MODERN FORMS OF PENDULUM SEISMOMETERS.

(THEIR DEVELOPMENT AND TESTS.)

BY JOHN MILNE.

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Pendulum Seismometers are the oldest forms of seismometers employed for obtaining records on a stationary plate. In 1841 pendulums of this description were employed to record shocks in Scotland. The chief objections to these instruments are that they are not provided with any arrangement to magnify the motion of the earth, and that at the time of large earthquakes the value of the records are destroyed because the pendulums invariably swing. (See Experiments in Observational Seismology by J. Milne. Trans. Seismological Society, Vol. III., p. 12.) The first pendulum seismometer with a multiplying index is the one described and constructed by Dr. G. Wagener. (See Trans. Seismological Society, Vol. I., p. 54.) From Dr. Wagener's description of this instrument, it is clear that it was the inventor's intention to counteract any tendency of the pendulum bob to oscillate by the inertia of the multiplying index, and from his account of the instrument, owing to frictional resistances, or otherwise, if the pendulum was set in motion it quickly came to rest.

The essential portions of this instrument are illustrated in Fig. 1. *W.* is the main pendulum, at the base of which there is a long lever *s o p* acting as a multiplying index or "indicating pendulum." The short arm of this is *s o*, and the long arm *o p*. At *s* and *o* there are universal ball joints. *B o* moving with the earth and *s* being at rest, the lower end of *s o p* gives a multiplied representation of the motion at *o*. As *s o* was 1 in., and *o p* 24 inches in the original instrument, it would appear that relative to *o* as a centre of percussion the centre of oscillation of the "indicating lever" was between *o* and *p*, and therefore when *o* moved to the right, *s* must receive an impulse to the right, and as the support of *w* received a displacement in a similar direction to *o*, the tendency of *w* to follow its point of support rather than being retarded in its motion would receive assistance. Its inventor argued otherwise. Notwithstanding this theoretical objection, the instrument did good service. It was the first where multiplying indices were used, the first where an attempt at compensation was introduced, and, although not fulfilling all the conditions required in this class of instrument, it was so suggestive that it may be regarded as the pioneer amongst modern pendulum seismographs.

Fig. 2 represents a pendulum seismograph described in the Transactions of the Seismological Society Vol. IV. p. 91. This instrument has done good service in Japan, and many of its records have been published. The improvements relative to instruments which preceded it are: 1st, the main pendulum is ring formed, and the steady point *s* is at its centre of inertia; 2nd, sliding pointers *o o* resting on a glass plate are used to render the pendulum dead beat; 3rd, by means of the ball *w* which is used as a universal joint, the centre of oscillation of *s w p* relative to *w* is above *w p*, and in this manner *s w p* rather than assisting *W* in following the movements of its point of support has a slight tendency to retard them. This important suggestion of loading *s w* originated with Mr. T. Gray. Later, Mr. Gray (Trans. Seis. Soc. Vol. III., p. 145) drew attention to the necessity of rendering an ordinary pendulum for small displacements absolutely astatic, and he suggested various means by which this might be accomplished.

In the same publication Vol. V., p. 89, Prof. Ewing described a duplex pendulum, a modified form of which he described in Vol. VI., p. 19. In this instrument an ordinary pendulum is rendered astatic for small displacements by placing an inverted pendulum beneath it and so uniting the bobs of the two pendulums that any horizontal motion is common to both, and the jointed system so proportioned that neutral or feebly stable equilibrium is obtained.

The essential parts of this instrument are shown in Fig. 3, where *W* is the main pendulum, *w* the inverted pendulum connected with *W* by a ball joint and resting on a pivot at *r*, *o p* the multiplying lever, receiving its motion through *B o*, there being at *o* a universal joint, and *t* the plate on which the records are written. If *L* is the length of the main pendulum *W*, and *l* the length of the inverted pendulum *w*, for astaticism or feebly neutral equilibrium $W l = w L$. An improved form of this instrument has been described by Prof. Sekiya. (Trans. Seis. Soc. Vol. VIII. p. 83.)

