ON A SEISMOMETER AND A TORSION PENDULUM SEISMOGRAPH.

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I.—The Seismometer.

The machine which I have called a seismometer is represented in figure I.

The principal part of the instrument is a pendulum with a heavy bob, the centre of inertia of which is connected by means of silk threads with a set of pulleys designed to show, by the aid of indices, the relative motion of the earth and pendulum bob on a magnified scale. The distinctive features are the mode of suspending the pendulum and the arrangement of the pulleys and indices for magnifying the motion.

The pendulum *P* (fig. I.) is suspended from the cross wire *W* which can be tightened to any desired degree by means of the screws *S S*. The object of tightening the wire is to obtain as nearly as possible uniformity in the indications of different machines of the same type. In practice the adjustment can be made either by tuning the wire to a certain pitch and afterwards hanging on the weight, or by counting the number of vertical vibrations made by the weight in a certain time, after it is hung on.

The mode of suspension just described is adopted for the purpose of giving the point of suspension a certain amount of vertical freedom, in consequence of which it can be set in a state of vertical vibration by the earthquake. The maximum amplitude of this vertical vibration is indicated by means of a pointer which turns along with the pulley *P*, fixed to the frame of the instrument. This pulley is turned by a

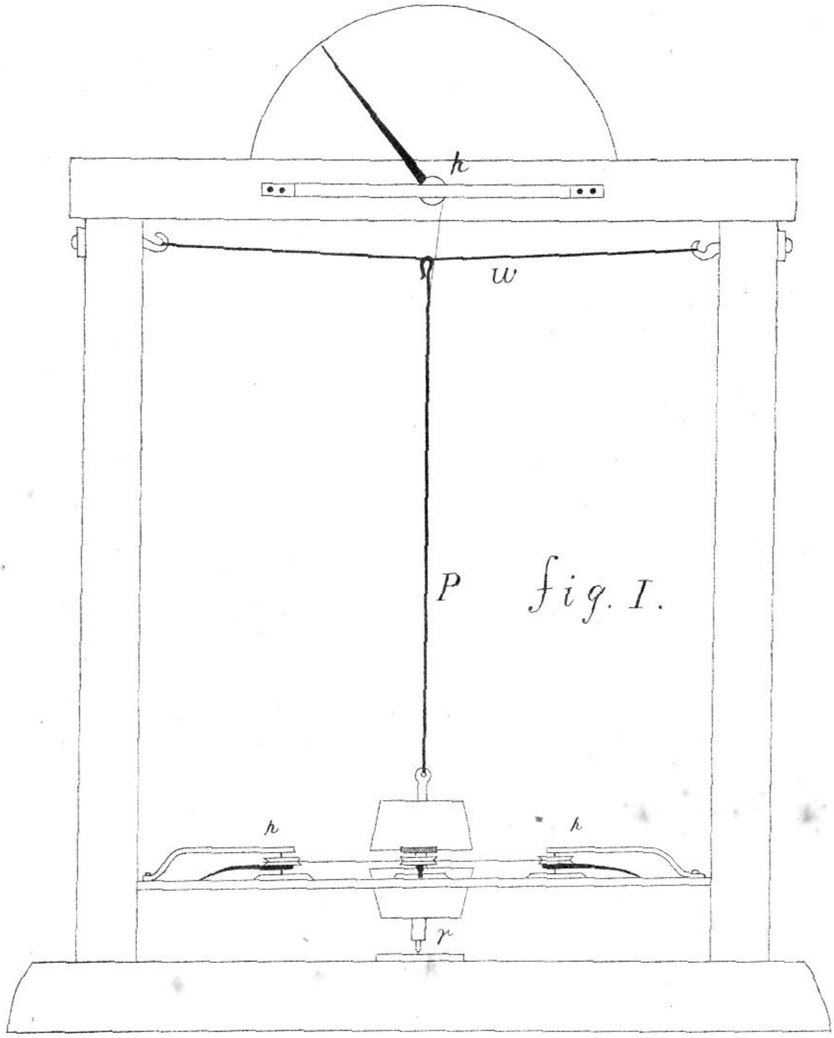

fig. I.

