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2. *Development of the Portable Easy-Operation Long-Period Seismometer. Part 2: Peripheral Device.*

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Abstract

In order to advance the stability of PELS (Portable Easy-Operation Long-Period Seismometer) in temporary or unattended operation, an application of feedback has been devised. Owing to the design, to minimize the number of electronic elements and power consumption, the circuit board can be set in the container of PELS and the power for the circuit can be provided commonly by the small DC power source prepared for the active parts of PELS. The details of the design and the effect of the device on the original frequency characteristics are discussed analytically and experimentally. By the use of PELS with this device, high magnification long-period observation can be carried out at any station without being disturbed by long-term drift due to the thermal effects or tilt effects.

1. Introduction

One of the main difficulties in the operation of a long-period seismometer is the large shift of the pendulum due to the environmental variation. Every observational seismologist has the experience that the shift of a long-period vertical pendulum reaches a few milimeters referred to the earth's motion, caused by the effect of daily temperature variation. He has also experienced a long-period horizontal pendulum shifting a few micrometers as an effect of the tilt variation of a seismometer base influenced by the operator himself, the tide or the insolation. Due to these phenomena, the successful operation of a long-period seismometer has been regarded as difficult. Though these difficulties have been partly solved[1)] by PELS [Project team for the development of small-size long-period seismometer, 1974], the shift

1) Owing to the elinvar (*élasticité invariable*) suspending spring, the shift rates of the vertical pendulum of PELS have been improved. They are only 60 and 240 μm/°C referred to the earth's motion when the natural periods are 5 and 10 seconds respectively. The shift rates of the horizontal pendulum of any seismometer can not be improved, because they are physically essential. They are theoretically 30 and 120 μm/arcsec when the natural periods are 5 and 10 seconds respectively.

rate caused by the long-term drift cannot yet be neglected in a high magnification observation at a normal station. For example, on one thousand magnification observation with a pendulum of ten seconds, the shift rate of the vertical displacement trace due to the thermal effects is 24 cm/°C and that of the horizontal displacement trace due to the tilt effects is 12 cm/arc-sec; these are quite beyond the ordinary recording range. So far, in order to reduce such an undesirable shift of the trace, most seismologists have been forced to utilize the signal of a velocity transducer of an electrodynamic coil. For either civil and architectural engineering or natural seismology, however, it would be better for the measurement of displacement to record directly the signal of a displacement transducer, if there were not any trouble in its operation, from the viewpoint of dynamic range and signal to noise ratio in the relevant low frequency range where the transfer efficiency of the velocity transducer goes down rapidly compared with the displacement transducer. For this reason, a high efficiency displacement transducer called 'magnesensor' manufactured by SONY Co. Ltd. is equipped with PELS, yet it has not been satisfactorily utilized due to the above-mentioned large shift of the trace.

A peripheral device to reduce the shift rates (advance the stability) of PELS has been devised by the application of feedback theories such as those of TUCKER (1958), SUTTON *et al.* (1964), LATHAM *et al.* (1969). The device can be assembled only with an IC operational amplifier, a great capacitance condenser and some resistances. It is inserted electrically between the magnesensor and the electrodynamic coil. Needless to say, the principle of the device is also applicable to all conventional seismometers. Details and examination of the device are shown in the course of the discussion.

2. Outline of the device

Suppose that a pendulum is suspended by not only a conventional mechanical spring but also a certain element for force of restitution which generates force in DC and the ultra low frequency range but does not generate it in a higher frequency range than the natural frequency of the pendulum. Then it is reasonable to expect that, in higher frequency ranges than the natural frequency, the characteristics of the pendulum do not differ from an ordinary one while the pendulum becomes insensitive to long-term obstructive phenomena such as temperature variation or tilt variation. Nevertheless, it seems to be difficult or rather impossible to make a purely mechanical element for force of restitution with such low-pass characteristics. On the contrary, an electrical device seems to make it possible. An electrical element for force of restitution with low-pass characteristics can be realized by the use of a combination of a magnesensor and an electrodynamic coil. In the following discussion, the element is called an 'electrical spring' in contrast to a mechanical spring. When the signal of the magnesensor, which is proportional to the displacement of the pendulum, is fed back through a low-pass filter to the coil and the current proportional to the displacement flows through the coil, the force of restitution with low-pass characteristics is generated provided suitable polarity. The 'electrical spring' with low-pass characteristics has been carried out like this.

The following problems have yet to be solved in practice.

1) The necessity of the amplifier to amplify the signal of the magnesensor.

2) The way to obtain a maximum flat response without any sharp peak.

3) The most suitable circuit for such a transfer function.

These problems are solved analytically in the next section.

