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The problem of recording small and perhaps rapid motions often comes up in research work and instrument design, and the pen and lever are often used where an optical method would be far superior. The latter method is not more used, probably because so little definite information is available on its design and possibilities. For this reason, the present report has been written from data obtained at the Field Station of the National Advisory Committee for Aeronautics in the hope that it may contribute some new information on the subject.

The optical method of recording is more complicated and requires greater skill in manipulation than does the mechanical one, so that where the latter will do the work satisfactorily, the optical method will have no advantages. On the other hand, when it is desired to make the instrument more compact or to greatly reduce the friction or moment of inertia of the moving parts, the optical method is immensely superior, and in many cases is a necessity. For example, the line traced on a film will have about 1/10 the width of a pen traced line, thus reducing the width of the film to 1/10 for the same accuracy, and the friction of a pivoted mirror is much less than 1/100 of the friction of a lever and pen, designed to do the same work. Also a photographic record is much more easily duplicated than a pen and ink record.

The Light Source.

The positive carbon of a direct current arc is the most intense source of light, and is very suitable for laboratory apparatus where weight and bulk are of little importance. The best results are obtained when the image of the arc is focused on a blackened slit. A water cell should be placed in the path of the rays in order that the slit may not be overheated by the intense beam. A sketch of the general assembly is shown in Fig. 1, and a cross section of the slit in Fig. 2. The width of the slit depends on the fineness and intensity of the record desired, .01 to .10 of a mm. being the usual range.

Where direct current is unavailable a concentrated filament nitrogen lamp can be used in place of the arc, but is much less satisfactory, as the intensity is less and it is impossible to evenly illuminate the slit.

For portable instruments the most satisfactory light source is a low voltage flash light bulb, using the filament itself as a line source. As the filaments in the commercial lamps are S shaped when viewed from the front, some special lamps were obtainedwith a straight filament and a dull black bead to prevent secondary reflections. One of these lamps is shown in Fig. 3. This source of light is very satisfactory as it gives a narrow and intense image, but in some cases where high period vibrations have to be recorded it is necessary to burn the lamps above their normal voltage thus reducing their life to only a few minutes. The design of the lamp holder for a portable instrument is quite important as the lamp must be held rigid, and a good electrical contact maintained under any condition of vibration or jar. The lamp must also be easily changed and the new filament should come in the same place as the old. As the filaments are not always in the same position with respect to the lamp base, each lamp should be mounted in an adjustable socket so that the filament will be in its correct position, thus allowing changing lamps and sockets quickly. The lamp holder should also have means for adjusting the focus. A cross section of a holder that fulfills these requirements is shown in Fig. 4.

The Optical System.

The essentials of the optical system consist of a light source, a mirror or prism for transmitting motion to the emergent beam, and a means for bringing the rays to a focus on the film. Any one of the methods shown in Figs. 5 to 11 can be used, but some have greater advantages than others. The desirable features are obviously first, brilliance of the image; second, large magnification of movement; and third, a small sized image.

Referring to Fig. 5, the movement of the image, $X = \ell$, $\tan^{-1} 2\alpha$, where α is the angle of rotation of the mirror and ℓ is the distance from the mirror to the film.

The size of the image, $S_1 = S \dfrac{\ell_2 - \ell_1}{\ell_3}$ where S is the size of the object.

$$\text{The total light in the image, } L_1 = (K_1 + K_2)\, L_2 \frac{\tan^{-1}\left(\frac{d}{2\,\ell_3}\right)}{180^\circ}$$

where L_2 is the total candle power of the source and K_1 is the efficiency of the lens and K_2 that of the mirror; d is the diameter of the lens.

In the same way, for Fig. 6.

$$X = (\ell_1 + \ell_2) \tan 2\alpha$$

$$S_1 = S \frac{\ell_1}{\ell_2 + \ell_3}$$

$$L_1 = (K_1 + K_2)\, L_2 \, \frac{\tan^{-1}\left(\dfrac{d}{2(\ell_2 + \ell_3)}\right)}{180^\circ}$$

In Fig. 7:

$$X = (\ell_1 + \ell_2) \tan 2\alpha$$

$$S_1 = S \frac{\ell_1}{\ell_3}$$

$$L_1 = (K_1 + K_2)\, L_2 \, \frac{\tan^{-1}\left(\dfrac{d}{2\,\ell_3}\right)}{180^\circ}$$

In Fig. 8:

$$X = \ell_1 \tan 2\alpha$$

$$S_1 = S \frac{\ell_2}{\ell_1}$$

$$L_1 = K_2\, L_2 \frac{\tan^{-1}\left(\dfrac{d}{2\,\ell_1}\right)}{180^\circ}$$

In Fig. 9:

$$X = \ell_2\, n \tan 2\alpha$$

$$S_1 = S \frac{\ell_2}{\ell_1}$$

$$L_1 = L_2 \frac{\tan^{-1}\left(\dfrac{d}{2\ell_1}\right)}{180^\circ} \left[(2\,n - 1)\, K_2 + K_1\right]$$

Where n is the number of reflections on the moving mirror.

In Fig. 10:

$$X = (\ell_3 + \ell_4) \tan 2\alpha$$

$$S_1 = S \frac{\ell_4}{\ell_1}$$

$$L_1 = 2 K_1 L_2 \frac{\tan^{-1}\left(\frac{d}{2 \ell_1}\right)}{180^\circ}$$

In Fig. 11:

$$X = \ell_3 \tan 2\alpha$$

$$S_1 = S \frac{\ell_2 + \ell_3}{\ell_1}$$

$$L_1 = (K_1 + K_2) L_2 \frac{\tan^{-1}\left(\frac{d}{2 \ell_1}\right)}{180^\circ}$$

The values of K and K_2 are given in the following table for clean, polished surfaces. These values are decreased 10 to 20% by dust or moisture.