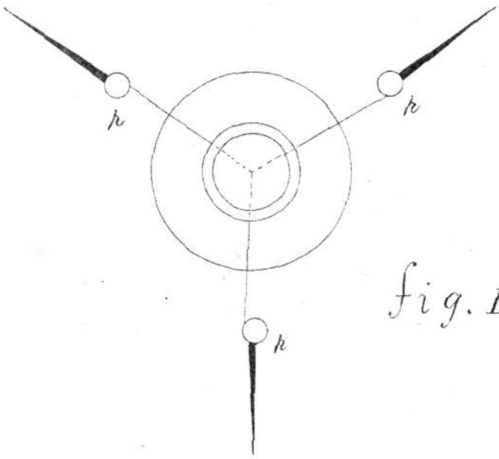

fig. II.

silk thread attached to a rigid rod which rests with one end in contact with the top surface of the pendulum bob.

Three horizontal components of the earth's motion are indicated in a similar manner, by means of pointers turning along with three pulleys *P*, placed at equal distances apart, on the circumference of a circle having its centre in the axis of the pendulum. These pulleys are turned by means of silk threads attached at one end to the pendulum bob, near its centre of inertia, and at the other end to the circumference of the pulleys.

The advantages claimed for the pulley and index arrangement for multiplication are, ease of adjustment, constancy in the multiplying power and, in consequence of the silk thread connection, absence of shock at the first sudden movement. The multiplication can be made 30 or 40 with this arrangement without introducing inconvenient resistance to the motion of the pulleys. Practically, the whole resistance to motion is the small amount of friction on the bearings of the pulleys necessary to retain them in their deflected positions after the shock. The sensibility of the instrument may be doubled and the effect of friction rendered more definite by placing a spring like the hair spring of a watch on the pulleys and then allowing the point of the index to mark on a smoked glass plate.

I indicate *three* horizontal components of the motion for two reasons, namely, that this arrangement gives greater symmetry to the forces acting on the pendulum, and that two components are generally insufficient to give the direction. When two components of the motion only are known the direction of shock may have been along either diagonal of a parallelogram described on these two components at adjacent sides. If three components are given the problem becomes determinate, and we have an obvious geometrical construction for the direction and amplitude of the motion.

The difficulty as to direction, just indicated, may be avoided if the pendulum is made, by means of a pencil or sharp point, to give a direct register of its actual motion on a suitable plate placed under the bob, as shown at *R* in fig. I.

Such a register, although in general somewhat indefinite, would be sufficient to enable the observer to decide between the two diagonals of a parallelogram.

The machine I have described was suggested by me some time ago to Professor Milne as likely to prove sufficiently accurate, easily managed, cheap and portable, to render it suitable for the purpose of taking simultaneous observations at a series of stations distributed over the Yedo plane. In order to make the instrument easily transported the frame carrying it has been made as small as possible, probably at the expense of a certain amount of accuracy in the amplitude indications.

The machine is only expected to give approximately the horizontal movement at any place, perhaps it may not give even approximately the vertical movement. What is wanted is a comparison of the horizontal and vertical movement at different places, during the same earthquake, and as nearly as possible the absolute horizontal direction. From such a set of observations the position on the earth's surface directly over the source may be approximately determined. Again the distance of this position from a series of stations taken along with the relative vertical movement will, on the assumption of a homogeneous earth, be sufficient to give the depth. It is probably too much to assume the earth homogeneous over any very great area, but it must be remembered that a similar assumption runs through the deductions made from an absolute determination of the vertical movement. Other deductions such as changes in the nature of the strata causing differences in the angle of emergence can be got from comparative as well as from absolute observations. The results obtained by these machines can of course be rendered absolute by comparison with another instrument giving absolute indications, if such can be found.

I have stated that I only expect my machine to give *comparative* indications and that only for the *same* earthquake. I made the statement in this form because I doubt very much whether pendulum machines can be relied on for comparative indications of the motions in different earthquakes. All pendulum machines are subject to error, sometimes considerably due to the forced oscillations of the bob, caused by the motion of the point of suspension. This error can only be the same for different earthquakes on the assumption of similar periodicity and duration in different cases. From my own observation I don't think this is a tenable assumption.

An indication of the probable error due to forced oscillations may be obtained in the following manner.