3. Frequency characteristics

To solve these problems, the equation of motion of the ideal pendulum and the equation of electromotive force are introduced at the start. The equation of motion can be written.

$$K\ddot{\theta}+D\dot{\theta}+U\theta=-MH\ddot{x}-GI\,, \qquad (1)$$

where (In the parentheses show the units under MKSA system)

- K: Moment of inertia of the pendulum around its rotation axis (kg·m^2),
- D: Moment of damping force per unit angular velocity of the pendulum (kg·m^2/sec),
- U: Moment of force of restitution per unit angular displacement of the pendulum (kg·m^2/sec^2),
- M: Mass of the pendulum (kg),
- H: Length from the gravity center of the pendulum to the rotation axis (m),
- G: Electrodynamic constant (V·sec *or* Joule/A),
- I: Electric current flow through the electrodynamic coil (A),
- θ: Angular displacement of the pendulum (radian),
- x: Sensible component of the earth's displacement (m).

Electromotive force E_S induced in the coil and the output of the magnesensor E_m can be written

$$E_S = G\dot{\theta}\ , \tag{2}$$

$$E_m = S\theta\ , \tag{3}$$

respectively. In equations (1)~(3), G and S have been ideally defined by

$$G = 2\pi aNBL$$

and

$$S = sL_m$$

respectively, where

a: Radius of the electrodynamic coil (m)
N: Number of turns of the coil (none),
B: Magnetic flux density across the coil (Wb/m^2),
L: Length from the center of the coil to the rotation axis (m),
s: Sensitivity of the magnesensor (V/m),
L_m: Length from the magnesensor to the rotation axis (m).

S is called simply 'S' in the following discussion because there is no name for it. Now the equivalent length is designated by l,

$$l = K/MH \quad (\text{m})\ .$$

's' is the sensitivity of the magnesensor itself, while S/l corresponds to the sensitivity of the magnesensor relative to the earth's displacement, that is, when the earth oscillates with unit amplitude 1 (m) and with sufficiently high frequency, the output of the magnesensor is S/l (V).

The circuit diagram which is devised to be most suitable for the present design is shown schematically in Fig. 1, on the basis of which the response of the pendulum is analyzed. In the analysis, the earth is assumed to oscillate sinusoidally with angular frequency ω, so that the pendulum oscillates sinusoidally with identical frequency. In the

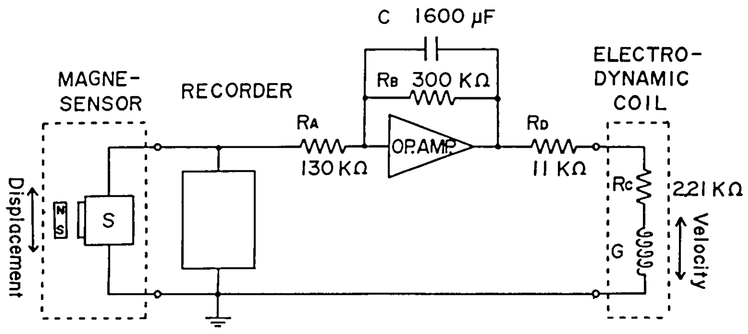

Fig. 1. Schematic diagram of the circuit of the present device. The entered values of the elements are taken from Table 1.

case, as can be seen from Fig. 1, both the electromotive force $G\dot{\theta}$ induced by the motion of the pendulum and amplified output of the magnesensor $(R_B/R_A)S\theta/(1+j\omega CR_B)$ simultaneously apply to the coil. So, the resultant current I flow through the coil is given by

$$I=\frac{1}{R_C+R_D}\left[G\dot{\theta}+\frac{R_B}{R_A}\frac{S\theta}{1+j\omega CR_B}\right], \tag{4}$$

where the output resistance of the amplifier is neglected, and the symbol $+$ in the brackets shows the specific electrical polarity of the magnesensor. Substituting (4) in (1) gives

$$K\ddot{\theta}+\left[D+\frac{G^2}{R_C+R_D}\right]\dot{\theta}+\left[U+\frac{GS}{R_C+R_D}\frac{R_B}{R_A}\frac{1}{1+j\omega CR_B}\right]\theta=-MH\ddot{x}\ . \tag{5}$$

In equation (5), the second term in the bracket of the third term is the above-mentioned electrical restitution term with low-pass characteristics. The other terms are identical to those of the conventional pendulum; namely, the first term of the left hand side is the inertia term, the second is the damping term, the first term in the bracket of the third term is the mechanical restitution term and the right hand side is the term of the external force. Equation (5) shows the relation between x and θ, while the relation between E_m and θ is shown in equation (3). Hence the relation between E_m and x can be completely represented by equations (3) and (5). Here, the parameters, which are defined as follows are introduced in order to simplify equation (5):

$$\omega_0=\sqrt{U/K} \quad \text{(natural angular frequency)}\ ,$$

$$h=\frac{1}{2\omega_0 K}\left[D+\frac{G^2}{R_C+R_D}\right] \quad \text{(damping constant)}\ ,$$

$$\omega_1=1/CR_B \quad \text{(corner angular frequency of the amplifier)}\ ,$$

$$\alpha=\sqrt{1+\frac{1}{\omega_0^2}\frac{SG}{K}\frac{1}{R_C+R_D}\frac{R_B}{R_A}} \quad \text{(magnification factor of the natural frequency).} \tag{6}$$