	For Yellow Light.
Thin simple Lens	K_1 = .90 - .95
Glass backed by silver	K_2 = .82 - .88
Silver Surface	K_2 = .93
Magnalium 69Al,31Mg	K_2 = .83
Stellite Surface	K_2 = .68

Method 1 is very commonly used in laboratory apparatus, but has the slight disadvantage in portable instruments of requiring a rather long system for the deflection obtained. The next arrangement gives a small image but will allow only a slight deflection before coming out of the field of the lens. In Method 3 the light passes twice through the lens, so that the latter need only be of half the focal length required in the other methods. If the mirror is placed close to the lens, a very compact and satisfactory system is obtained, having the advantage that the moving mirror can be placed in an air-tight chamber, with the lens as a window. A modification of this method that is considerably used consists in moving the whole lens, whose rear plano surface is silvered, although this greatly increases the moment of inertia of the moving parts. Method 4 is very simple, but the concave mirror is heavier than a plane one and the definition is inferior to that obtained with a lens. Method 5 can be used when it is desired to obtain a record of a very slight angular movement. It is not advisable to use more than four reflections on the moving mirror as the definition and brilliancy of the image fall off very rapidly as the number of reflections is increased. Methods 6 and 7 offer no particular advantages over those already described.

The lenses may be satisfactorily made of the simple plano-convex type, but if critical definition is required a corrected photographic doublet should be used. The plane mirrors are satisfactorily made of silvered microscope cover glasses cut to the right size with a diamond. Recently good success has been had with polished stellite mirrors. These have the great advantage of eliminating the surface reflection from the glass, which in the silvered mirrors is at times very annoying. Stellite seems to hold its polish well and although it is yet only an experiment, looks very promising.

By using a powerful arc, illumination enough can be obtained from a 1 mm. square mirror to trace a curve with oscillations at the rate of several thousand per second. When using a flashlight bulb, a 10-in. distance from light to mirror, and a mirror 3 mm. square, sufficient illumination is obtained when burning the lamp at normal voltage to obtain a readable record when the oscillations are 1 cm. long on the film, and occur at a rate of 20 per second. The lamp must be burned at 50% over voltage however to obtain a strong enough record for satisfactory reproduction under the same conditions.

As the image from the lamp filament or illuminated slit is a line perpendicular to the axis of the film drum, a slit must be placed before the film, normal to the image in order that a point of light may fall on the film surface. The width of this slit may be anywhere from 0.1 to 0.02 of a m.m. depending on the fineness of the desired record and the intensity of the image. The slit should be constructed in the same manner as the one shown in Fig. 2, although it will be considerably longer and it should be placed as close as possible to the film.

The light from the source should be so restricted that it will just cover the lens or mirror, as any scattered light will fog the film. This restriction must be accomplished without introducing any reflecting surfaces that would form secondary images. Fig. 12 shows a satisfactory method of doing this by a number of carefully blacked diaphragms. It is well to keep the angle between the entering beam, and the beam to the film, as small as possible.

When a lens is used, its axis must be turned away from the light beam enough to throw the images from its surfaces away from the slit, as they would otherwise fog the film. If, as is usually the case, the lens is plano-convex, the angle between the lens surface and the surface of the mirror is given by the following expression.

$$\alpha = \frac{1}{2} \tan^{-1} \frac{d}{\ell} + \beta \quad \text{(Fig. 13)}$$

where α = angle between planes of lens and mirror.

d = diameter of lens.

ℓ = distance from lens face to slit.

β = angle to bring edge of image slightly away from the slit, its value may be 1° to 3°.

The plane of the mirror is of course, normal to the bisector of the entering and emergent beams.

Mirror Mounting.

The original motion which it is desired to record is almost always rectilinear, so that it must be transformed into rotary motion of the mirror staff. This may be accomplished in many ways, some of which are described below. The motion originates in a diaphragm in the majority of cases, but sometimes it may come from a flat spring as in the N.A.C.A. accelerometer.

In Fig. 14 is shown the mounting of the mirror in the Knott sonograph which is used to analyze musical sounds. The mirror is mounted on a thin steel strip stretched tightly, and a strut, rigidly connected to the diaphragm rests on the back of the mirror slightly to one side of the center. The slight motions of the mica diaphragm are thus transmitted in an almost frictionless manner to the mirror. This method gives a very high natural period and is satisfactory for its purpose, but the angular deflection is too small for a compact instrument and the zero is not apt to be constant.

The recording air speed meter used by the National Physical Laboratory (Fig. 15) employs a Perry twisted strip in order to convert the motion of the diaphragm into a rotary motion of the mirror. The magnification obtained in this way is quite large, but for structural reasons this method is not as satisfactory as some of the others.

The airspeed meter constructed by the National Advisory Committee for Aeronautics to record the fluctuations of flow in wind tunnels (Fig. 16) has a mirror mounted on knife edges and is connected to the diaphragm and held in place by a light spring strut. The position of the mirror is adjusted by moving the knife edge sockets in or out by a screw passing through the face of the instrument. This instrument proved very useful for laboratory use but would not stand heavy shocks, as the mirror holder would then be displaced from its sockets.

After this instrument had been tried out, another one was designed and constructed for use in flight, as shown in Figs. 17 and 18. Here the mirror was mounted on a light staff with 60° conical pivots at its ends. A short hardened screw passing through a bushing in the diaphragm transmitted the motion to the mirror. A fine watch hair spring held the mirror staff up against this screw, the sensitivity being changed by eccentric socket screws which raised or lowered the mirror. This instrument worked very satisfactorily, and a large number are now being constructed to record the pressure at various points on the surfaces of an airplane in flight. This same mirror mounting is also used in the N.A.C.A. accelerometer described in Report No. 100.

One of the most refined optical recording instruments ever constructed is the Phonediek designed by Prof. D. C. Miller, of the Case School of Applied Science, for obtaining the wave forms of sound. The mirror is fastened to a steel shaft mounted in jeweled bearings and a very fine silk or platinum fibre is wound around a drum on the staff, one end being fastened to the diaphragm and the other to a light spring. Because of the very low weight of the moving parts a natural period of nearly 10,000 vibrations per second is obtained. A diaphragm of this instrument is shown in Fig. 19.

Film Holder.

In order to obtain a record from a light spot moving up and down in a straight line, a sensitized surface must be moved, preferably with uniform motion, across this line. This can be done, as in some of the older instruments, by letting a plate move down under gravity, its speed being controlled by a dashpot. While this method is all right for short records taken in the laboratory, the apparatus is very bulky. A long record can be taken by reeling a film from one drum to another behind the slit, as is done in the R.A.F. accelerometer. While this method gives a long record in a very compact instrument, it is almost impossible to obtain a uniform speed, as the diameter of the driving drum is always changing. A third method is to place the film smoothly on the surface of a cylinder which is revolved at uniform speed. This cannot give a very long record on one drum without great size and weight, but it will give a smooth and uniform speed.