Suppose a pendulum freely suspended in space has its point of suspension suddenly displaced and then set into a state of simple harmonic oscillation :—

Let a=amplitude of this oscillation.
T $'$=period ,, ,,
l=length of pendulum.
T=period ,,
u=angular displacement of the axis of the pendulum from its equilibrium position at any instant.
p=ratio of circumference of a circle to its diameter.

$$n=\frac{2\,p}{T} \text{ and } n^1=\frac{2\,p}{T^1}$$

Then the equation to the motion of the pendulum is

$$\frac{d^2 u}{d t^2}+n^2 u=\frac{a}{l}\,n^2 \cos n^1 t$$

The solution for the case considered is

$$u=\frac{a}{l}\;\frac{n^2 \cos n^1 t + n^{1\,2} \cos n\,t}{n^{1\,2}-n^2}$$

If besides we assume that the bob experiences frictional resistance to its motion, due to levers or other registering apparatus, we have for the equation of motion

$$\frac{d^2 u}{d t^2}+f\frac{d u}{d t}+n^2 u=\frac{a}{l}\,n^2 \cos n^1 t$$

The proper integral of the equation in this case is

$$u=\frac{a}{l}\;\frac{(n^2 \cos n^1 t + l)}{\sqrt{(n^2-n^{1\,2})^2+n^{1\,2} f^2}}$$

where $l=tan^{-1}\,\frac{n^1 f}{n^{1\,2}-n^2}$

If $tan^{-1}\frac{n^1 f}{n^{1\,2}-n^2}$ differs from $2\,p$ the equation shows a periodic oscillation of the pendulum in unison with the earthquake *but differing in phase.* This at once shows the fallacy of assuming that the ripples on a moving plate are not affected by oscillations of the point of suspension.

A full discussion of the consequences of these equations would be out of place in this paper ; and I therefore leave each one to study them for himself.

II.—The Torsion-pendulum Seismograph.

The chief feature of this machine is the use of a torsion-pendulum to furnish at the same time both an approximately steady point, and a moving body on which the motions of the earth may be recorded.

The pendulum consists of a pianoforte wire about three feet in length, carrying at its lower end a heavy ring of lead *W*. The weight and diameter of this lead ring are so adjusted that the period of torsional vibration of the pendulum is more than double the duration of an ordinary earthquake shock. The mode of suspension adopted for the pendulum is shown at *A*, fig. I. and II., *R R* are two steel rods, meeting in a curved joint at *A*, resting at *K K* on knife edges, and held in a horizontal position by two springs *S S*. The ends of the rods *R R* are so formed that a considerable motion of the point *A* produces only a very small increase in the force exerted by the springs. The pendulum has thus a long vertical period and is therefore capable of showing approximately the actual movement of that part of the earth's surface on which the frame rests.

The knife edges *K K*, and springs *S S*, are fixed to a table *T*, which rests on three hard balls *B*, placed between hard metal plates. The object of this table is to obtain, as nearly as possible, a steady point for the suspension, this being, in my opinion, one of the first things to be looked for in connection with pendulum machines. The principle of obtaining a steady body by resting it in a state of neutral equilibrium on the top of balls, was, so far as I am aware, first used in connection with earthquake measurements by Dr. Verbeck. The principle, if properly applied, is far better than that of a pendulum, no matter how long, rigidly attached to a body resting on the earth's surface. I have introduced the principle into this instrument more as a matter of experiment than