So, (5) becomes

$$\ddot{\theta}+2h\omega_0\dot{\theta}+\left[\omega_0^2+(\alpha^2-1)\omega_0^2\frac{1}{1+j\cdot\omega/\omega_1}\right]\theta=-\frac{\ddot{x}}{l}\ . \tag{7}$$

In equation (7), (α^2-1) represents the strength ratio in DC of the 'electrical spring' to the mechanical spring. As can be seen from equation (7), if the electrical restitution term does not provide the low-pass characteristics (This corresponds to $\omega_1\rightarrow\infty$.), the equation of motion of the pendulum is exactly similar to that of the pendulum of whicn the natural frequency is $\alpha\omega_0$. This is the reason why α is named the 'magnification factor of the natural frequency'.

Equation (7) can be rewritten

$$\left[-\omega^2+j\cdot 2h\omega_0\omega+\omega_0^2+(\alpha^2-1)\omega_0^2\frac{1}{1+j\omega/\omega_1}\right]\theta=\omega^2\frac{x}{l}, \tag{8}$$

or

$$\theta=\frac{x}{l}\frac{\omega^2}{-\omega^2+j\cdot 2h\omega_0\omega+\omega_0^2+(\alpha^2-1)\omega_0^2/(1+j\omega/\omega_1)}. \tag{9}$$

Substituting (9) to (3) gives

$$E_m=S\frac{x}{l}\frac{\omega^2}{-\omega^2+j\cdot 2h\omega_0\omega+\omega_0^2+(\alpha^2-1)\omega_0^2/(1+j\omega/\omega_1)}. \tag{9$'$}$$

Equations (9) and (9)$'$ show the frequency characteristics of θ and E_m respectively. The rigorous frequency characteristics can be calculated from equations (9) or (9)$'$. Here the authors return back to (8) in order

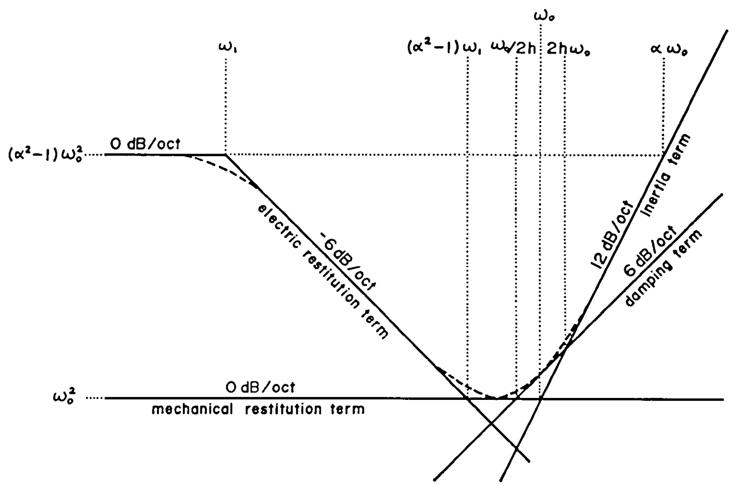

Fig. 2. Relation between angular frequency ω and the absolute values of the terms in the brackets of Eq. (8). Solid lines and dashed line represent the absolute values of the terms and their sum respectively. The inclination of the inertia term is +12 dB/oct., and that of the mechanical restitution term is zero, and the lines of the both terms intersect at $\omega=\omega_0$. The inclination of the damping term is +6 dB/oct., and its line intersects with the lines of the inertia term and the mechanical restitution term at $\omega=2h\omega_0$ and $\omega=\omega_0/2h$ respectively. The inclination of the electric restitution term is zero in $\omega\ll\omega_1$ and -6 dB/oct. in $\omega\gg\omega_1$ (where ω_1 is the corner angular frequency of the low-pass filter), and its line intersects with the line of the mechanical restitution term at $\omega=(\alpha^2-1)\omega_1$.

to give an outline of the frequency characteristics. In Fig. 2, the relation between angular frequency ω and the absolute values of the terms in the bracket of (8) are shown on a log scale. Their sum (dashed line in figure 2) represents the acceleration of the earth's motion which makes θ constant. Therefore double integration (division by ω^2) of the sum represents the displacement of the earth's motion which makes θ constant, and its reciprocal (shown in figure 3 on a log scale) represents θ (or E_m) which is observed when the earth oscillates with constant displacement amplitude. So, Fig. 3 is the outline of the frequency characteristics.