Although these instruments are, for seismometrical work, theoretically perfect, in practice such of them as I have had have presented certain objections, amongst which I may mention the following.

1. The difficulties of adjustment; 2. The limited size of diagram which can be obtained; 3. The difficulty in inserting and removing the smoked glass plates; and, 4, the fact that the pointer being cranked at its upper end does not give a satisfactory record in directions at right angles to the plane of the crank.

Fig. 4 illustrates an instrument which may be regarded as a modification of the old form shown in Fig. 2, where *w* has been increased in size and *s o* in length, or it may be looked upon as similar to Fig. 3, with the stem of the inverted pendulum *w o* prolonged downwards to become a pointer. The objection to this form of instrument is that there is considerable weight bearing upon the gimbals at *o*, and *o p* to obtain the requisite multiplication has to be increased in proportion to *s o*. Notwithstanding this, a very satisfactory machine may be constructed about 2 ft. 3 in. in height, which on account of the position of the pointer is more convenient to manipulate, and which yields records more satisfactory than any of the duplex pendulums which were previously in my possession.

A form that is still more compact than that shown in Fig. 4 in the one in Fig. 5 where the inverted pendulum resting on a pivot at *o* has its weight *w* which, as in the other instruments is adjustable, is above *W*. A prolongation of *w s o* forms the writing lever *o p*. In this arrangement astaticism for small displacements is obtained when $\frac{w}{W} = \frac{p^2}{Ll}$, where $p = s\ o$, L the length of the main pendulum and l the length of the inverted pendulum.

The dimensions of a machine which I am now using (see Fig. 7) are as follows. Total height of tripod carrying *W*, which is suspended by three strings from a screw passing through a plate which can be moved horizontally, is 2 ft. 9 in. Side of triangular base, 2 ft. Height of triangular table, in the centre of which there is a hole crossed by the bar *B*, is 1 ft. 1 in., $s\ o = 1\frac{1}{2}$ in. *W* is a lead ring 7 in. diameter and $\frac{3}{4}$ in. thick. *w* is a brass disc $1\frac{3}{4}$ in. in diameter, and $\frac{3}{16}$ in. thick.

The lower end of a pointer is shown in Fig. 7; *p* is the end of the pointer carrying a fine glass tube *g*, through which a pin slides and is shown resting on the smoked glass plate *t*. The sliding pointer is used in preference to several other common forms, as experiment indicates that it writes with the least friction. *t* rests on the shelf *m*, hinged at *o*. When the wedge *w* which is attached to a pivotted handle is drawn back, then *m* is lowered so that the plate falls beneath the range of the sliding pointer, and the plate may be withdrawn.

NOTE.—Since writing the above, several machines similar to Fig. 7 have been made; amongst the rest there is one which only measures 6 × 7 in. It is enclosed in a crystal case and firms a useful ornament for the mantlepieces of all residents in an earthquake country.

TESTING PENDULUM SEISMOGRAPHS.

Several of the seismographs which have been described were tested by placing them on a small table which could be easily shaken and comparing the diagram given of a shaking by a seismograph with a diagram of the actual motion of the table. The table was especially constructed with legs which were slightly flexible and loose. Beneath the centre of the table and extending downwards there was an ordinary seismograph pointer connected with the table by a ball joint, and, a short distance below, connected by a universal joint with a frame standing on the ground. This indicating pointer or lever gave a record on smoked glass 6.3 times larger than the motion of the table. All the instruments which were tested were placed immediately above this pointer and in similar positions. In the accompanying table the record of an instrument and the simultaneously obtained record of the actual motion of the table are placed side by side.

The instruments tested were :—

One of type 5, with *w s o* adjusted, first, so that the pendulum had a 4-second period, and second when it had a 2-second period.

Two of type 4. In one *w* was larger than in the other.

Two of type 3. This was an improved form of Ewing's duplex pendulum. (Trans. Seis. Soc. Vol. VIII. p. 83.) These instruments were lent to me by Professor S. Sekiya, and are similar to seismographs used by Professor Sekiya in his own laboratory. I believe the instruments to be as good as any of this type used in Japan.