After some experimenting, it was found that a revolving film drum encased in a light tight holder was the most satisfactory as this gave an even speed without jerks, and at the end of a film the whole holder could be changed in a few seconds. An assembly drawing of a drum of this type is shown in Fig. 20, and photographs in Figs. 21, 22 & 23. The film is straightened and tightened by a pair of rubber rollers, - so that it is unnecessary to touch the film surfaces with the fingers, and the film is stretched smoothly and tightly on the drum. In order to tell how much film has been used, a set of figures is stamped around the top of the revolving drum and a red window allows them to be seen without fogging the film. An automatic shutter is attached to the slit on the drum and is normally closed by a spring. When the drum is put in position on its instrument a pin opens the shutter, thus allowing a quick interchange of drums without danger of fogging, or of leaving the slide in when taking a record.

The holder, as well as the instrument case should be, of course, absolutely light tight, even in the bright sun, and the surface of the drum and the inside of the holder should be coated with dull optical black to prevent reflections. As far as possible all fastenings should be simple and quick acting, as any small loose parts are hard to find in the dark room.

Driving Motor.

The recording drum is usually driven by an escapement clock, when the rate of turning is slower than once an hour as is generally the case in meteorological instruments. The clock, for the optical method, may be very small, as the pen friction is eliminated. In the laboratory the most satisfactory method is an electric motor drive, the speed being easily varied by a rheostat, or if very constant speed is desired a synchronous motor can be used

The problem that comes up in aeronautics is more difficult to solve, as here it is desired to have a light, portable instrument with a comparatively rapid drive (1 R.P.M.) and a constant speed under vibration or extreme changes in acceleration. For the N.A.C.A. accelerometer a governor-controlled clock was constructed as shown in Report No. 100. The governor was built as shown in Fig. 24, so that any downward accelerations, which would tend to increase the bearing friction, would at the same time act on the lower friction disc of the governor and relieve some of the friction on the brake. In this clock the weight of this part was not great enough to secure perfect regulation but it is much better than on an uncompensated mechanism.

While this clock gave perfectly satisfactory service, it required several seconds to reach its steady speed, and required winding for every record. As it is necessary to have a source of electricity at hand for the light, a small direct current motor was designed to drive the drum through two worms, the motor running at 2000 R.P.M. An electric governor of the Leeds and Northrup type is used to keep the speed constant. Only an experimental motor has, as yet, been constructed, and complete tests have not been made, but so far the results are quite promising, the motor starting and stopping almost instantly. A photograph of this motor is shown in Fig. 25.

OPERATION AND ADJUSTMENT OF RECORDING INSTRUMENTS.

The mirror should be provided with an adjustment for bringing the image on the vertical slit, and also for raising the image up or down the slit. The lamp should first be moved along its axis until the maximum definition of the image is obtained on the plane of the film, and the image should be adjusted correctly up and down as well as sideways, then all parts should be clamped securely in place. When all adjustments are properly made, a sharp spot of light with no diffusion around its edges should be projected on the film.

When placing the film on the drum it is better not to touch the surface in any way, as abrasion and finger marks are very prominent on such a transparent negative. The joint in the film should be placed opposite the slit in the holder so that a complete record can be obtained around the drum. The exposed film can be developed in any contrast developer such as pyro, and should be kept in the solution as long as possible without fogging. Prints can be made directly from the films on hard paper, or if a black line is desired the record can first be transferred to a process plate. A record taken with a recording yawmeter is shown in Fig. 26. This record is enlarged about eight times from the original negative, and still shows as much sharpness as the usual pen and ink record.

Conclusions.

From the work that has been done on optical recording instruments, it is clear that this method is far more satisfactory than the recording pen, in compactness, in high natural period, and in elimination of friction. The expense of construction is little more in the first case than in the second, and the optical method can be made fully as fool proof as the mechanical one in as far as actually taking the record is concerned. The development and reproduction of the record is an added complication, but the ease of duplicating the records is a decided advantage.

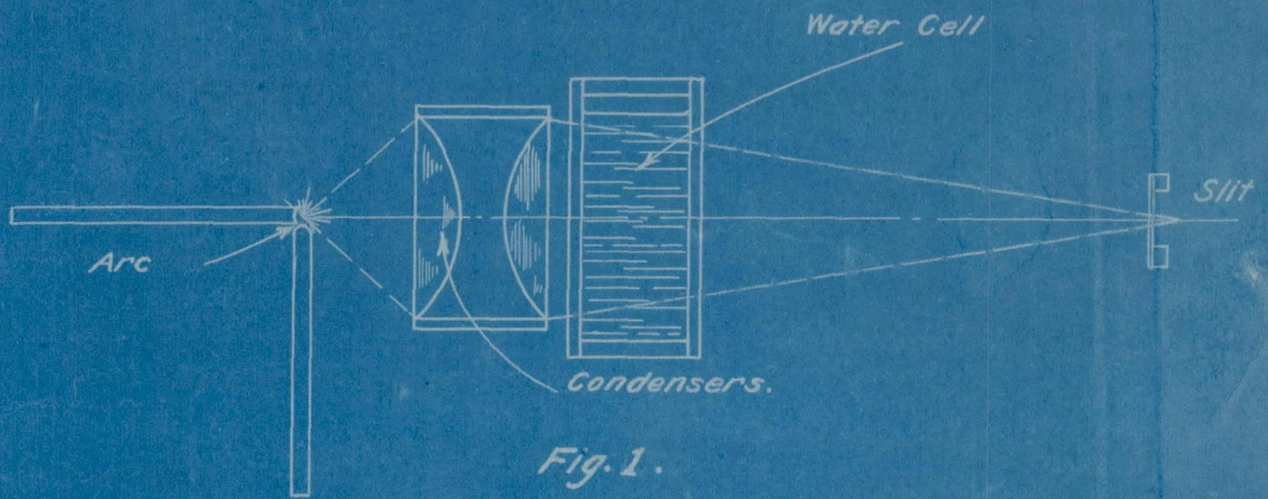


Fig. 1.