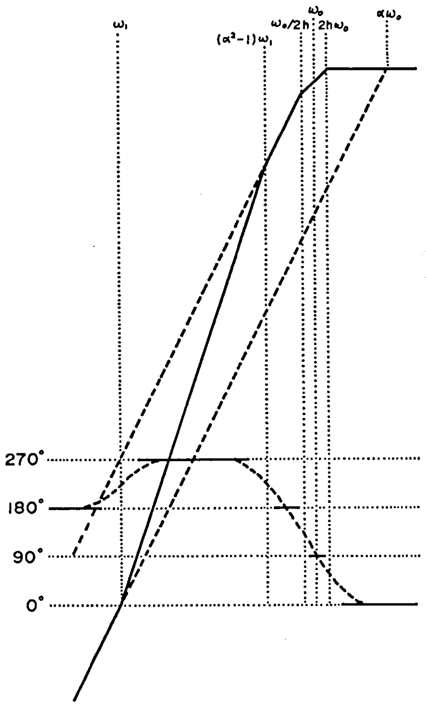

Fig. 3. Outline of the frequency characteristics of PELS with the present device. The upper one and the lower one represent schematic amplitude and phase characteristics respectively.

In Fig. 1, the high-cut characteristics of the 'electrical spring' is -6 dB/oct. At first sight, the steeper high-cut characteristics seems to be better from the viewpoint of small capacitance. But if high-cut characteristics of -12 dB/oct. is chosen, the 'electrical spring' acts as negative force of restitution in the frequency range higher than the corner frequency. This causes the undesirable sharp peak in the frequency characteristics. The high-cut characteristics of -18 dB/oct. or more is also unsuitable from the viewpoint of the simplicity of the phase-frequency characteristics as well as the circuit constitution. This is the reason why the high-cut characteristics of -6 dB/oct. is most suitable for the transfer function of the present device.

In Fig. 2, if the condition

$$(\alpha^2-1)\omega_1<\omega_0/2h \tag{10}$$

is not satisfied, the damping term and the electrical restitution term intersect with each other above the mechanical restitution term. As both terms are opposite in sign, they cancel each other completely at the point of intersection of the lines in Fig. 2. This causes the undesirable peak in the frequency characteristics. As shown in Fig. 6 in the next section, if the condition

$$(\alpha^2-1)\omega_1<\omega_0/4h \tag{11}$$

is satisfied, the undesirable peak never appears in the frequency characteristics. Thus, not (10) but (11) is the necessary condition for the design of the present device.

As can be seen from Fig. 3 or equation (7), the pendulum behaves exactly as if its natural frequency were $\alpha\omega_0$ in the frequency range lower than ω_1. This is because the pendulum is stable against the long-term drift due to thermal effects or tilt effects, and this device makes PELS as stable as a short-period seismometer. Another merit of this device is the improvement of linearity of the magnesensor. As the pendulum does not shift largely with long-term drift, the magnesensor always works near its central position where the linearity of sensitivity is best.

4. Procedure of design

Here the authors show the procedure of design with a concrete example.

4.1 *Measurements of the basic constants of the transducers.*

When the pendulum is oscillated by a vibration table or *AC* current which flows through the auxiliary electrodynamic coil, the output of the magnesensor and that of the main coil should be $S\theta$ and $G\omega\theta$ respectively, where θ and ω are the amplitude and the angular frequency of the pendulum respectively. On the experiment, the output of the magnesensor 0.760 V^{P-P} and that of the coil 0.233 V^{P-P} were measured when *AC* current flow through the auxiliary coil was 1 Hz (*i.e.* 2π rad/sec) and 3 mA^{P-P}. Hence,

$$\frac{S}{G}=2\pi\ \mathrm{sec}^{-1}\frac{0.760\ \mathrm{V}}{0.233\ \mathrm{V}}=20.5\ \mathrm{sec}^{-1}. \tag{12}$$

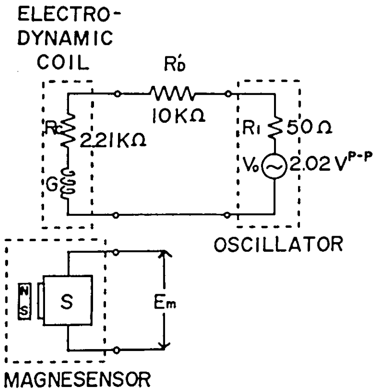

Fig. 4. Schematic circuit diagram for the measurement of SG/K. The values of the elements shown are those on the experiment. R'_D is selected so as to give the maximum flat response.

Subsequently, an oscillator, a resistance and the main coil are connected in series as shown in Fig. 4 in which the resistance R'_D should be chosen so as to give the maximum flat response. In the figure, the current

$$I=\frac{G\dot{\theta}+V_0}{R_C+R'_D+R_I}$$

flows through the coil, where

R_I: Internal resistance of the oscillator (Ω),

V_0: Output of the oscillator (V).

