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20. *An Electromagnetic Horizontal Seismograph for Recording Microseisms.*

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An electromagnetic seismograph of self-vibration period 10 sec was newly made by the writers to record the horizontal component of microseisms for investigation of microseisms. The senior writer had previously designed a mechano-optical seismograph[1] for the same purpose. In this case electromagneto-optical recording was adopted, because it has the following merits in comparison with the former method: (i) practically no friction, (ii) high magnification can be obtained easily, (iii) hardly affected from slow tilting of the ground which is apt to cause, in the case of the mechano-optical method, the image of the earth motion to run off the recording paper, (iv) simultaneous observation at many places can be recorded at one place, and (v) recording can be managed by a few men.

The instrument consists of a horizontal pendulum, or transducer, a galvanometer and an optical recording camera. The galvanometer was bought from a maker, and pendulum and recorder were designed by the writers.

Horizontal Pendulum Transducer

A pair of horse-shoe magnets were put as a bob of the pendulum, with unequal poles facing each other. A spool made of bakelite wound with copper wire was stood on the table of the pendulum between the poles of the magnets. The spool was wound with two coils: the inner coil was for an electromagnetic damper of the pendulum, and the outer coil for transducer or generation of electromotive force by earth motion. The magnets were made of "MK magnet Steel No. 5" (similar to "Alnico"), remnant magnetism about 12000 gauss. With these strong magnets we could design the seismograph (Figs. 1 and 2).

1) F. KISHINOUYE, *Bull. Earthq. Res. Inst.*, **20** (1942), 215-219.

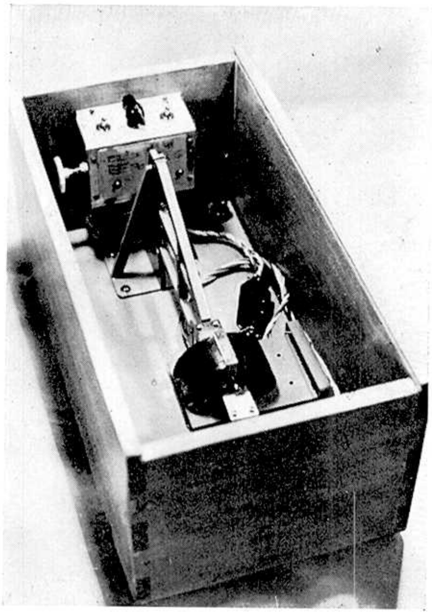

Fig. 1. Pendulum in a wooden cover. The upper box in the photograph is resistor box to make critical damping for the galvanometer and the pendulum.

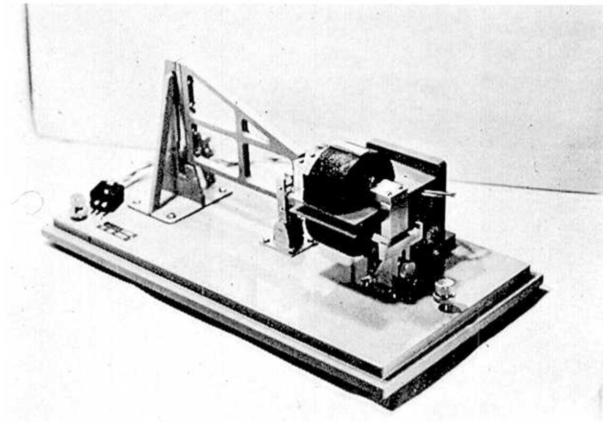

Fig. 2. The Pendulum.

Theory of the Seismograph[2)]

Suppose a rectangular electric circuit $ABCD$ and AD, the length of which is l, moves with a velocity v in the direction perpendicular to it in a magnetic field H. Then in an elementary time interval dt magnetic flux $\Delta\phi$ in the rectangle $ABCD$ increases as

$$\Delta\phi = Hlvdt$$

and an electromotive force e is induced in the circuit

$$e = \frac{d\phi}{dt} = Hlv\ .$$

If the number of turns of the coil is increased to n, the force becomes

$$e_n = n\frac{d\phi}{dt} = Hlnv\ .$$

2) Notations of the theory was described after Wenner's well-known paper, F. Wenner, Bur. Stand. Journ. Res. **2** (1929), 962–999.

