EARTHQUAKE ISOLATION METHOD OF STRUCTURE
BY A HIGH SPEED ELECTROHYDRAULIC SERVOMECHANISM

BY

CHITOSHI KATSUTA* AND NAOKAZU MASHIZU**

ABSTRACT

This paper proposes the new idea of earthquake isolation method of structure by a high speed electrohydraulic servomechanism and discusses some applications of this idea for the dynamic characteristics, through theoretical calculation, model test of our earthquake isolation apparatus and results.

The results are summarized as follows.

1) These earthquake isolation apparatus by a high speed electrohydraulic servomechanism may be suitable for isolation of vibration of low frequency such as strong ground motion of earthquake.

2) These apparatus may be applied for earthquake isolation of structure and as supporting table of seismograph.

3) The transmissibility of these apparatus are given as a function of frequency of ground motion and constant of apparatus. In designing this apparatus, we can pick up the constant of apparatus for the purpose of the most effective earthquake isolation of structure.

4) In the case of model test of this isolation apparatus, the minimum value of transmissibility of isolation apparatus is reduced to about 0.03, when the frequency and the amplitude of shaking table were 1 c/sec and 10 cm.

5) In the case of application of these apparatus to large structures, the development of special servovalve and actuator of large scale and practical construction of earthquake isolation apparatus for horizontal two direction yet remain as subject matter for further research in future.

§1 INTRODUCTION

In Japan, seismo-free apparatus was proposed by Ryuiti Oka and Yukio Otsuki about 20 years ago which was actually applied to a few

* Professor, Tokyo Institute of Technology, Department of Architecture, Dr. Eng.
** Assistant, T. I. T.

building in Tokyo.

In Oka's method, a vertical pendulum of dynamically variable length was employed and in Otsuki's method, a roller bearing set and a set of springs with a certain constraint were employed.

This method may be called as earthquake isolation method by vibration system like pendulum, spring and damper.

However, to minimize the transmissibility of ground motion, the natural period of the pendulum or of the springs is required to be sufficiently longer than periods of ground motion (0.1 - 5 sec.) but it may be very difficult to make the period longer in the case of isolation apparatus by vibration system.

This paper introduces the new idea of earthquake isolation method of structures by a high speed electrohydraulic servomechanism.

In this method, isolation apparatus by vibration system such as pendulum, spring or damper is not employed and mechanical and electrical isolation apparatus such as high speed electrohydraulic servomechanism is employed.

This isolation method may be suitable for irregular vibration of low frequency about 0.1 - 10 c/s such as strong ground motion of earthquake.

§2 PRINCIPLE AND COMPONENTS OF EARTHQUAKE ISOLATION SYSTEM BY A ELECTROHYDRAULIC SERVOMECHANISM

To simplify the explanation a horizontal earthquake isolation method is considered here, but the vertical or rotational earthquake isolation method is also explained quite similarly.

Fig. 1 shows some applications of this earthquake isolation method for structures.

In Fig. 1, 1, 2, 4 are columns supporting vertical load and having very small resistant shearing force, and 3 is horizontally supporting member with actuator controlled by servovalve.

In structures, horizontally supporting members may be set symmetrically in two directions.

Fig. 2 shows the principle of this earthquake isolation method.

Fig. 3 shows the total schematic diagram and block diagram of tested earthquake isolation apparatus.

Main components of this apparatus are as follows:

1. Hydraulic system

2. Controller of system

3. Electric error detector and amplifier

4. Horizontally supporting member with actuator

2.1 HYDRAULIC SYSTEM

Oil hydraulic system is as follows.

(a) Pump unit consists of motor, pump (vane type), oil filters, relief valve (balanced piston type), cooler, accumulators and oil tank.

Photo. 1 shows tested pump unit.

(b) Servovalve used in the model test as shown in Fig. 4A is made by Tokyo Keiki Co., Ltd.

(c) Manifold and actuator used in the model test are shown in Fig. 4B.

In structures, servovalves or special servovalves, manifolds and actuators may be designed in accordance with the conditions of earthquake isolation apparatus of structure.

2.2 CONTROLLER OF SYSTEM

Controller of isolation system for horizontal ground motion of earthquake is the bob of seismograph (or accelerogram).

When the ground is displaced by x, the controller minimizes the displacement y of structure by controlling the actuator of horizontally supporting member 3.

Controller may be set on ground or structure as shown in Fig. 2.

2.3 ELECTONIC ERROR DETECTOR AND AMPLIFIER

Fig. 5 shows the circuit diagram of the electonic error detector which is electric differential transformer type. (Fig. 5b)

In this system, neutral detector is employed for the sake of restitution of structure. (Fig. 5b)

2.4 HORIZONTALLY SUPPORTING MEMBER WITH ACTUATOR 4

Horizontally supporting members in Fig. 1 and Fig. 2 balance horizontal force of earthquake and of typhoon.

Moreover, in the case of earthquake, the length of these members increase or decrease to minimize the displacement y of structure by the action of actuator.

In Fig. 2, when the ground is displaced by x and the piston of actuator is displaced by Δl, in the case of $\Delta l \rightarrow x$, y minimizes to zero. The motion of the piston in the actuator is controlled by servovalve, electric error detector and by the bob of seismograph to minimize y to zero.

Photo 2 shows tested earthquake isolation apparatus by high speed electrohydraulic servomechanism and Fig. 6 shows schematic diagram of vibrating table, isolated table, bob of seismograph, actuator and servovalve of tested apparatus.

§3 BLOCK DIAGRAM, TRANSFER FUNCTION, GAIN, TRANSMISSIBILITY OF EARTHQUAKE ISOLATION SYSTEMS BY THE HIGH SPEED ELECTROHYDRAULIC SERVOMECHANISM IN SEVERAL CASES

3.1 CASE I: SYSTEM CONTROLLED BY A IMMOVABLE POINT IN SPACE

Schematic diagram and block diagram are shown in Fig. 6.