Substituting to (1) gives

$$K\ddot{\theta}+\left[D+\frac{G^2}{R_C+R'_D+R_I}\right]\dot{\theta}+U\theta=-\frac{GV_0}{R_C+R'_D+R_I},$$

where $\ddot{x}$ is put zero. If the angular frequency of the oscillator is sufficiently greater than the natural frequency, the damping term and the restitution term can be neglected. Hence,

$$K\ddot{\theta}=-\frac{GV_0}{R_C+R'_D+R_I},$$

or

$$\theta=\frac{G}{K\omega^2}\frac{V_0}{R_C+R'_D+R_I}.$$

Substituting to (3) gives

$$E_m=\frac{SG}{K\omega^2}\frac{V_0}{R_C+R'_D+R_I},$$

or

$$\frac{SG}{K}=\omega^2\frac{E_m}{V_0}(R_C+R'_D+R_I).$$

On the experiment, $E_m=0.960\ \mathrm{V}^{\mathrm{P\text{-}P}}$ and $V_0=2.02\ \mathrm{V}^{\mathrm{P\text{-}P}}$ where $\omega=2\pi$ rad/sec and $R'_D=10\ \mathrm{k\Omega}$. So,

$$\frac{SG}{K}=(2\pi\ \mathrm{sec}^{-1})^2\frac{0.960\ \mathrm{V}}{2.02\ \mathrm{V}}(2210\,\Omega+10000\,\Omega+50\,\Omega)$$
$$=2.30\times10^5\ \mathrm{V}^2\cdot\mathrm{sec/kg}\cdot\mathrm{m}^2\,. \tag{13}$$

The above procedure would be bypassed if reliable values of the basic constants of the seismometer were given. The authors expect, however, to remeasure these values with the above-mentioned methods. The measurement methods for K itself and S itself are very trouble-some and sometimes include much error. Nevertheless the present methods are handy and accurate methods, and furthermore you will find in 4.2 and 4.3 that they are fit our present purpose.

Otherwise,

$$\omega_0 = 2\pi \cdot 0.1 \text{ rad/sec} \tag{14}$$

and

$$D/2\omega_0 K = 0.010 \quad \text{(mechanical damping designated by } h_0) \tag{15}$$

are obtained easily by conventional methods.

4.2 *Determination of R_D.*

For usually use, the value of h has been determined to be $1/\sqrt{2}$ (maximum flat response). h is given by

$$h = h_0 + \frac{1}{2\omega_0 K} \frac{G^2}{R_G + R_D} .$$

Substituting known values (G^2/K can be calculated from (12) and (13)), gives $R_D = 10.6\,\text{k}\Omega$. But actually the authors put

$$R_D = 11\,\text{k}\Omega . \tag{16}$$

Therefore $h = 0.686$.

4.3 *Determination of R_A, R_B and C.*

The authors tried to operate the 0.1 Hz's pendulum with the stability of 1 Hz's; this corresponds to $\alpha = 10$. From the relation of (6),

$$10 = \sqrt{1 + \frac{1}{(2\pi \cdot 0.1\,\text{sec}^{-1})^2} (2.30 \times 10^5\,\text{V}^2 \cdot \text{sec/kg} \cdot \text{m}^2) \frac{1}{2210\,\Omega + 11000\,\Omega} \frac{R_B}{R_A}} ,$$

or

$$R_B/R_A = 2.24 . \tag{17}$$

And from the necessary condition of (11),

$$(100-1)\omega_1 < \frac{2\pi \cdot 0.1\,\text{sec}^{-1}}{4 \cdot 0.686} ,$$

or

$$\omega_1 < 0.00231 \text{ rad/sec} ,$$

or

$$CR_B > 432\,\text{F}\Omega . \tag{18}$$

(17) and (18) are the sufficient conditions for R_A, R_B and C. There is a fair amount of arbitrariness in the determination of these values. But in practice, preparation of a great and an exact capacitance condenser requires much trouble. Therefore, it is advisable to determine R_A and R_A after C value is given. For the authors, it was easy to prepare

$$C=1600\,\mu\mathrm{F}\,. \qquad (19)$$

Hence they got $R_B>270\ \mathrm{k}\Omega$ from the relation of (18). Actually they put

$$R_B=300\ \mathrm{k}\Omega\,. \qquad (20)$$

From equations (17) and (20), they got $R_A=134\ \mathrm{k}\Omega$. Actually, for convenience, they put

$$R_A=130\ \mathrm{k}\Omega\,. \qquad (21)$$

These values obtained by the procedure 4.1~4.3 are summerized in Table 1. With the use of these values, the rigorous frequency characteristics are calculated from equation (9) and shown in Fig. 5 in which the experimental results are also shown in parallel. The experimental data were obtained by the use of an oscillator and the auxiliary coil of PELS. They are in good agreement with each other.

In order to examine whether the frequency characteristics in the interesting frequency range has varied or not, the parallel experimental observation by the use of an $X-Y$ recorder has also been carried out by PELS with and without the device. The records are in good agreement with each other. Thus the theory is proved experimentally.