On a frame of the horizontal pendulum two horse-shoe shaped magnets were fixed. When they moved by earth movements, in coils interposed between the magnets induced electromotive force (EMF) generated as the magnets moved. The electric current generated in the pendulum flows to a galvanometer as shown in Fig. 3. In the diagram R denotes electric resistance of the pendulum coil, R_g that of the moving coil of the galvanometer, and r resistance of inserted resistor and wire.

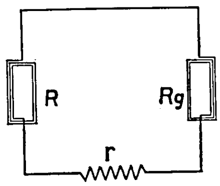

Fig. 3.

The electromotive force caused by angular displacement ϕ of the pendulum motion is

$$E_1 = G\frac{d\phi}{dt} \tag{1}$$

where

$$G = nHlL,$$

and L is the distance from the axis of rotation to the centre of the pendulum coil.

When the electromotive force goes to the galvanometer, opposite electromotive force E_2 generated,

$$E_2 = -g\frac{d\phi}{dt} \tag{2}$$

where g is a constant of the galvanometer

$$g = N'A'H'$$

and N' is number of turns of coil,
A' is area of the coil,
H' is intensity of magnetic field,
and electric current i_1 is excited in the galvanometer

$$\dot{i}_1 = G\frac{d\theta}{dt}\frac{1}{R_g + r + R}, \qquad \text{or} \qquad \dot{i}_1 = \frac{G}{Q}\frac{d\theta}{dt}. \tag{3}$$

where θ is angular displacement of the galvanometer coil,

$$Q = R_g + r + R,$$

Q is total resistance of the circuit,
R_g is resistance of the galvanometer coil,
R is resistance of the pendulum coil,
r is resistance of wires connecting the coils and inserted resistor.

Next, electric current i created by the movement of the galvanometer coil is obtained.

$$i=-g\frac{d\phi}{dt}\frac{1}{R_g+r+R}, \qquad \text{or} \qquad i=-\frac{g}{Q}\frac{d\phi}{dt}. \tag{4}$$

Induced EMF due to current in the transducer coil is expressed as

$$E_3=-\Lambda\frac{di_d}{dt} \tag{5}$$

where Λ is mutual inductance between the pendulum coil and the galvanometer coil.

i_d is current in the damper coil.

Induced EMF in the damper coil by the motion of the pendulum is

$$E_4=G'\frac{d\theta}{dt}$$

and then the current in the damper coil is expressed by the formula

$$i_d=\frac{E_4}{R_d}=\frac{G'}{R_d}\frac{d\theta}{dt} \tag{6}$$

where R_d is resistance of the damper coil, and $G'=n_dHlL$ (n_d number of turns of the damper coil).

Putting (6) in (5), current in the transducer coil i_3 is obtained,

$$i_3=\frac{E_3}{Q}=-\frac{\Lambda G'}{QR_d}\frac{d^2\theta}{dt^2}. \tag{7}$$

Total current I flowing in the transducer coil in the condition of free vibration is

$$I=i_1+i_2+i_3=\frac{G}{Q}\frac{d\theta}{dt}-\frac{gd\phi}{Qdt}-\frac{\Lambda G'd^2\theta}{QR_d dt^2}. \tag{8}$$

When current i_3 flows in the damper coil, the pendulum is influenced by force $G'i_3$. But the force due to EMF in the transducer coil and force acted on by the current in the transducer may be neglected because these are very small.

The pendulum is acted on by force due to the current in the damper coil

$$-G'i_d \tag{9}$$

and the galvanometer is acted on by force gI.

Consequently the equations of motion of pendulum and galvanometer are given by

$$K\frac{d^2\theta}{dt^2}+D\frac{d\theta}{dt}+U\theta=-ML\frac{d^2x}{dt^2}-G'i_a \qquad (10)$$

and

$$k\frac{d^2\phi}{dt^2}+d\frac{d\phi}{dt}+\mu\phi=gI \qquad (11)$$

where x is earth motion,

K is moment of inertia of the pendulum,
D is liquid damping of the pendulum,
U is restitutive force of the pendulum for deflexion angle θ,
L is the pendulum length,
k is moment of inertia of the galvanometer coil,
d is liquid damping of the galvanometer coil,
μ is restitutive force of the galvanometer coil.