Transfer function G(S) of this system is

$$G(S) = \frac{Y}{X} = \frac{S}{S+K} \qquad (3.1)$$

Where, S is Laplace variable and K is gain constant of error detector, servovalve and of actuator.

In Fig. 7 and Fig. 8 frequency response of y and phase lag of this system are shown.

This system is an ideal and fundamental case of the systems mentioned below.

In this system controlled by a immovable point in space, dynamic characteristics are very stable and transmissibility of this system is very small.

One example of results by model tests is shown in Fig. 9.

When frequency and amplitude of shaking table are 1 c/sec and 10 cm respectively, amplitude of isolated table is 3 mm in the case of K = 215, and drifting of isolated table is not recognized, because this system is controlled by a immovable point in space (in model test, a immovable point is a point on the floor of the laboratory room).

In Fig. 7, when K is given as 100, 215, 300, 400 and frequency of ground motion as 1 c/sec, transmissibility of this system is 0.06, 0.027, 0.02, 0.015 respectively.

Transmissibility can be minimized by increasing the value of K.

In our model test, value of K was 215.

In this system, the technique of locating an immovable point or almost immovable point and increasing value of K remain subject matter for further research in future.

Bob of seismograph set on ground or structure is used as almost immovable reference point in the systems mentioned below.

3.2 CASE II: SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE GROUND

In Fig. 10, schematic diagram and block diagram of this system are shown.

In this case, transfer function G(S) is

$$G(S) = \frac{Y}{X} = \frac{S^3 + 2\zeta\omega_n S^2 + \omega_n^2 S - \omega_n^2 k}{S^3 + (2\zeta\omega_n - k)S^2 + (\omega_n^2 - 2\zeta\omega_n k)\,S - \omega_n^2 k} \qquad (3.2)$$

Fig. 11 and Fig. 12 show response diagram of y and phase log of this system. In Fig. 11 and 12, f_o is natural frequency of seismograph c/sec, ζ is damping ratio of seismograph and K is gain constant of error detector, servovalve and of actuator.

Response curves vary according to the values of f_o, ζ and K.

Fig. 11 shows response diagram of y in the case of K = 215, ζ = 0.42, f_o = 0.1, 0.2, 0.4, 1.0 c/sec respectively. Where, K = 215, ζ = 0.42 are values of earthquake isolation apparatus employed in our model test.

In Fig. 11, when natural frequency of seismograph is given as 1.0, 0.4, 0.2, 0.1 c/sec and frequency of the ground motion is given as 1 c/sec, transmissibilities of this system are 1.30, 0.20, 0.053 and 0.033 respectively.

To minimize transmissibility of this system, we must employ the seismograph with sufficiently small natural frequency about $f_o = 0.1$ c/sec.

In this system, the technique of making the seismograph with $f_o <$ 0.1 c/sec has yet to be developed but this system has good dynamic characteristics in low frequency of ground motion, and then neutral detector is not necessary in order to restitute structures.

3.3 CASE III: SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON STRUCTURE (WITHOUT NEUTRAL COMPENSATION)

In Fig. 13, schematic diagram and block diagram of this system are shown.

In this case, transfer function G(S) is

$$G(S) = \frac{Y}{X} = \frac{S^2 + 2\zeta\omega_n S + \omega_n^2}{S^2 + (2\zeta\omega_n + k)S + (\omega_n^2 + 2\zeta\omega_n k)} \qquad (3.3)$$

Fig. 14, 15, 16, 17 show response diagram of y and phase lag of this system.

Fig. 14 and 15 represent response diagram of Y and phase lag when

$$K = 215, \zeta = 0.42, f_o = 0.1, 0.2, 0.4, 1.0 \text{ c/sec}$$

Fig. 16 represents response diagram of y when $f_o = 0.4$ c/sec, $\zeta = 0.42$, K = 100, 215, 300, 400.

Fig. 17 represents response diagram of Y when $f_o = 0.4$ c/sec, K = 215, $\zeta = 0.1, 0.42, 0.7, 1.0$. Where, $f_o = 0.4$ c/sec, K = 215, $= 0.42$ are values of earthquake isolation apparatus employed in our model test.

Response curve of Y vary according to values of f_o, ζ, K respectively.

We can minimize the value of transmissibility by employing the seismograph with low frequency and low damping ratio and increasing gain constant K of error detector, servovalve and of actuator.

Generally, by setting the seismograph on the structure, transmissibility became very small as compared with CASE II, but as for the defect of this system, it is pointed out that the system is too sensitive against the external disturbance due to inclination of the seismograph employed as detector and therefore it causes drifting with very low frequency and then in this system we can not expect the restitution of structure.

Fig. 17' shows the drifting of isolated table, when frequency and amplitude of shaking table are 2 c/sec and 12.5 mm respectively.

In this system, the problem of minimizing the drifting remains a subject matter for further research in future.

3.4 CASE IV: SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON STRUCTURE WITH NEUTRAL COMPENSATION

In this system, neutral detector is employed as a remedy to minimize the drifting.

In Fig. 3 and Fig. 18 schematic diagram and block diagram of this system are shown.

Transfer function G(S) of this system is

$$G(S) = \frac{Y}{X}$$

$$= \frac{S^3 + (2\zeta\omega_n + KK')S^2 + (\omega_n^2 + 2\zeta\omega_n KK')S + \omega_n^2 KK'}{S^3 + (2\zeta\omega_n + KK' + K)S^2 + (\omega_n^2 + 2\zeta\omega_n KK' + 2\zeta\omega_n K)S + \omega_n^2 KK'} \qquad (3.4)$$

In Fig. 19, 20, 21, 22 and 23, response diagram of y and phase lag are shown.