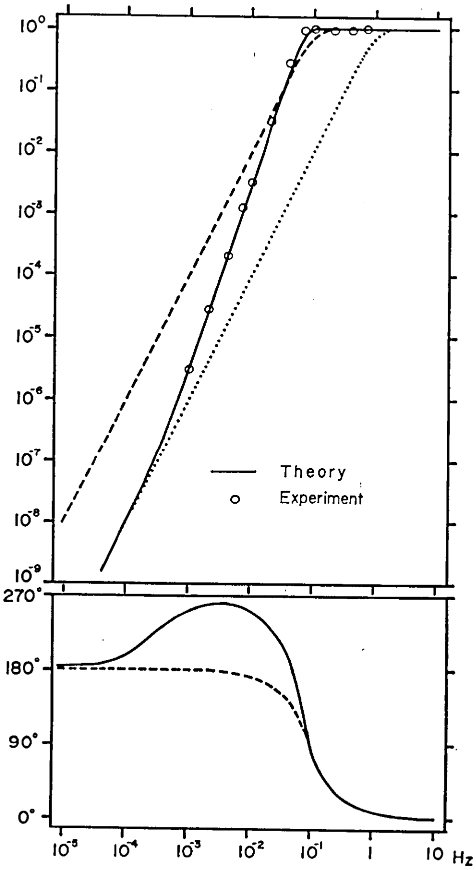

Fig. 5. Rigorous frequency characteristics of PELS with the present device. The upper one and the lower one represent amplitude and phase characteristics respectively. Solid lines represent the theoretical ones and the open circles represent the experimental data. Both are in agreement with each other. Characteristics of 1 Hz's pendulum with $h=1/\sqrt{2}$ (doted line) and 0.1 Hz's pendulum with $h=1/\sqrt{2}$ (dashed line) are simultaneously shown.

Table 1. Table of constants obtained with the procedure 4.1~4.3.

	value	unit	ref. eq.
S/G	20.5	sec^{-1}	(12)
SG/K	230000	$V^2 \cdot sec/kg \cdot m^2$	(13)
ω_0	0.628	rad/sec	(14)
h_0	0.010	(none)	(15)
R_C	2210	Ω	
R_D	11	kΩ	(16)
R_A	130	kΩ	(21)
R_B	300	kΩ	(20)
C	1600	μF	(19)

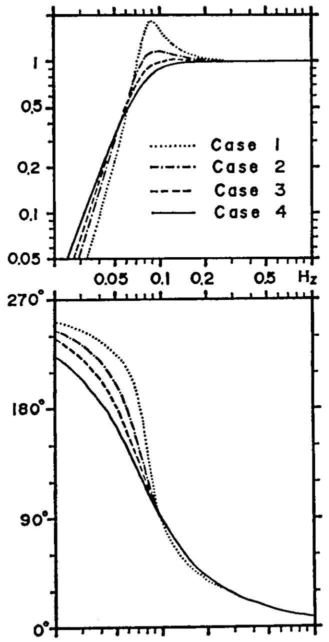

Fig. 6. The change of the characteristics of the seismometer when the corner angular frequency of the amplifier is changed by the change of capacitance. This figure clearly shows that (11) is the necessary condition.

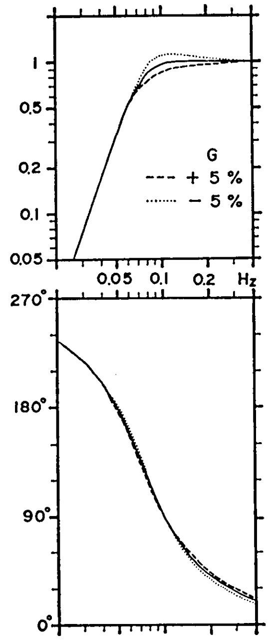

Fig. 7. The change of the characteristics when the G value changes by +/− 5%.

To show the necessity of the condition (11), the frequency characteristics are calculated when $\omega_1(=1/CR_B)$ is changed by the change of the C value satisfying the following four equations:

$$(\alpha^2-1)\omega_1=\omega_0/2h \;, \qquad \text{(Case 1)}$$

$$(\alpha^2-1)\omega_1=\omega_0/3h \;, \qquad \text{(Case 2)}$$

$$(\alpha^2-1)\omega_1=\omega_0/4h\ , \qquad \text{(Case 3)}$$

$$(\alpha^2-1)\omega_1=\omega_0/6h\ , \qquad \text{(Case 4)}$$

The frequency characteristics for each case is shown in Fig. 6. The figure shows that if the condition (11) is not satisfied (Case 1 & 2), the peak in the frequency characteristics is large. This is the reason why (11) is the necessary condition.