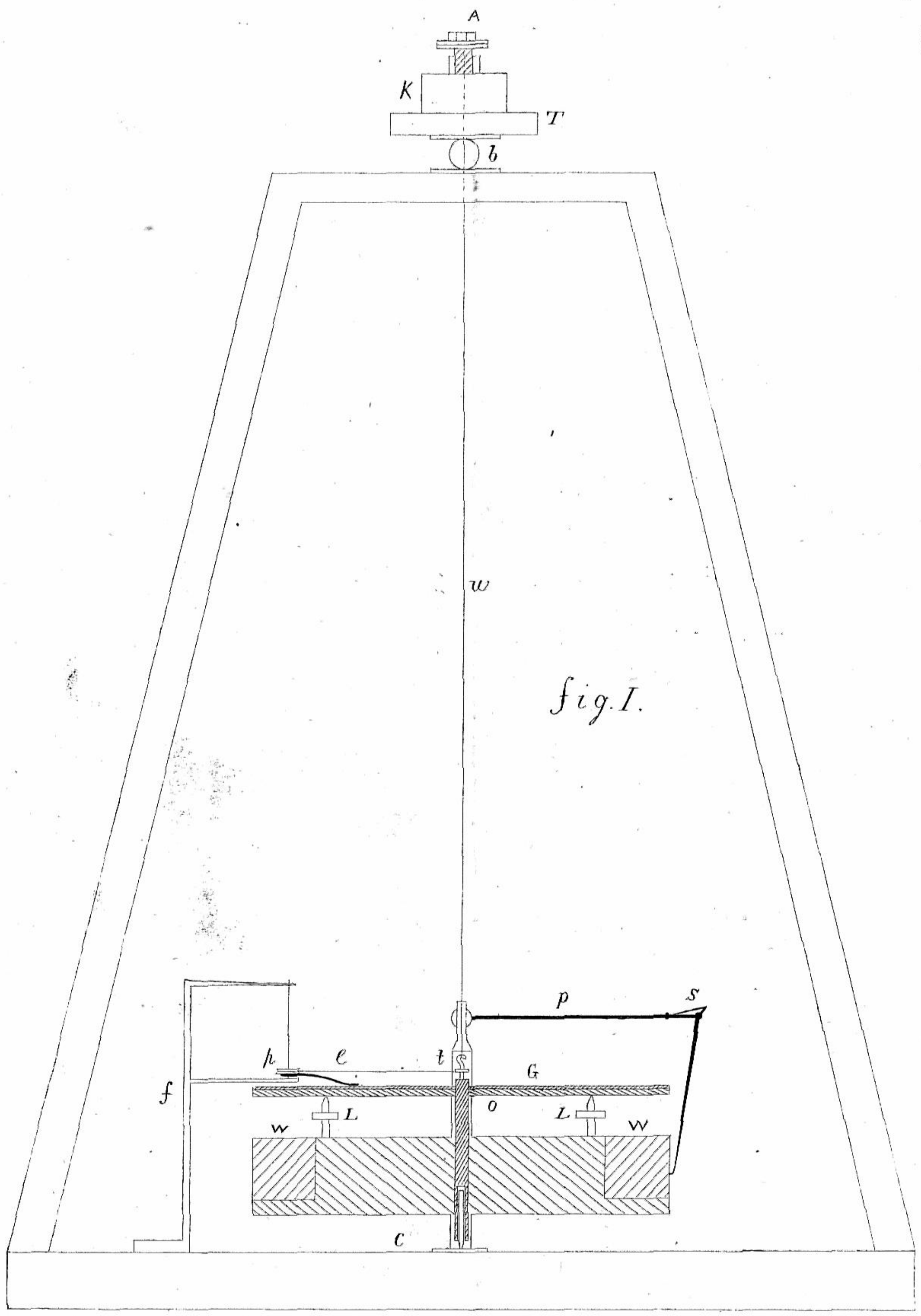

fig. I.