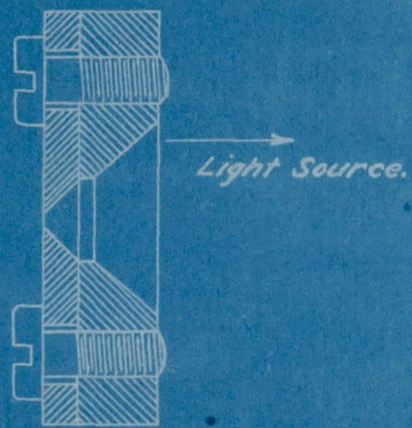


Fig. 2.

Fig. 3.

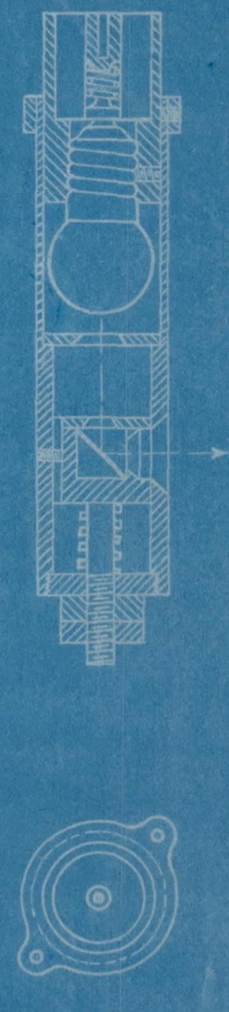


Fig. 4.

Method 1.

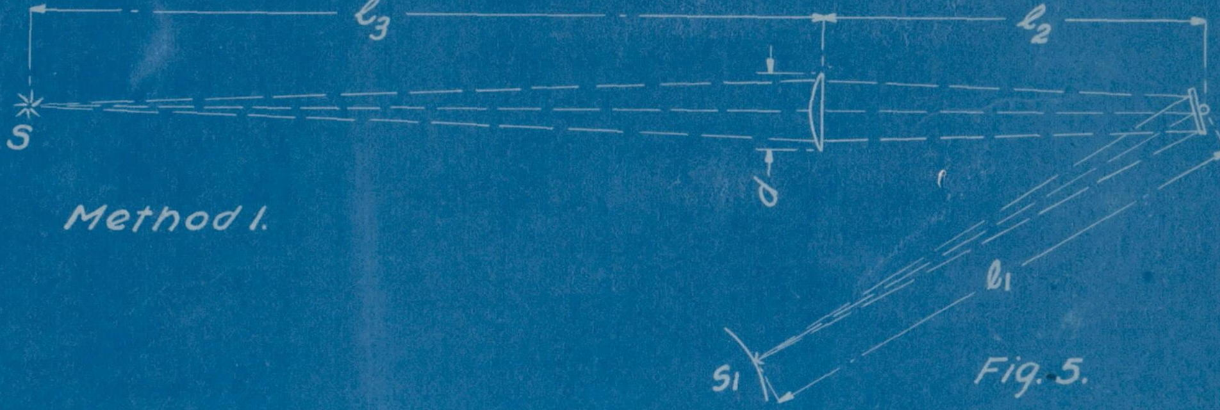


Fig. 5.

Method 2.

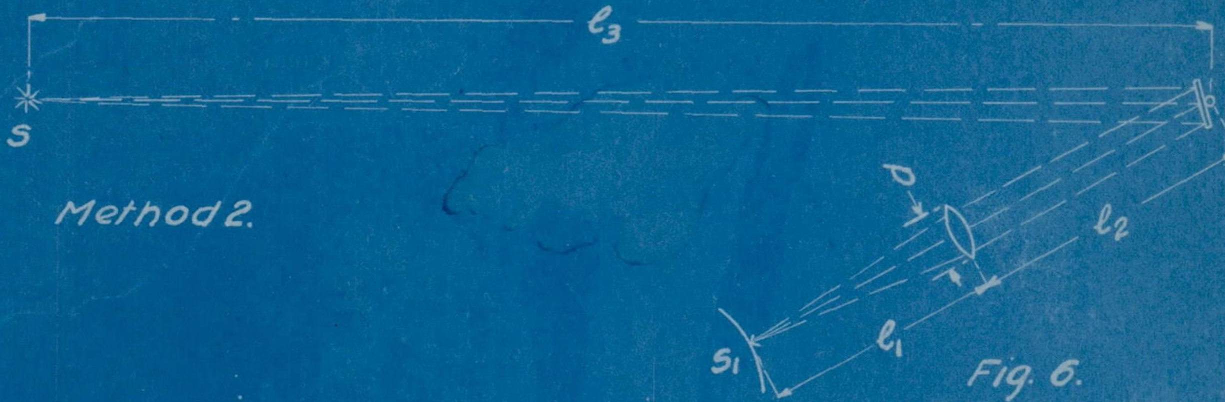


Fig. 6.