Now the authors study the effects of changes of the G, S and C values on the frequency characteristics. Fig. 7 shows the frequency characteristics when only the G value changes by +/− 5%, though neither measurement error nor environmental effects reach that extent. As h is proportional to G^2, the frequency characteristics change as shown in Fig. 7. But this does not mean that, by the addition of the device, the effect of the change of G on frequency characteristics becomes much. Fig. 8 shows the frequency characteristics when only the S value changes by +/− 10%. Figure 8 shows that the change of frequency characteristics is negligible if the change of S is less than +/− 10%. Fig. 9 shows the frequency characteristics when only the C value changes by +/− 30%. As you know, the capacitance of some chemical condensers decrease by more than 30% when temperatures

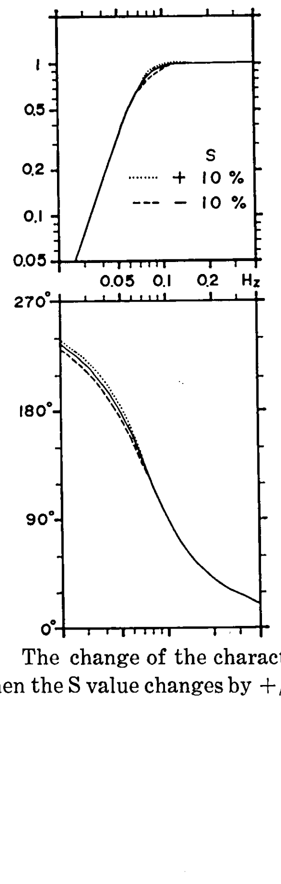

Fig. 8. The change of the characteristics when the S value changes by +/− 10%.

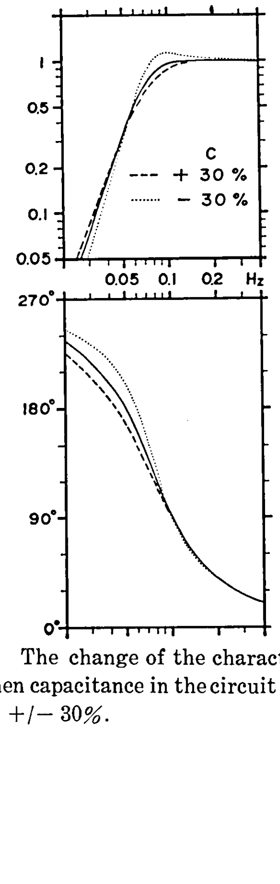

Fig. 9. The change of the characteristics when capacitance in the circuit changes by +/− 30%.

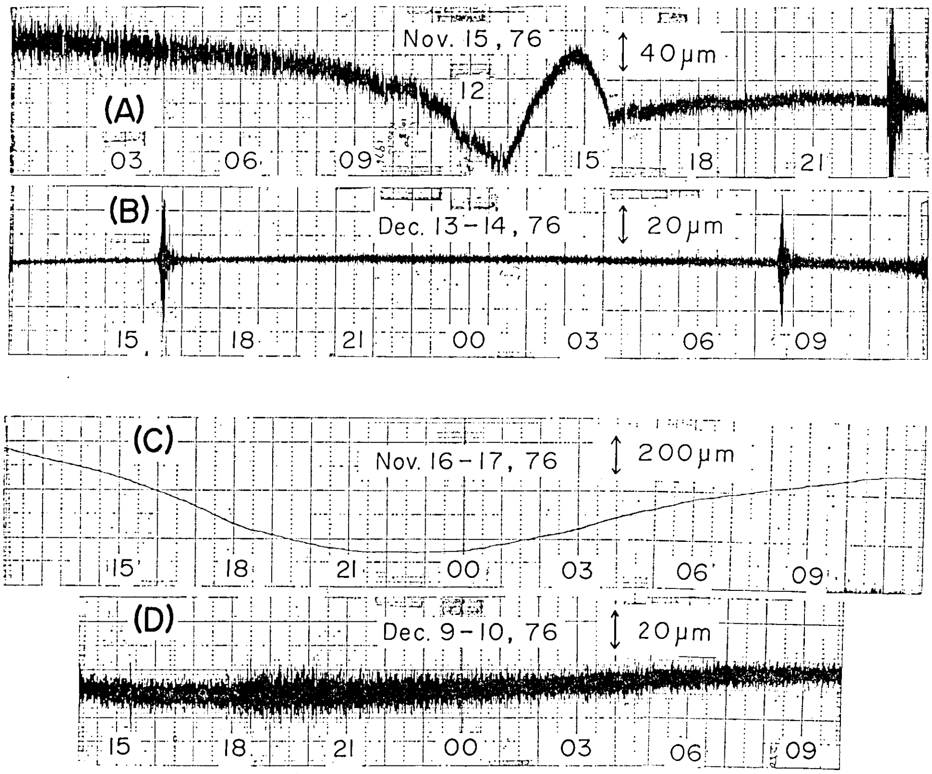

Fig. 10. Examples of the traces. Traces (A) and (B) are horizontal displacements observed with 0.1 Hz's PELS without and with the device respectively. Traces (C) and (D) are vertical displacements observed with 0.1 Hz's PELS without and with the device respectively. Data and time are Japan standard time.

drop below freezing point. This causes a sharp peak in the frequency characteristics as shown in Fig. 9. This trouble can be avoided by the use of sufficiently great capacitance initially.

Fig. 10 shows examples of the horizontal and vertical displacement traces observed with PELS in a room where daily temperature variation is about 1°C and daily tilt variation due to the insolation is a few arc-seconds. By the device, 0.1 Hz's PELS can operate as stably as 1 Hz's seismometer with little effect on the original frequency characteristics. Fig. 10 shows the great improvement of stability of 0.1 Hz's PELS.