I shall call the diagrams given by these instruments, numbers 1, 2, 3, 4, and 5. The records given by seismometers are marked S. while the records of the motion of the table are marked T.

Looking at records No. 1. (Instrument Fig. 7) it will be seen that for displacements of small range the record of the table and the record of the machine are practically absolutely identical, while for large movements where the diagrams are 54 millemeters in greatest length the deviations from the actual motion of the table are very small. The diagrams are correct in form and size. In diagrams 2 and 3 (Instrument Fig. 4) the correctness is not so near as in No. 1, the errors, which, however, are only slight, being more marked with the smaller diagrams.

For diagrams No. 4 (Instrument Fig. 3), all that can be said is that the diagrams are correct in amplitude. In form they are barely recognizable as delineations of the movement of the table. The diagrams given are the best that could be obtained. The pendulum had but feeble stability, and there were no arrangements by which the stability could be increased.

The machine giving the diagrams No. 5 (also Instrument Fig. 3) was set on the shaking table by Professor Sekiya's assistant, who understood the instrument. Its stability was much greater than No. 4, it having a period of 3 seconds. One source of error in the diagrams was due to the pendulum invariably swinging for some time after the motion of the table had ceased.

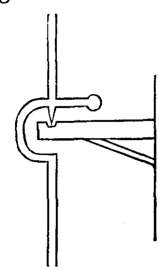
The instrument shown in Fig. 7 is here described for the first time, and I am led to describe it on account of its simplicity, compactness, and the satisfactory character of its records.

Its friction point and surfaces it will be observed are three in number. A sliding pointer, the point of a light secondary pendulum, and a ball joint.

In other instruments sources of frictional error are more numerous. Thus, in Fig. 3 there are no less than eight bearing-points and surfaces,—a writing point, the bearing point of a heavy secondary pendulum, two ball joints, and four points in a universal joint.

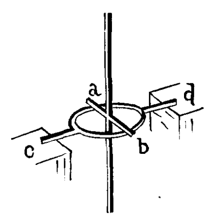
Discussion.

Dr. Knott's remarks were as follows :—Professor Sekiya has pointed out what may be called a kinematical imperfection in Professor Milne's new form of Seismograph. The vertical rod, just below the heavy weight, has to rest on a fixed support, and is then continued down to form the style which traces the motion on the usual smoked glass plate. To get past the horizontal bar which offers the needed support, the rod is expanded into an eye or ring through which the bar passes. Evidently there is here a danger that, by virtue of rotation of the rod about its own central axis, the sides ot this ring expansion may come in contact with the bar, and so render valueless the tracery of the motion. This danger may be so far minimised by cutting away the one side of the ring expansion, and substituting a bracket for the bar, as shown in the diagram. By initially adjusting the rod so that the semi-circular bulge lies in the same plane with the fixed bracket, we render the chances of fouling much less than in the former case. Still, however, it is quite possible that a rotation of two right angles may occur, especially during a shock of some duration.



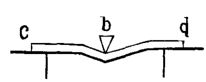
Theoretically, the following arrangement is kinematically perfect. A cross-piece ending in knife-edges is fixed perpendicularly to the vertical rod—as shown by *a b* in the diagrammatic sketch. This cross-piece rests on a circular ring, which in its turn rests by means of the knife-edges *c*, *d*, on fixed supports. *a b* is at right angles to *c d*; and the whole should be so arranged as to bring all the knife-edges into the same horizontal plane. In this way the point of intersection of the two lines of edges is a fixed point, and should be in the axis of the vertical rod.

FIG. 1



The co-planarity of the knife-edges is most easily effected by giving a suitable shape to the ring, making it dip at the points *a* and *b* as shown in Fig. 2. Such a shape of ring will also give slightly greater stability to the ring as resting on its own knife-edges. Dynamically of course, such an arrangement is not symmetrical; the rod and connec-

FIG. 2.



tions having less moment of inertia about the *a b* axis than about the *c d* axis. But the difference will be of very small account in the pendulum seismograph, in which the action of the heavy weight will completely mask all possible irregularities due to the distribution of other matter. The frictional effect of the knife-edges will be quite insignificant in the presence of other frictional constraints.