Response curve of Y vary according to the values of f_o, ζ, K, and K' respectively.

In Fig. 19 and 20, response diagram of Y and phase log are shown where

$$K = 215, \quad \zeta = 0.42, \quad K' = 0.047$$

$$f_o = 0.1,\ 0.2,\ 0.4,\ 1.0 \text{ c/sec}$$

In Fig. 21, response diagram of Y are shown where,

$$f_o = 0.4, \quad \zeta = 0.42, \quad K' = 0.047$$

$$K = 100,\ 215,\ 300, \text{ and } 400$$

In Fig. 22, response diagram of Y are shown, where

$f_o = 0.4$, $K = 215$, $K' = 0.047$

$\zeta = 0.1$, 0.42, 0.7, and 1.0

In Fig. 23, response diagram of Y are shown, where

$f_o = 0.4$, $K = 215$, $\zeta = 0.42$

$K' = 0$, 0.02, 0.047, 0.2

In this system, by the effect of neutral detector, the drifting of isolation apparatus is minimized but transmissibility $\frac{Y}{X}$ becomes somewhat larger as compared with CASE III.

By employing the neutral detector as shown in Fig. 3 and 18, we can minimize the drifting of the apparatus and can expect the restitution of structure.

One example of results of model test by our isolation apparatus is shown in Fig. 24.

When frequency and amplitude of shaking table are 1 c/sec and 10 cm respectively amplitude of isolated table is 4.5 mm, and the drifting of isolated table which has as long a period as 15 second is recognized as little in the case of $K = 215$, $K' = 0.03$, $\zeta = 0.42$, $f_o = 0.4$ c/s.

In Fig. 25, bode diagram of loop transfer function of y shows that this system is stable.

By consideration of Fig. 19 - 25, we can recognize that this system may be most suitable of CASES I - IV for the earthquake isolation apparatus of structures.

When we employ this system for the earthquake isolation apparatus of structures, we must pick up most suitable values of f_o, ζ, K, K' of this system, by assuming the spectrum of strong earthquake motion as shown in Fig. 26.

Fig. 27 shows one example of isolation result of strong earthquake motion by earthquake isolation apparatus of $K = 215$, $\zeta = 0.42$, $f_o = 0.4$ c/sec and $K' = 0.03$

3.5 CASE V: SYSTEM CONTROLLED BY THE BOB OF ACCELEROGRAM SET ON STRUCTURE WITH NEUTRAL COMPENSATION

Fig. 28 shows frequency response of y in this system. By increasing value of damping ratio of seismograph, we can decrease the value of transmissibility, but it may be difficult to increase the value of ζ .

In our experiment, we could not increase value of ζ ($\zeta \approx 0.25$) and then transmissibility was larger than 0.1. Therefore we consider that this system may be not suitable to the earthquake isolation apparatus.

§4 EXPERIMENT WITH MODEL DEVICE

On the basis of principles as mentioned above, the model device as shown in Fig. 3, Fig. 4, Photo. 1, and Photo. 2 was built and the frequency response test was carried out.

The constructive diagram and the block diagram of the model device of CASE IV are shown in Fig. 3 and Fig. 4 respectively.

Amplifier of error detector, neutral compensator and torquemotor of servovalve are shown in Photo. 3.

Seismograph used as controller is nothing but inverted pendulum as shown in Fig. 29 with natural frequency of 1.25, 2.5 or 5 second by changing weight of bob.

The vibration of shaking table was imparted to the isolation apparatus by means of the vibrator which essentially consists of a fly wheel, an amplitude exchanger, and a motor (5 HP).

The vibrator has a maximum rotating speed of 8 revolutions per second and a minimum of 0.5 revolutions per second. In experiment, the frequency and the amplitude of shaking table are found as follows.

Frequency c/sec	0.5	1	2	4.5
amplitude mm	100	100	50	12.5

The displacement of shaking table and isolated table were recorded by potentiometer and recording oscillograph. Example of recording are shown in Fig. 9, 17' and 24.

Standard conditions for the tests of apparatus are as follows. Oil pressure; 35 kg/cm^2, piston area; 5 cm^2, weight of load; 40 kg and gain constant K; 215, gain constant of detector K'; 0.03, natural frequency of seismograph; 0.4 c/sec, damping ratio of seismograph; 0.42.

4.1 TEST OF CASE I

The frequency response test of the system controlled by the immovable point was carried out. Immovable point is the point on the floor of vibration research room. Gain constant K in this case was 300. The results of test are shown in Fig. 7 and Fig. 8.

4.2 TEST OF CASE III

The frequency response test of the system controlled by the bob of seismograph placed on the structure was carried out, in the case of f_o = 0.4 c/sec, $\zeta = 0.42$, K = 215. The results of test are shown in Fig. 14. The experimental results agree fairly with the theoretical calculations. Transmissibilities of displacement of isolated table are very small for the frequency to be isolated, but as shown Fig. 17', remarkable drifting were recognized.

4.3 TEST OF CASE IV

The frequency response test of the system controlled by the bob of seismograph placed on the structure with neutral compensation was carried out, in the case of f_o = 0.4 c/sec, $\zeta = 0.42$, K = 215, K' = 0.047. The result of test are shown in Fig. 19, 20 and 24. The result of test shows good coincidence with the result of theoretical calculation.

As shown in Fig. 24, drifting of the isolated table is recognized but is minimized effectively by the existence of gain constant of neutral detector K'.