5. Particulars

Further particulars about the elements used in the device are given below.

5.1 *Displacement transducer.*

The displacement transducer is the element which generates a voltage proportional to the displacement of the pendulum. As for PELS, the magnesensor is installed on its pendulum at the point of $l/L_m=5$ with the gap of 0.5 mm. The sensitivity (S/l) is 2 mV/μm ($s=10$ mV/μm) within the dynamic range of +/− 2.5 mm (+/− 5 mm at the sacrifice of the linarity) referred to the motion of the pendulum. The magnesensor is remarkably sensitive as a displacement transducer, and has enough power to shorten the natural frequency of PELS without an amplifier. But as mentioned above, an amplifier with more than two times gain has been necessary for the present design.

5.2 *Amplifier.*

The amplifier is used to strengthen the 'electrical spring' in the *DC* and ultra low frequency range. As the minimum detectable signal of the magnesensor seems to be less than 0.1 μm, the corresponding output of the magnesensor is 200 μV. So, the noise of the amplifier referred to the input voltage has to be less than several tens of microvolts. It is easy to satisfy this condition with the conventional IC operational amplifiers. Fig. 1 shows the most suitable circuit for the present purpose from the viewpoint of simplicity of the power source, the number of electronic elements and desirable frequency characteristics. Even a conventional chemical condenser is available for the electrical part if the temperature does not drop below freezing point.

5.3 *Recorder.*

Any recorder is available if it has a higher input impedance than few ten kiloohms. But when a horizontal seismometer operates on tall buildings or when a vertical one operates in the field where the daily enviromental variation is great, the helical recorder with small pitch of traces may not yet be suitable because some zero shifts would remain.

5.4 *Electrodynamic coil.*

The electrodynamic coil is an element which generates an electric force of restitution by the current flow through the coil, and at the same time controls the damping constant of the pendulum. The great electrodynamic constant contributes to lower the gain of the amplifier, so the greater the electrodynamic constant is, the simpler the device becomes. Most conventional electrodynamic coils of transducers seem to be suitable.

5.5 *Auxiliary coil.*

In the calibration of seismometers, the application of the auxiliary coil method [MATUMOTO *et al.* 1976] is better than that of the vibration table method from the viewpoint of accuracy and handiness. Calibration with a vibration table seems to be unreliable and furthermore it can not be carried out in the field. In the present paper, calibrations have been carried out only by the auxiliary coil method. Speaking of details, the size of the electrodynamic constant of the coil should be selected suitably. In the calibration, too great an electrodynamic constant causes an undesirable change of the damping constant and too small an electrodynamic constant requires a high power oscillator.

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2. 小型可搬長周期地震計の開発

その 2. 周辺装置

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野外でも容易に使用できる長周期地震計として PELS の開発が計画され，1973 年に開発が完了し，地震研究所研究速報に紹介されている．PELS の開発により，

① 装置の小型軽量化.

② 構成部品の寄生二次振動を帯域外 (0.1～50 Hz) へ駆逐したことによる特性の広域化.

③ 高感度変位出力による周辺装置の簡略化.

等の面で使用上の容易さが向上し，しかも観測対象を広げることに成功したといえる.

しかしながら PELS が普及するとともに，長周期地震計に本質的につきまとう調整の困難さあるいは望ましくない対環境 (温度，傾斜運動) 特性の面から，長周期地震計を使用した経験のないユーザーから Easy-operation と呼ぶのに値しないのではないかという声もでてきている.

もちろん，短周期地震計の出力を等化しても同様の特性を持つ地震計を構成することは可能であり，操作上はむしろこの方が容易な場合もあろうが，特性および装置の大きさの面からは PELS の方が格段に有利であると判断される．よってこの論文では上記の批判に応えるために，指摘されている操作の困難さを除去するための周辺装置，その設計手順および効果を第2報として紹介する．また第1報のみでは PELS の諸元および部品の附加目的について説明の不充分と思われる箇所も存在するので，この周辺装置を構成する増幅器あるいは記録器の具備すべき条件とともに補足説明をおこなった.

なおこの論文で筆者が強調したい内容は，

① 振子の固有周期よりも短周期の領域 (いわゆる帯域) における特性は変化させず，しかも超長周期の環境変化に対する特性およびその他の帯域外特性も良好な PELS を構成するためには，帰還路に，できるだけ小さなコーナー周波数をもつ (多数階でなく) 1階の積分回路を挿入する方式が最も望ましい.

② 設計どおりの特性を正確に得るためには，本文中に述べてある方法で G^2/K そして SG/K を測定して回路定数を決定する必要がある.

③ この周辺装置を付加した PELS を用いれば，市販されている通常の記録器と組合せるだけの最小構成で，10～15 秒までを帯域とし千倍以上の高倍率変位観測を，かなり悪い環境のもとでも安定に行うことができる.

等である.