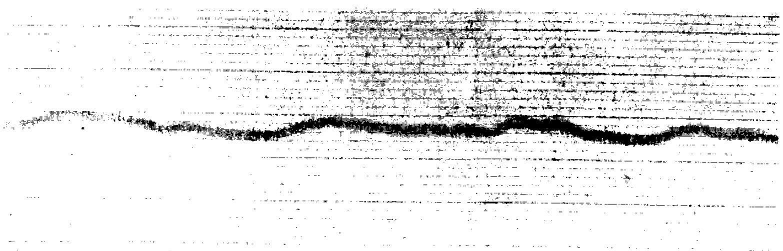
(*a*)



No. of revolution : per min.

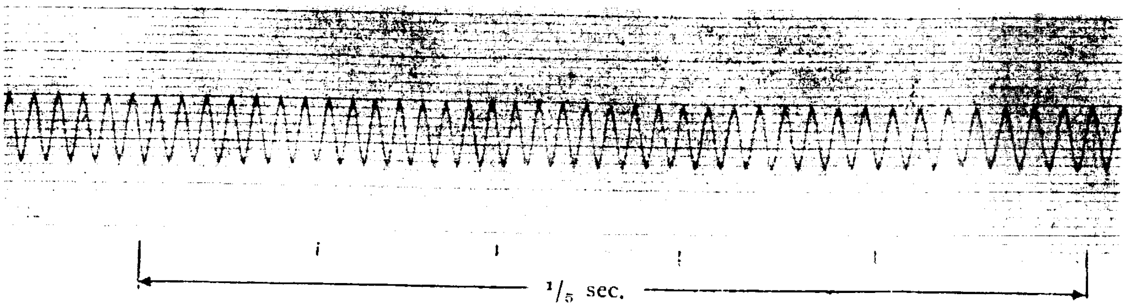
Fluctuation : $4 \times 1270 = 5080$ per $\fallingdotseq 85$ per

(*b*)



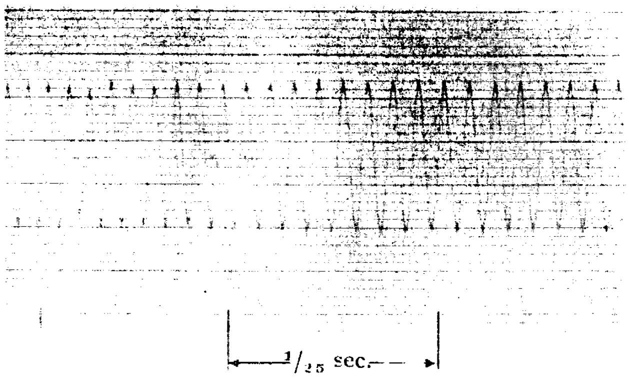
No. of revolution : 800 per min.

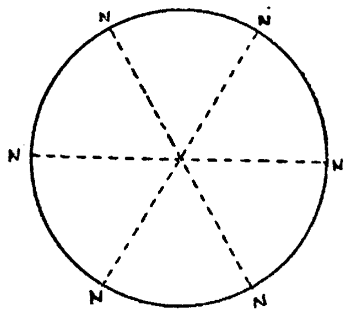
(F) Vibration of a Tuning Fork



n

) Vibration of a Circular Brass Plate supported at the Centre





Mode of vibration

Dia. = 26 c

Thickness =

N–N : N

$n = 214$/sec.

(H) Ultramicrometer