And in the experiment, this drifting curve have long period of about 15 second and a certain damping ratio. This interesting fact point out that the isolated table by servomechanism has a certain long period and damping ratio, and these dynamic characteristics have relation to response diagram of y' (displacement of center of gravity of the bob of seismograph) as shown in Fig. 30. This response diagram shows that seismograph placed on the table isolated by servomechanism has aparently long period. (See §5, 5.1)

4.4 RESPONSE DIAGRAM (OF CASE IV) FOR IRREGULAR VIBRATION OF SHAKING TABLE

Irregular vibration of shaking table as shown Fig. 30 was imparted by means of vibrator which was driven by electromagnetic force. Response diagram of displacement of isolated table shows desirable dynamic characteristics of the apparatus.

§5 APPLICATION OF EARTHQUAKE ISOLATION APPARATUS BY A HIGH SPEED ELECTROHYDRAULIC SERVOMECHANISM

5.1 APPLICATION TO SEISMOGRAPH

The natural period of seismograph should be sufficiently longer than the fundamental period of the ground motion of earthquake. Accordingly, the pendulum of these apparatus has designed to have as long natural period as possible.

To make easy the design of the seismograph having extremely long natural period, we can apply the earthquake isolated table by servomechanism described in CASE IV as the supporting table of the seismograph. These seismograph may be called "Servo-Seismograph". Possibility of making the servo-seismograph may be recognized from frequency response of Y' (displacement of center of gravity of bob of seismograph) in the isolated apparatus as shown in Fig. 30.

In Fig. 30, dotted curves are frequency response of Y' of seismograph itself and other curves are frequency response of Y' of seismograph placed on the table isolated by servomechanism. We know by Fig. 30 that natural frequency f_0 of seismograph itself is 0.4 c/sec but natural frequency f of seismograph placed on the earthquake isolated table is apparently 0.1 - 0.07 c/sec. Therefore the natural frequency of servoseismograph is remarkably reduced as compared with the natural frequency of the seismograph itself. In such a case, approximate natural frequency and damping ratio of servoseismograph may be expressed as follows.

NATURAL FREQUENCY AND DAMPING RATIO OF SERVOSEISMOGRAPH

In CASE IV, transfer function G(S) of Y' is as follows.

$$G(S) = \frac{Y'}{X}$$

$$= \frac{\omega_n^2 S + \omega_n^2 KK'}{S^3+(2\zeta\omega_n+KK'+K)S^2+(\omega_n^2+2\zeta\omega_n KK'+2\zeta\omega_n K)S+\omega_n^2 KK'} \qquad (5.1)$$

If we consider low frequency and neglect $\omega_n^2 S$, S^3 and $2\zeta\omega_n$, G(S) is

$$G(S) = \frac{\omega_n^2 KK'}{(KK'+K)S^2+(\omega_n^2+2\zeta\omega_n KK'+2\zeta\omega_n K)S+\omega_n^2 KK} \qquad (5.2)$$

putting, $_s\omega_n = \eta\,\omega_n = \sqrt{\frac{K'}{1+K'}}\cdot\omega_n$

$$G(S) = \frac{_s\omega_n^2}{S^2 + 2\,_s\omega_n\left(\frac{\eta\,_s\omega_n}{2KK'} + \frac{\zeta}{\eta}\right)S + {_s\omega_n}^2} \qquad (5.3)$$

Then transfer function of the servoseismograph may be approximately considered as the function of second order system such as seismograph itself and natural angular frequency ${}_s\omega_n$ and damping ratio ${}_s\zeta$ of servoseismograph is as follows.

$$ {}_s\omega_n = \sqrt{\frac{K'}{1+K'}}\,\omega_n = \eta \cdot \omega_n \qquad (5.4)$$

$$ {}_s\zeta = \frac{\eta \cdot \omega_n}{2KK'} + \frac{\zeta}{\eta} \qquad (5.5)$$

η may be called "frequency reduction factor".

For example in the case of $f_o = 0.4$ c/s, $K = 215$, $K' = 0.03$, $\zeta = 0.42$

$$\eta = \sqrt{\frac{K'}{1+K'}} = \sqrt{\frac{0.03}{1+0.03}} = 0.17,$$

$$f = 0.17 \times 0.4 \text{ c/s} = 0.068 \text{ c/s}$$

Natural period of servoseismograph = 14.7 sec.

Otherhand, period of drifting curve of tested earthquake isolated table is about 15 sec. as shown in Fig. 24. Experimental result agrees with theoretical calculation.

As mentioned above, we can make easy the design of the seismograph having extremely long natural period.

To simplify the explanation, horizontal servoseismograph is considered above, but the vertical servoseismograph is also explained quite similarly.

Further study on the theoretical and experimental aspect of servoseismograph is in progress and research is scheduled to be completed in near future.

5.2 APPLICATION TO STRUCTURES

In §1 – §4, we already explained the principle and the theory of the earthquake isolation method by servomechanism and discussed the dynamic characteristics and experimental results of this system.

From above results, we believe that these apparatus may be suitable for the earthquake isolation of structures, because these apparatus have the excellent dynamic characteristics for the isolation of vibration with low frequency.

But to apply these apparatus, to the structures in large size, much effort will be necessary in future. It will require further study of the theoretical and practical aspect of the system to design and construct an apparatus large enough to be applied to structures.