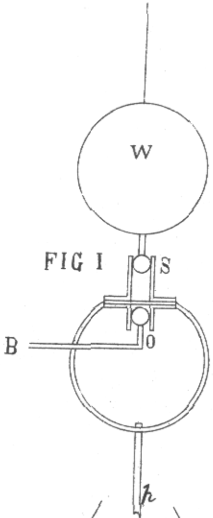


FIG 1

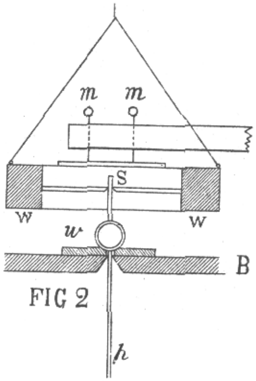


FIG 2

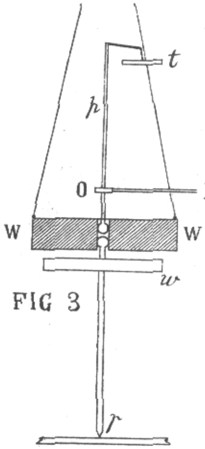


FIG 3

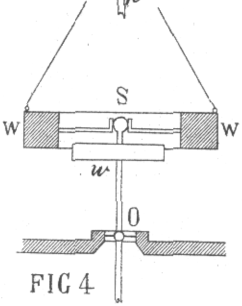


FIG 4

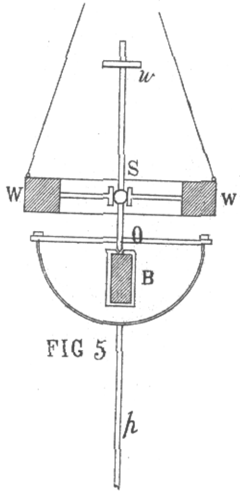


FIG 5

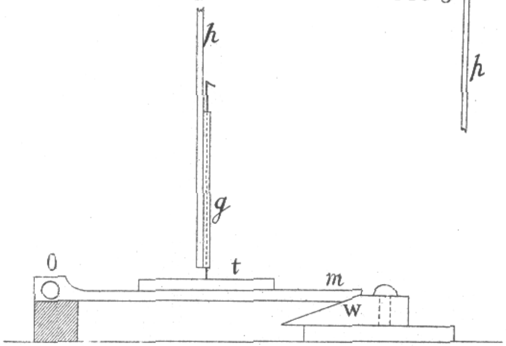


FIG 6

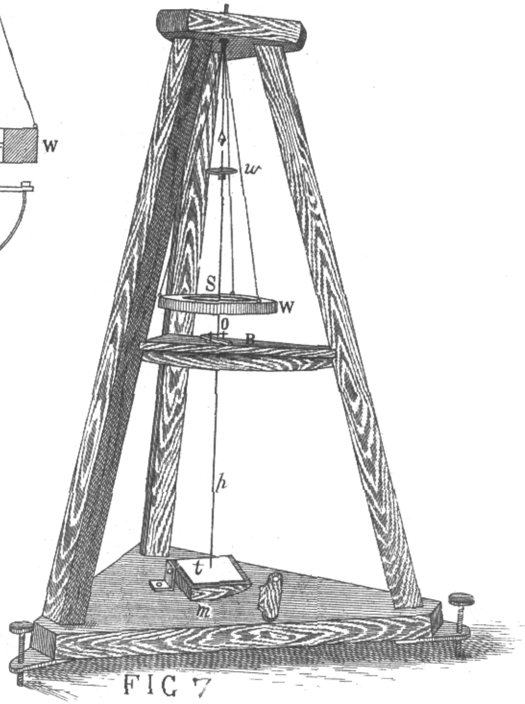


FIG 7

TESTS OF PENDULUM SEISMOGRAPHS