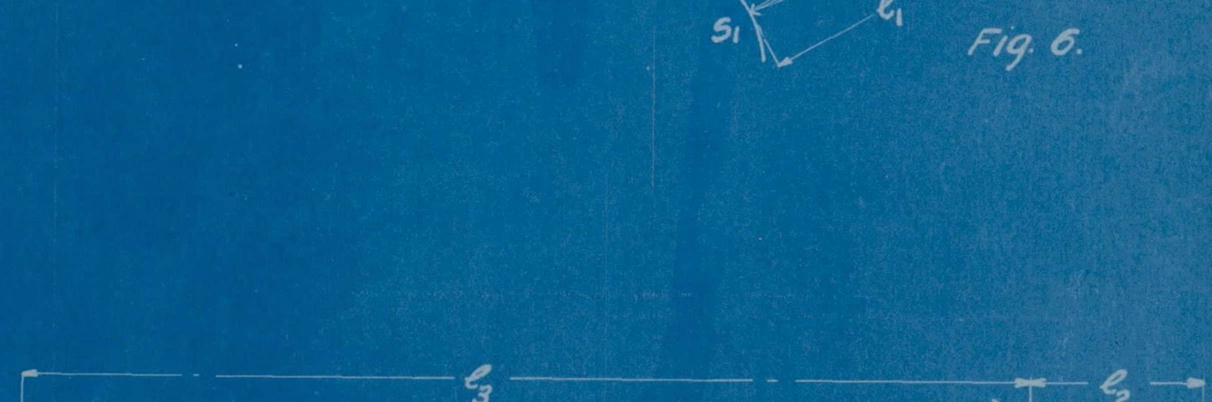
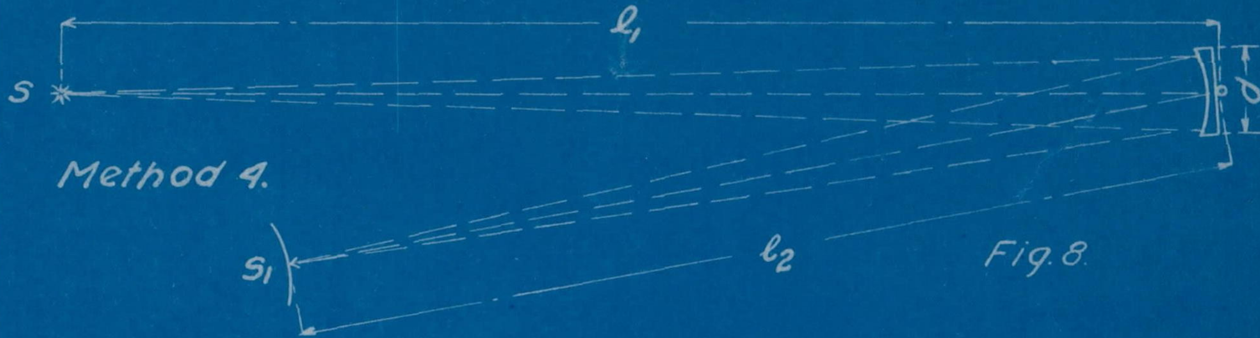


Fig. 7.

Method 3.

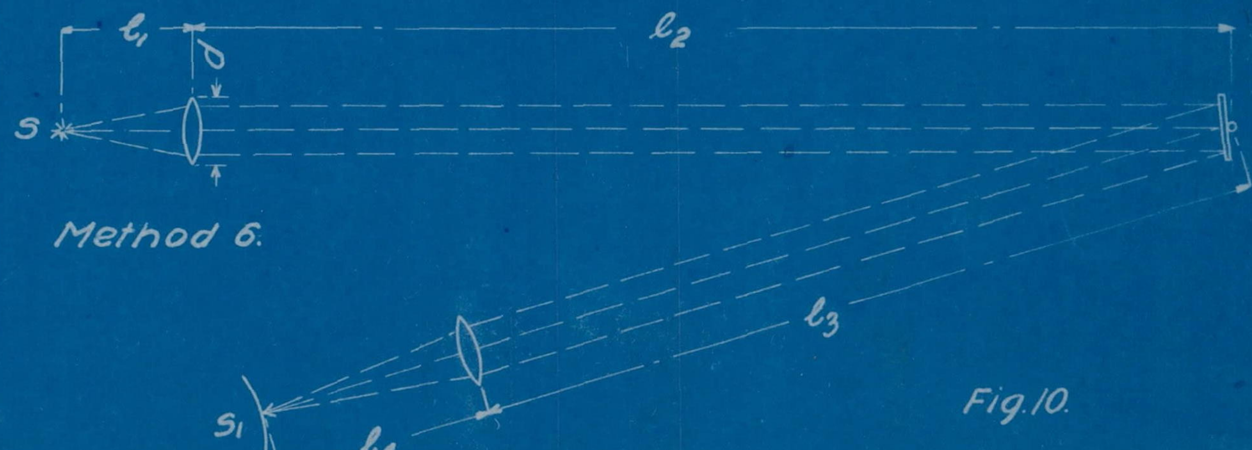


Method 4.

Fig. 8.

Method 5.

Fig. 9.



Method 6.

Fig. 10.

Fig. 11.

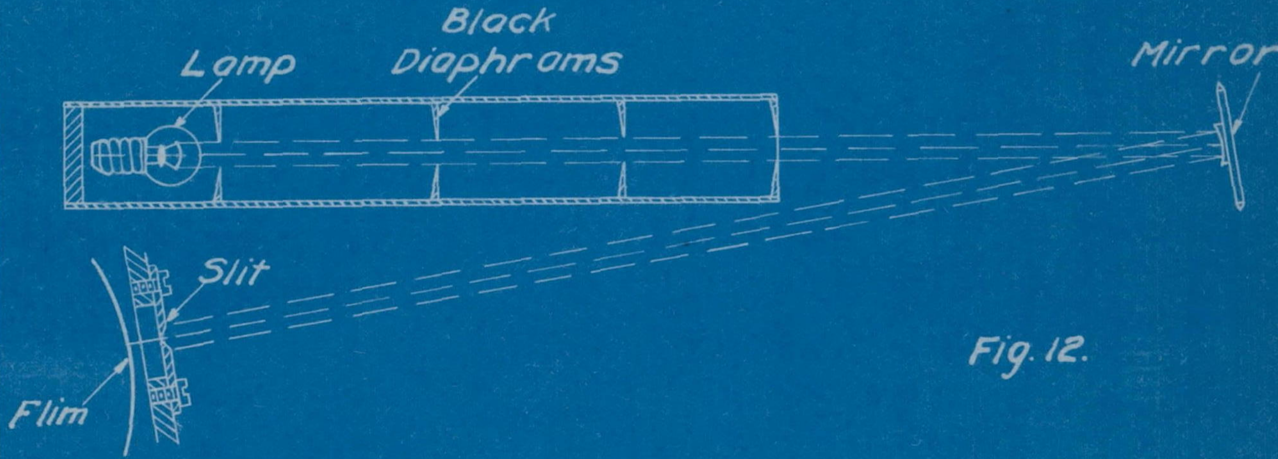


Fig. 12.

Fig. 13.

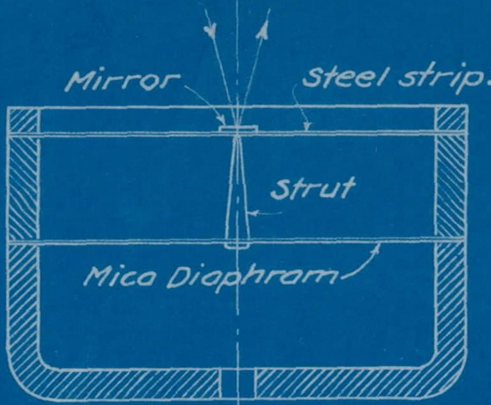


Fig. 14.