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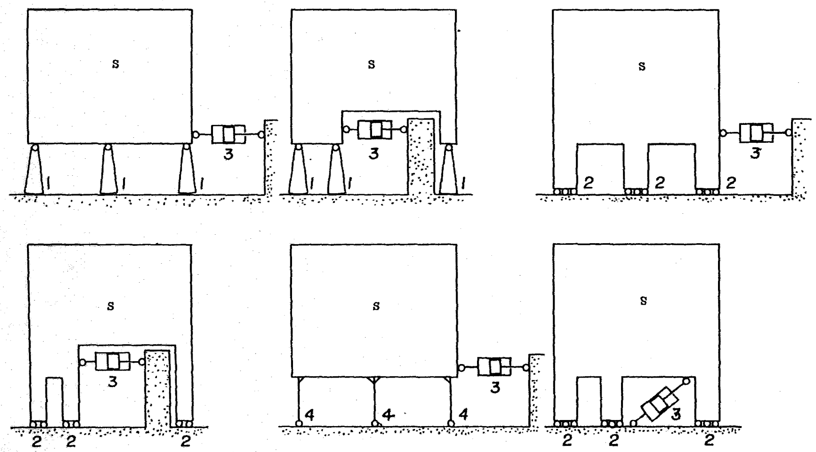


FIG. 1. APPLICATION ON STRUCTURES OF EARTHQUAKE ISOLATION SYSTEM BY THE HIGH SPEED ELECTROHYDRAULIC SERVOMECHANISM

1: COLUMN SUPPORTING VERTICAL LOAD; UPPER END BALL HING AND LOWER END IS SPHERICAL SURFACE
2: BALL BEARING
3: HORIZONTALLY SUPPORTING MEMBER WITH ACTUATOR
4: COLUMN SUPPORTING VERTICAL LOAD AND HAVING VERY FLEXIBLE ELASTICITY FOR BASE SHEAR

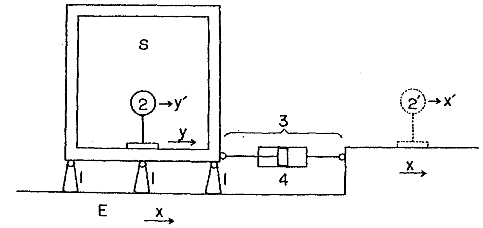


FIG. 2A SCHEMATIC DIAGRAM ON PRINCIPLE OF EARTHQUAKE ISOLATION SYSTEM OF STRUCTURES BY THE HIGH SPEED ELECTRO HYDRAULIC SERVOMECHANISM

S: STRUCTURE, E: GROUND OR STRUCTURE IN CONTACT WITH GROUND

1: COLUMN 2: SEISMOGRAPH
3: HORIZONTALLY SUPPORTING MEMBER WITH ACTUATOR
4: ACTUATOR WITH SERVOVALVE 5
X, Y, Y': DISPLACEMENT OF GROUND, *STRUCTURE AND CENTER OF GRAVITY* OF THE BOB RESPECTIVELY

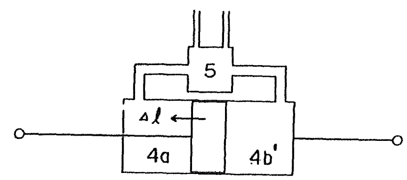


FIG. 2B SCHEMATIC DIAGRAM OF SERVOVALVE AND ACTUATOR

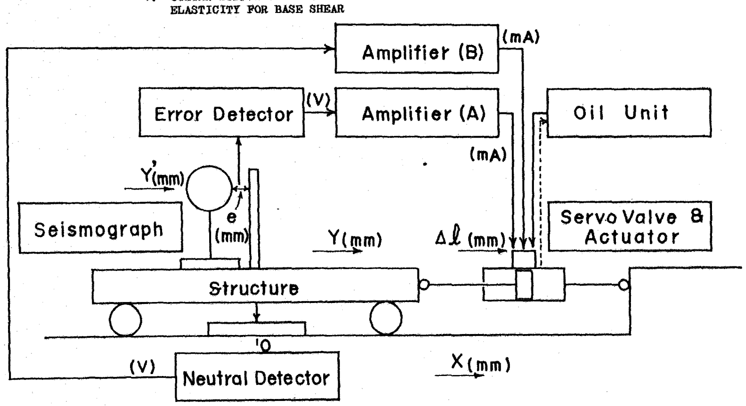
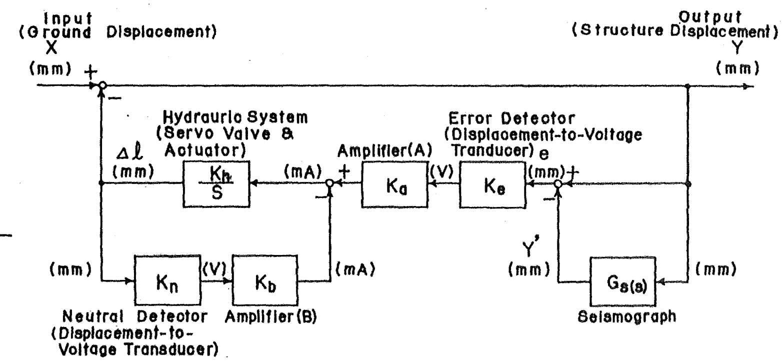


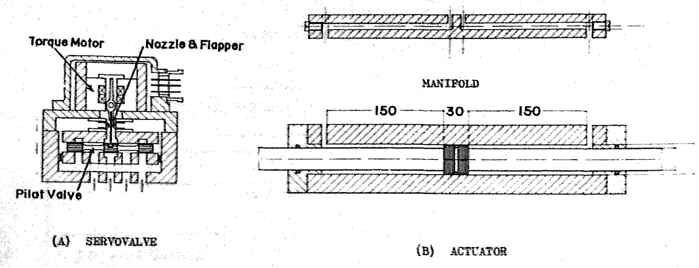
FIG. 3A TOTAL SCHEMATIC DIAGRAM OF EARTHQUAKE ISOLATION APPARATUS BY THE HIGH SPEED ELECTRO-HYDRAULIC SERVOMECHANISM

X: DISPLACEMENT OF GROUND
Y: DISPLACEMENT OF EARTHQUAKE ISOLATED STRUCTURE



$G_s(s) = \frac{\omega_n^2}{S^2+2\zeta\omega_n S+\omega_n^2}$, $K_e \times K_a \times K_h = 215$, $\frac{K_n \times K_b}{K_e \times K_a} = 0.03$, $K_e = 1.6 \times 1.12 = 2$, $K_a = 2.5$, $K_h = 48$, $K_n = 0.015$ $K_b = 8.7$, $\zeta = 0.42$, $\omega_n = 2\pi f_n = 2.5$