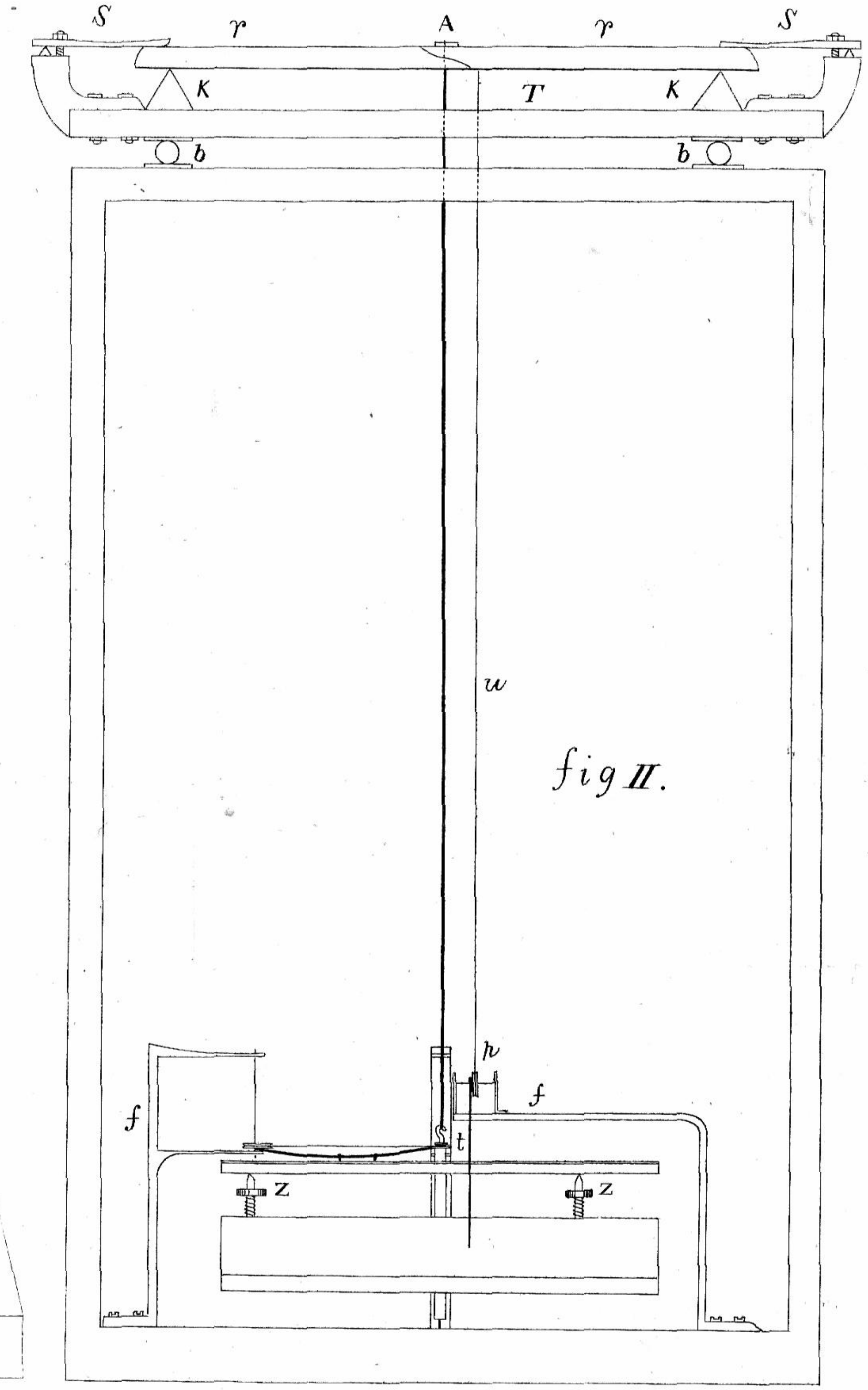

fig II.

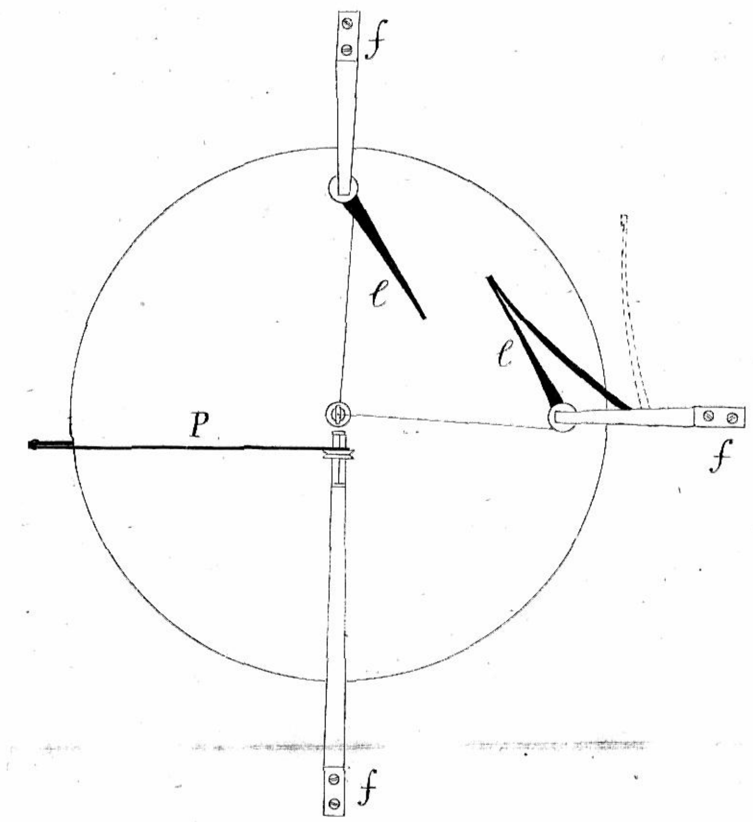

fig. III.

as an essential element of the machine, but I hope to point out one or two interesting modifications of the machine in which it would figure as an essential part. In this machine the balls can be removed at any time, and the top of the pendulum fixed to the framework. By making experiments with this and other machines, on artificially produced earthquakes, I hope to obtain some valuable information on the necessary elements of an earthquake machine.