Put (6) and (8) in (10) and (11), the equations of motion become

$$K\frac{d^2\theta}{dt^2}+\left(D+\frac{G'^2}{R_a}\right)\frac{d\theta}{dt}+U\theta=-ML\frac{d^2x}{dt^2} \qquad (12)$$

and

$$k\frac{d^2\phi}{dt^2}+\left(d+\frac{g}{Q}\right)\frac{d\phi}{dt}+\mu\phi=\frac{Gg}{Q}\frac{d\theta}{dt}-\frac{gG'A}{QR_a}\frac{d^2\theta}{dt^2}\,. \qquad (13)$$

To solve these equations, we assume earth motion to be harmonic

$$x=x_m\cos(\omega t+\alpha)\,, \qquad \text{or} \qquad x=x_m e^{j\alpha}e^{j\omega t}=Xe^{j\omega t}\,, \qquad (14)$$

where

$$j=\sqrt{-1}\,.$$

Deflexion angle of the pendulum is expressed also in complex form

$$\theta=\theta_m e^{j\beta}e^{j\omega t}=\Theta e^{j\omega t} \qquad (15)$$

and deflexion angle of the galvanometer mirror

$$\phi=\phi_m e^{j\gamma}e^{j\omega t}=\Phi e^{j\omega t} \qquad (16)$$

Putting the above relations in the equations of motion, relations between X, Θ and Φ are obtained,

$$\frac{\Theta}{X}=\frac{\omega^2 ML}{U-\omega^2 K+j\omega(D+G'^2/R_d)} \tag{18}$$

and

$$\frac{\Phi}{\Theta}=\frac{\omega^2 gG'\Lambda/R_dQ+j\omega Gg/Q}{\mu-\omega^2 k+j\omega(d+g^2/Q)} \tag{18}$$

The above relations give the relation between deflexion of the galvanometer mirror and earth motion as follows:

$$\begin{aligned}\frac{\Phi}{X}&=\frac{\omega^2 ML(\omega^2 G'\Lambda/R_dQ+j\omega Gg/Q)}{\{U-\omega^2K+j\omega(D+G'^2/R_d)\}\{(u-\omega^2k)+j\omega(d+g^2/Q)\}}\\&=\frac{\omega^2 H(\omega K+jN)}{(\omega^3A-\omega B+C/\omega)+j(E-\omega^2F)}\end{aligned}$$

where

$$\begin{aligned}A&=Kk\\B&=kU=Ku+Dd+Dg^2/Q+dG^2/R_d+g^2G'^2/(QR_d)\\C&=Uu\\E&=dU+Ug^2/Q+Du+G'^2u/R_d\\F&=Kd+Kg^2/Q+kD+kG'^2/R_d\\H&=ML\\K&=gG'\Lambda/(R_dQ)\\N&=Gg/Q\end{aligned}$$

The deflexion of the galvanometer mirror is drawn on photographic paper which is s cm distant from the mirror. Then the magnification V of the seismograph is

$$V=2s\frac{\Phi}{X}\,.$$

The magnification for this instrument can be changed by increasing or decreasing the number of turns of the transducer coil. In Fig. 4 variation of Φ/X with period of earth motion for the number of coil turn 300, and when increasing of magnification is necessary coil taps or 600, 900 and 1200 turns can be used. In such case magnification becomes large in proportion to the ratio of numbers of coil turns.

Phase lag of the motion of galvanometer mirror from that of earth motion is an important factor in seismometry. It is computed by the following formula.

$$(\alpha-\gamma)=\tan^{-1}\frac{\omega^4(NA+KF)-\omega^2(NB+KE)+NC}{\omega\{\omega^4KA-\omega^2(KB+NF)+KC+NE\}}$$

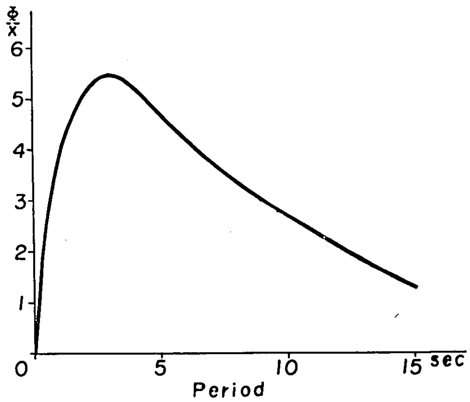

Fig. 4. Magnification curve.

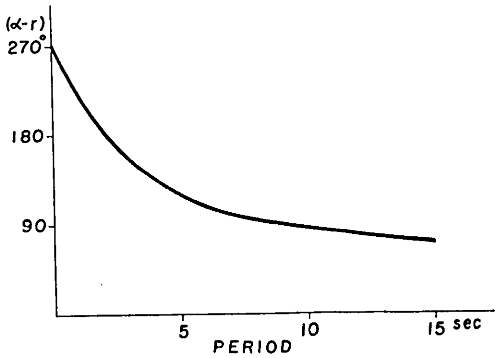

Fig. 5. Phase lag.