FIG. 3B BLOCK DIAGRAM OF EARTHQUAKE ISOLATION APPARATUS BY THE HIGH SPEED ELECTRO HYDRAULIC SERVOMECHANISM



(A) SERVOVALVE

(B) ACTUATOR

FIG. 4. SERVOVALVE AND ACTUATOR

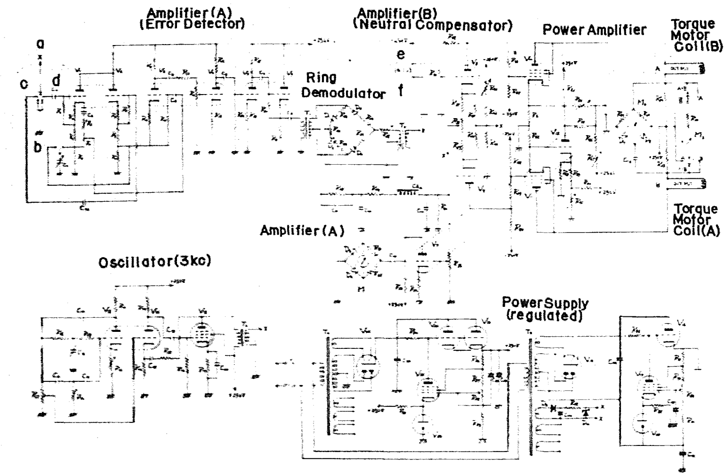


FIG. 5A CIRCUIT DIAGRAM OF THE ERROR DETECTOR, AND THE AMPLIFIER FOR THE TORQUE MOTOR IN THE SERVOVALVE AND NEUTRAL COMPENSATOR.

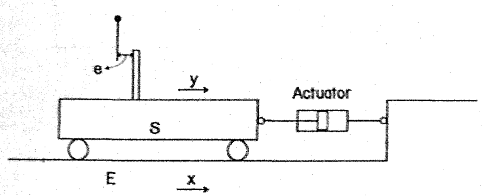


FIG. 6A SCHEMATIC DIAGRAM OF SYSTEM CONTROLLED BY THE IMMOVABLE POINT

X: DISPLACEMENT OF GROUND
Y: DISPLACEMENT OF EARTHQUAKE ISOLATED STRUCTURE

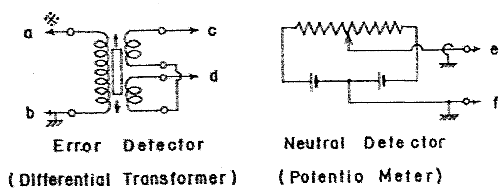


FIG. 5B SCHEMATIC DIAGRAM OF ERROR DETECTOR AND NEUTRAL DETECTOR

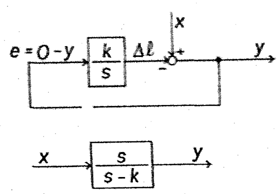


FIG. 6B BLOCK DIAGRAM

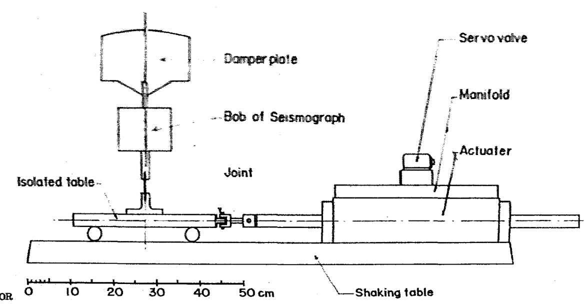


FIG. 5C SCHEMATIC DIAGRAM OF TESTED APPARATUS.

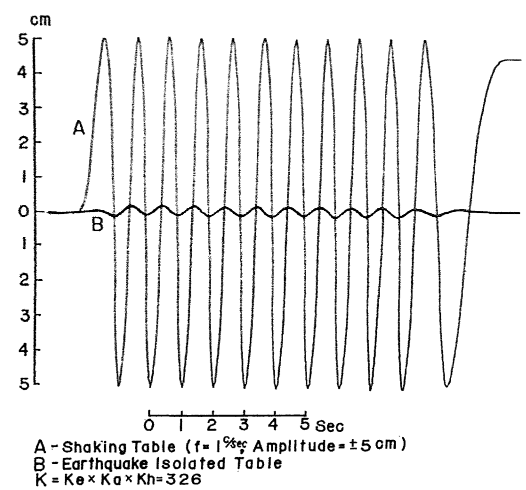


FIG. 9. RESPONSE OF DISPLACEMENT OF THE ISOLATED TABLE AGAINST SHAKING TABLE HAVING AMPLITUDE 10 CM AND FREQUENCY 1 C/SEC.