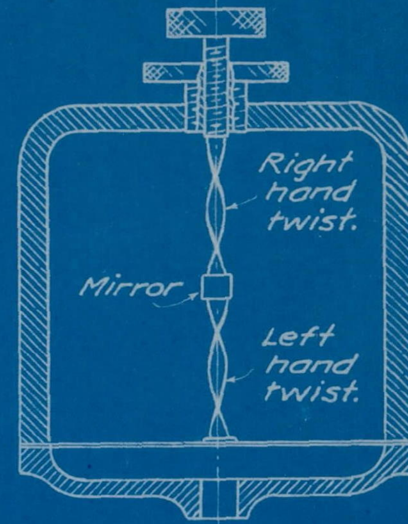


Fig. 15.

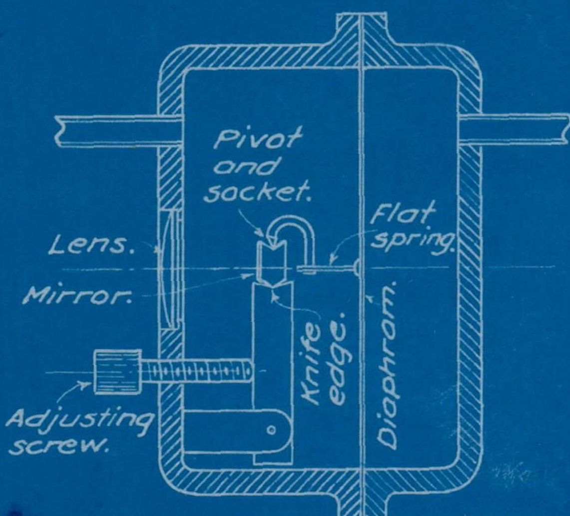


Fig. 16.

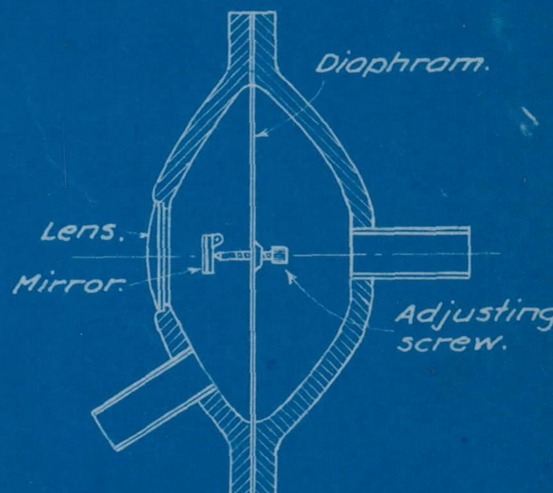


Fig. 17.

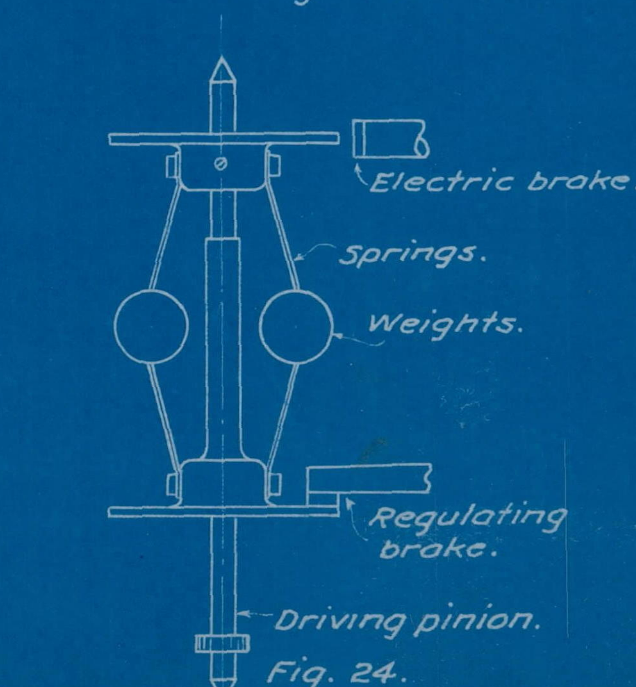


Fig. 24.

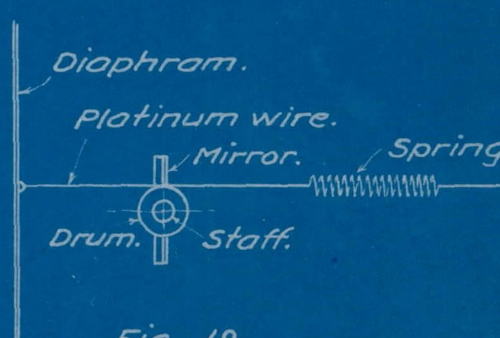


Fig. 19.

ASSEMBLY OF RECORDING DRUM.