The remaining portions of the machine will be easily understood from the following description of how it records the earthquake shock.

A disk of wood *D* rests on three levelling screws *L*, fixed in the ring of the pendulum, and carries a plate of smoked glass. Through a slit in the glass plate, used for allowing it to slide past the rod of the pendulum, a small pin rises, which when the bob of the pendulum is twisted through 180° can be caught by a catch *C*. This catch consists of a weak spring, held bent by the friction between it and the pin. The catch *C* rests in contact with one of the levers attached to the pulley *P* and is released immediately this begins to move, if not previously released by the earthquake itself taking off the friction between it and the pin.

The bob of the pendulum then begins to move slowly round, with a velocity which is at any point of its path, calculable from the well known laws of simple harmonic motion. During this motion of the bob, two levers *l l*, fixed to pulleys *p p*, are turned by means of silk threads attached to the axis of the pendulum, and write simultaneously two rectangular components of the earth's motion on the same radius of the bob. The threads are prevented from winding round the rod of the pendulum by attaching them to a small ring *t*, which turns freely along with them. The pulleys are turned in one direction by the motion of the earth and pulley, relative to the pendulum bob, and in the other direction by the torsion of fine wires which form the axis of the pulleys. The wires forming the axes of the pulleys, shown clearly in the diagram, are kept taut by means of threads attached to the lower prongs of the forks *F*. By causing the points of the levers to write on the same radius of the bob it is easy to tell whether at any particular instant the pulleys were both turning in the same or in opposite directions. This may perhaps serve to show whether there is a distinct change in the direction of shock during the earthquake, even although that change is such as to give the same relative value for the components of the motion. Arrangement is also made for marking the motion of the bob on a plate beneath it, so that a check can always be obtained on the indication of the components.

The vertical component of the motion is recorded, in a similar manner to that just described, on the edge of the bob, by means of a pulley and crank lever *P* which is turned by a thread attached to the end of a rod or wire passing down vertically from the rod to which the pendulum is suspended. The crank lever is hinged at *H*, and the vertical arm made to press against the edge of the weight by means of a weak spring *S*.

This machine, then, aims at giving both the horizontal and vertical movement in so far as these can be given by means of a pendulum. It also attempts to give the number of vibrations, their periodic times, and their amplitudes. The duration of the shock, after it has reached a sufficient force to start the apparatus, and the intensity previous to that, will also be given. The calculation of the interval between different shocks in the earthquake is very easy when the period of torsional vibration of the pendulum is known. The indications will be independent of the ordinary pendulum period of the pendulum provided the amplitude of swing is not so great as to drive the levers off the plate.

I have stated above that the duration of the shock, after it has reached a certain intensity will be given. It is easy however to introduce an arrangement which will make this instrument record as much of the earthquake as can be done by means of any clock work machine with the same magnification. All that is necessary is to introduce another lever into the instrument so arranged as to turn at right angles to the levers already described. If the end of this lever be made to move under the point of one of the levers formerly described the latter lever will record a series of figures like lemniscates of gradually increasing amplitude on the former. The number of these can be readily counted and the period of each obtained from those which immediately follow the starting of the pendulum.

An obvious modification of the machine just described would be got by sacrificing the vertical component, and substituting for he twisted suspending wire a flat spiral spring. We would in this case get an arrangement exactly similar to that which we would have, if we laid a watch on the table *T*, and wrote the earth's movement on the balance wheel. To perform all the operations for the horizontal movements which my pendulum performs the watch mechanism is of course unnecessary, but the illustration suggests many simple applications in which the use of the mechanism might form a principle part. It would be easy for instance so to modify our mantle piece clocks that they would serve both as time keepers and as seismographs capable not only of recording the different motions of the earthquake, but also the exact hour, minute, and second, at which they occurred. If we could only persuade people to use clocks of this class, and time them properly, we should in a very short time know more of the earthquakes of this country than is known of the earthquakes of any other country at the present time.