In Fig. 5 variation of phase lag with period of earch motion is shown.

Construction of the Seismograph

The diagrams in Figs. 4 and 5 were calculated from following values of the pendulum.

M:	1.35×10^3	g	
L :	2.2×10	cm	
K:	6.53×10^5	g cm^2	
U (10 sec):	1.19×10^4	g cm/sec^2	
G :	1.0×10^8	dyne cm/e.m.u.	
G':	5.0×10^8	dyne cm/e.m.u.	
Q :	1.0×10^{12}	c.g.s. e.m.u.	(1000 Ω)
R :	1.2×10^{11}	〃	(120 Ω)
A :	1.5×10^7	〃	(6.8×10^{-2}h)
D:	0	g cm^2/sec	

Constants of the galvanometer published were period of vibration 9 sec, sensitivity 7×10^{-10} A or 0.8×10^{-6} V and the critical damping resistance 1100 Ω. The writers were kindly told by the maker about constructional data of the galvanometer, but they were not permitted to describe here the data for certain reasons of him.

Calibration of the seismograph was carried out by comparison of records of microseisms registered with this instrument and those with the mechano-optical seismograph mentioned above. The result of the calibration was satisfactory to the writers, and they were taken to record microseisms in the International Geophysical Year (IGY) 1958. A recording apparatus was specially made to fit the project of microseismic observation for IGY. Recording drum was 60 cm in peripheri and rotated in 20 minutes, namely from 10 minutes before to 10 minutes after every hour specified by IGY Committee. The drum shifted 0.8 cm sideway in every rotation. Lamps for recording photographic image were lighted several seconds after the drum began rotation. The time lag of the lamp was caused by applying delay of plate current of heater type diode after electric current supplied to the drum.

The instruments are also employed for tripartite observation of microseisms. In such time recording is made with applying a long-recording camera of an electromagnetic oscillograph. Velocity of recording paper for microseisms is usually set at about 6.5 mm/sec.

Appendix. An electronic circuit to change duration of timing

Time marks on seismogram play an important part in seismometry. Timing is usually made by electric contact clock or by wireless time signals. To increase reading accuracy of time on seismogram, shortening or sometime lengthening of duration of electric action on timing

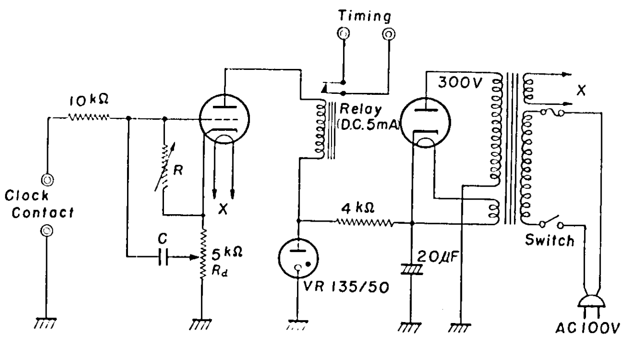

Fig. 6.

apparatus is required. But it is difficult to change the duration of ordinary timing clocks. Then the writers divised an electronic circuit to change length of timing. Fig. 6 shows the circuit. The maximum duration is fixed by time constant, or product of capacity C and resistance of the circuit R, and the duration can be changed with variable resistance R_a. Using power voltage regulator, error of the duration of timing may be less than 1%.

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20. 電磁水平動脈動計

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土地の脈動の水平成分を記録するために電磁脈動計をつくつた，精密級検流計の周期 9 秒のものに組合せ，水平振子の重錘として馬蹄形の MK 鋼磁石 2 個を上下に異なる極を相対して取付け，磁極の間に固定したコイルをおいた．コイルは 2 個をかさねて巻き．内側のコイルは電磁制振器の回路とし，外側のコイルはその起電力によつて検流計を偏れさせる．鏡の偏れは写真印画紙の上に光学的に拡大して記録させる．この器械と前に岸上のつくつた器械–光学的の微動計とで脈動の比較記録をした．その結果は良好であつたので，1958 年の国際観測年の東京本郷における観測につかい，脈動の三点観測にもつかい，脈動の研究を進めるのに用いる．

なお刻時時間を長くし，または短かくする装置を考案し実用したものについて記した．