E : ERROR
K/S : TRANSFER FUNCTION OF ERROR DETECTOR; SERVOVALVE AND ACTUATOR
Δl : DISPLACEMENT OF PISTON IN ACTUATOR
S : LAPLACE VARIABLE

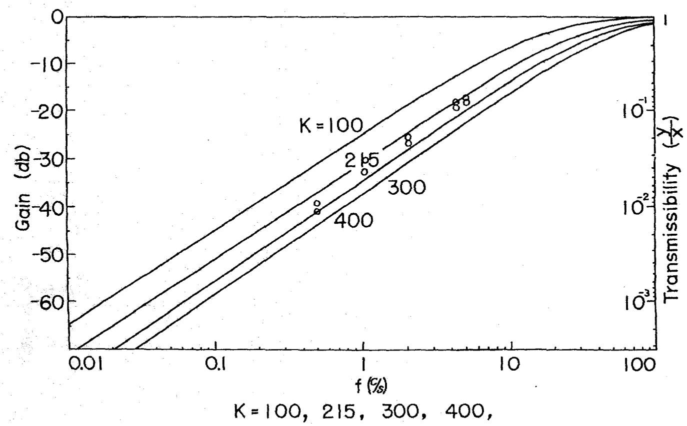


FIG. 7. FREQUENCY RESPONSE OF Y IN THE SYSTEM CONTROLLED BY THE IMMOVABLE POINT

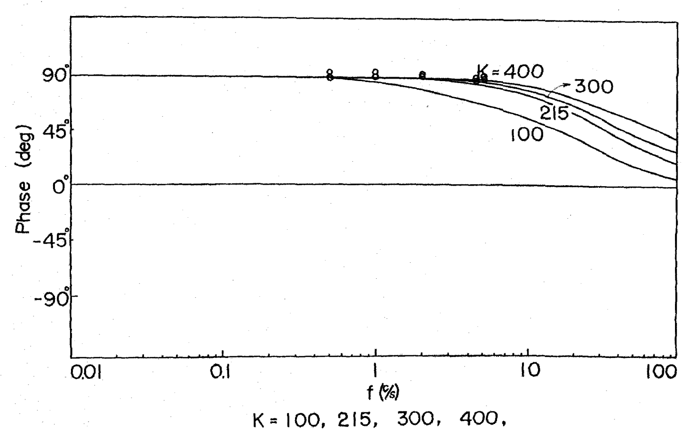


FIG. 8. FREQUENCY RESPONSE OF PHASE LAG

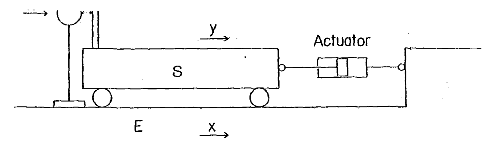


FIG. 10A SCHEMATIC DIAGRAM OF SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE GROUND

E = ERROR = X' − Y

X': DISPLACEMENT OF CENTER OF GRAVITY OF THE BOB OF SEISMOGRAPH SET ON THE GROUND

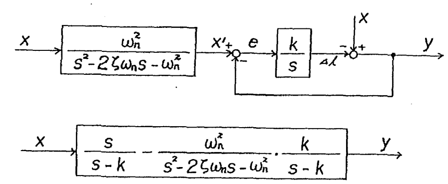


FIG. 10B BLOCK DIAGRAM OF SYSTEM

E : ERROR
ω_n : NATURAL ANGULAR FREQUENCY OF SEISMOGRAPH

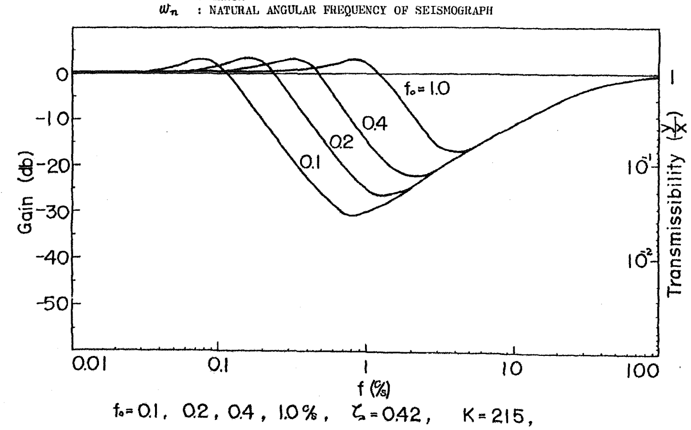
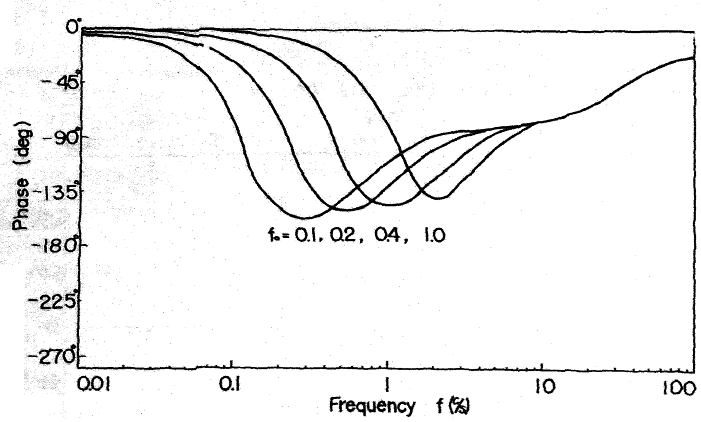


FIG. 11. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE GROUND



f_o = 0.1, 0.2, 0.4, 1.0 %, ζ = 0.42, K = 215.

FIG. 12. FREQUENCY RESPONSE OF PHASE LAG

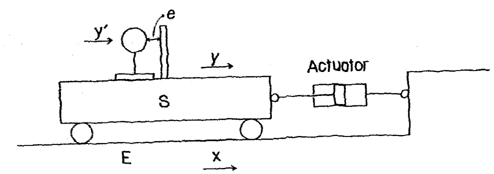


FIG. 13A SCHEMATIC DIAGRAM OF SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE

E: ERROR = Y - Y'

Y': DISPLACEMENT OF CENTER OF GRAVITY OF THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE