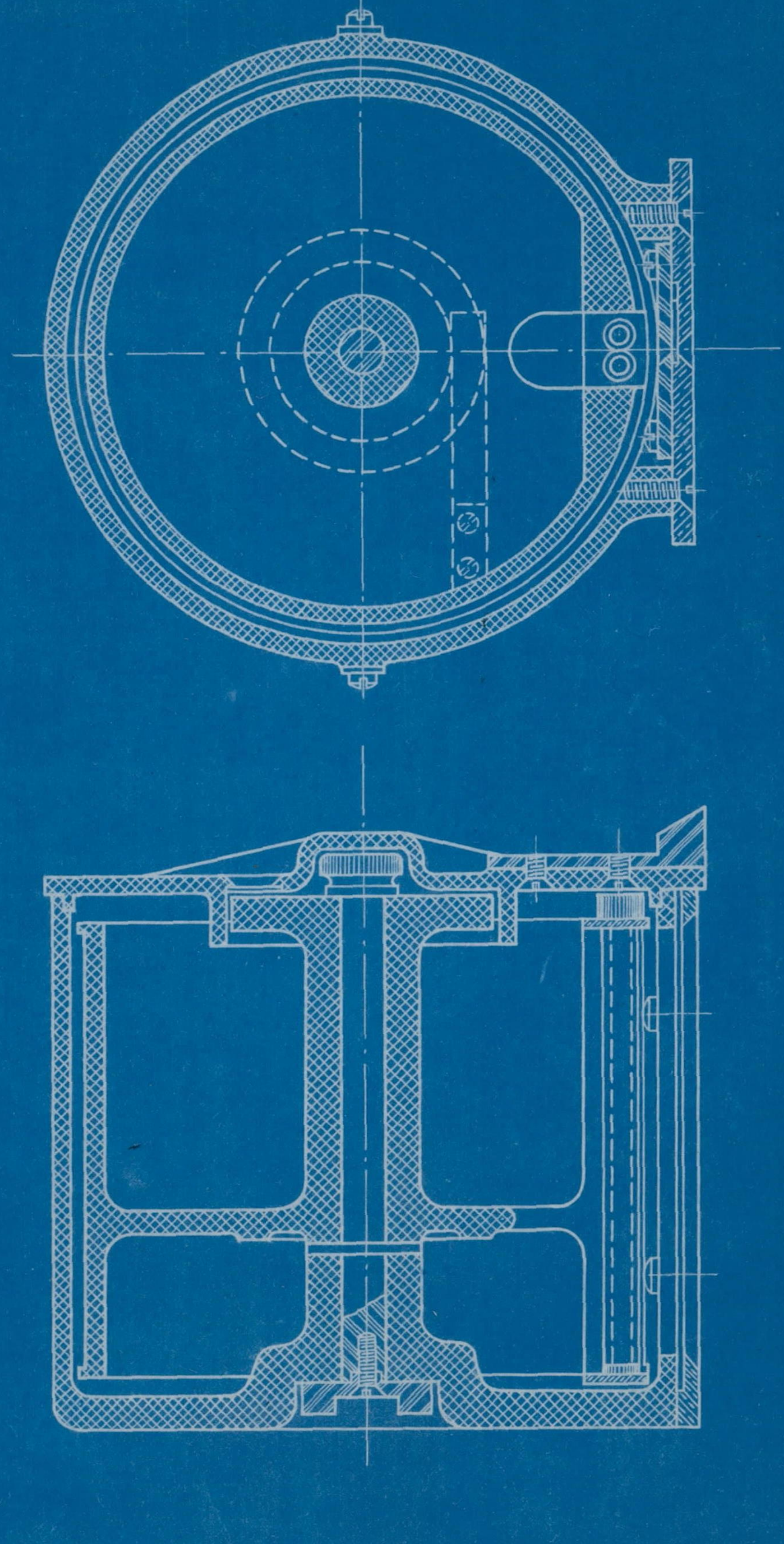


Fig. 20.

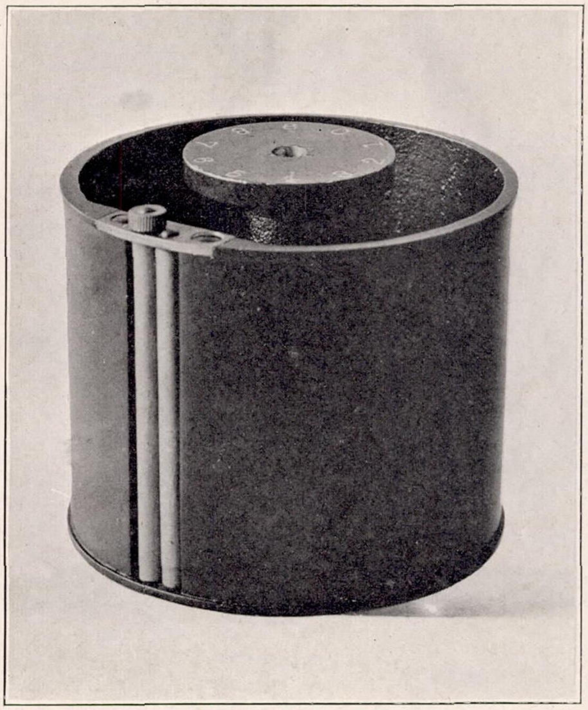


FIG. 23.—RECORDING DRUM.

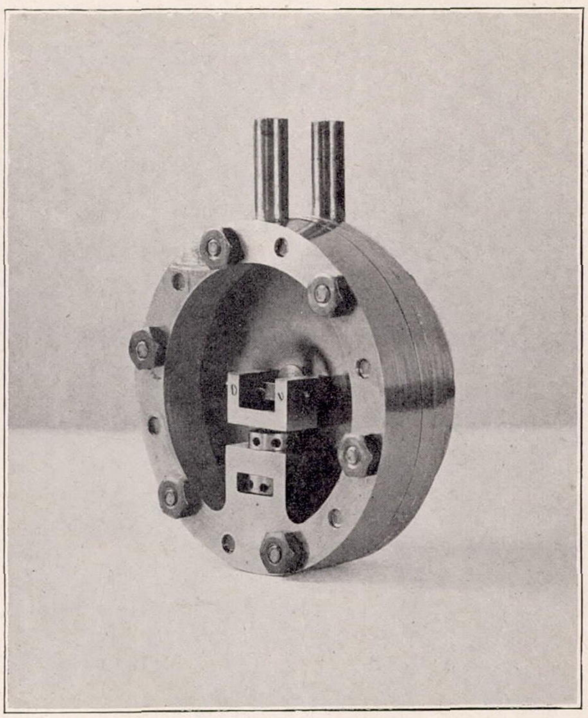


FIG. 18.—RECORDING AIR SPEED METER WITH CAP AND LENS REMOVED.

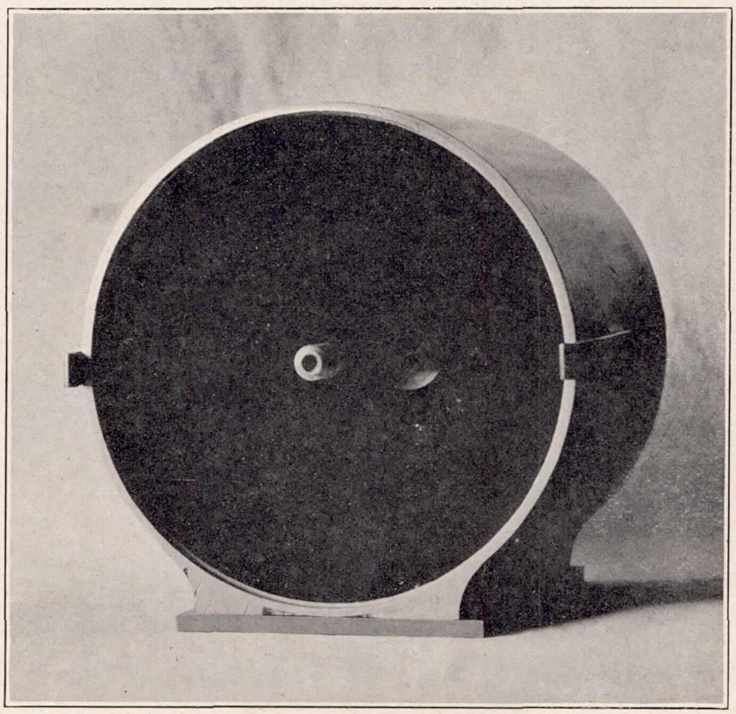


FIG. 22.—RECORDING DRUM CASE.

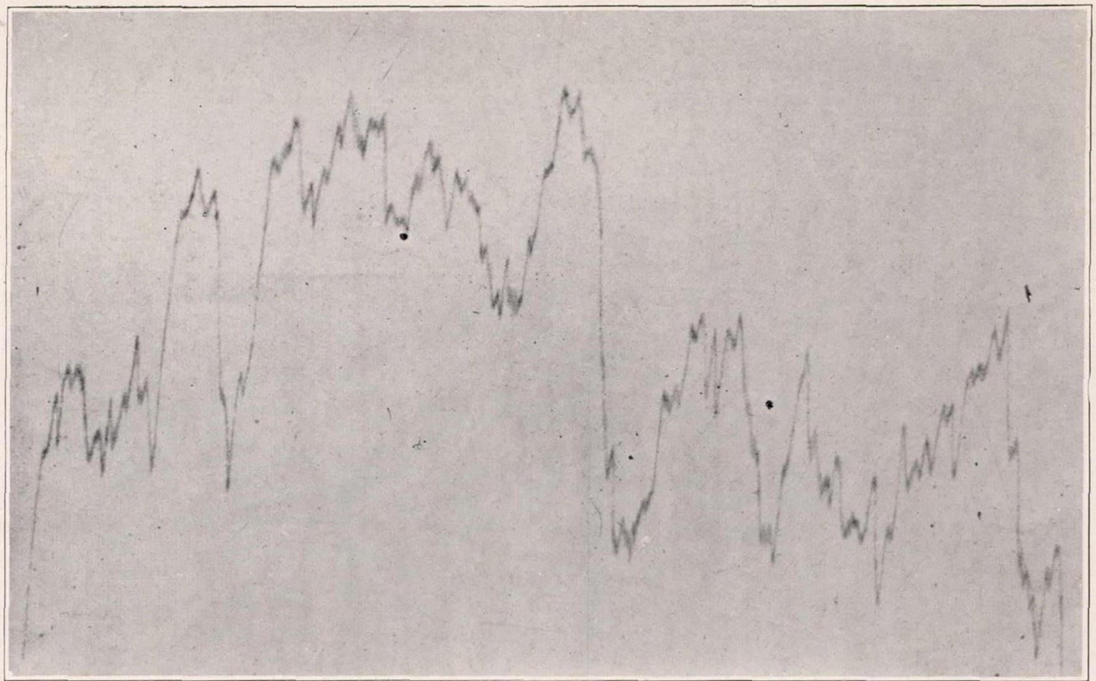


FIG. 26.—A RECORD OBTAINED WITH A RECORDING YAWMETER.

The reproduction is enlarged about 8× from the original film.

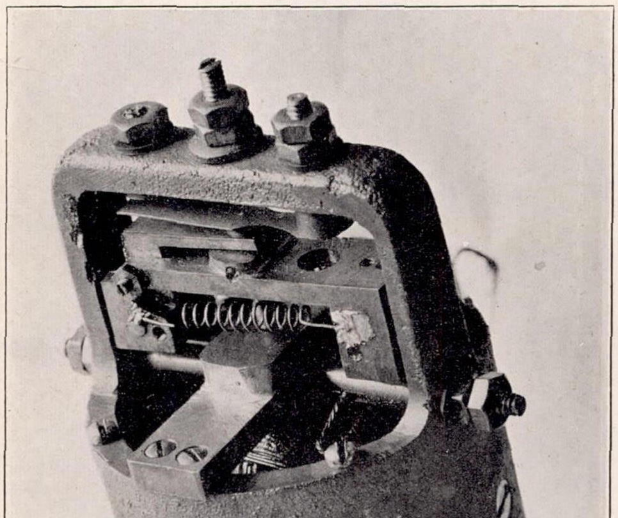


FIG. 25.—CONSTANT SPEED DRIVING MOTOR.

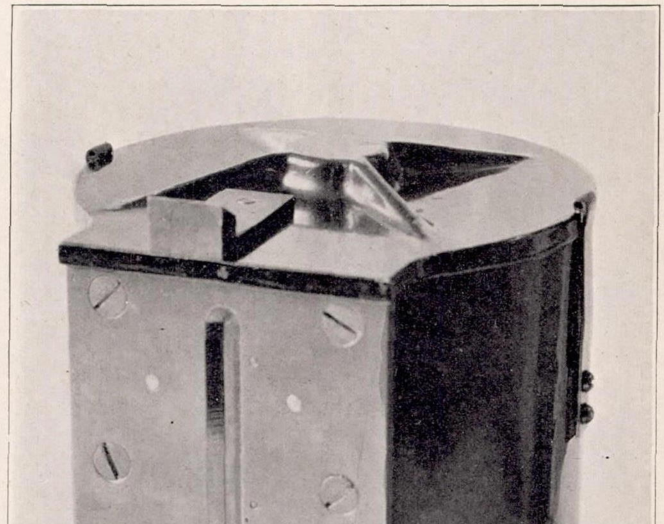


FIG. 21.—RECORDING DRUM HOLDER ASSEMBLY.