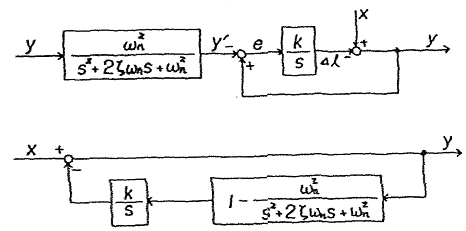
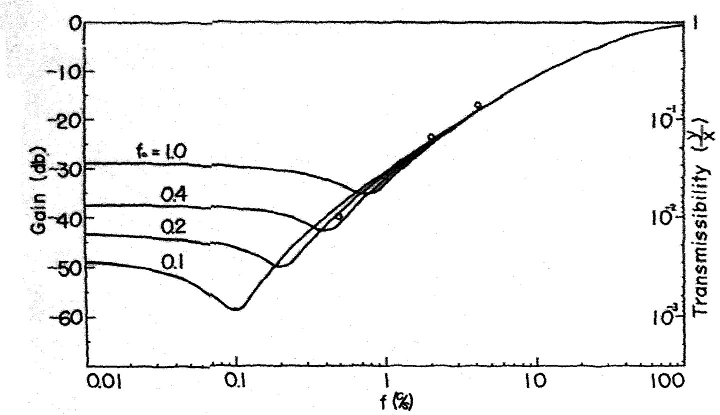


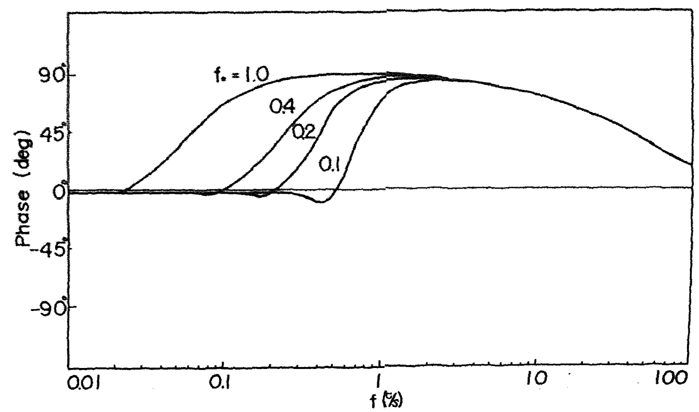
FIG. 13B BLOCK DIAGRAM



f_o = 0.1, 0.2, 0.4, 1.0 %, ζ = 0.42, K = 215.

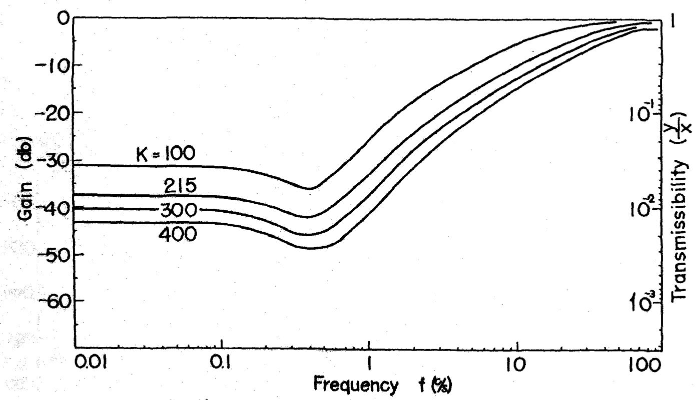
FIG. 14. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE

EFFECT OF FREQUENCY OF SEISMOGRAPH



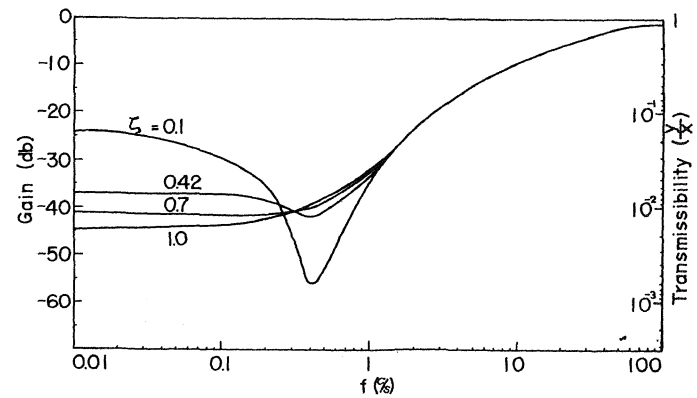
f_o = 0.1, 0.2, 0.4, 1.0 %, ζ = 0.42, K = 215.

FIG. 15. FREQUENCY RESPONSE OF PHASE LAG



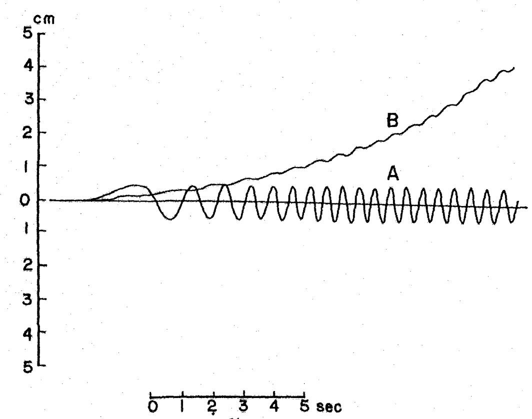
f_o = 0.4 c/s, ζ = 0.42, K = 100, 215, 300, 400,

FIG. 16. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE



f_o = 0.4 c/s, ζ = 0.1, 0.42, 0.7, 1.0, K = 215,

FIG. 17. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLE BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE



A - Shaking Table (f = 2 c/sec Amplitude = ±0.6 cm)
B - Earthquake Isolated Table
K = $K_e \times K_a \times K_h$ = 215 , f_o = 0.4 c/sec , ζ = 0.42

FIG. 17' RESPONSE OF DISPLACEMENT OF THE ISOLATED TABLE AGAINST SHAKING TABLE HAVING AMPLITUDE 12.5mm AND FREQUENCY 2 C/SEC.
REMARKABLE DRIFTING IS RECOGNIZED

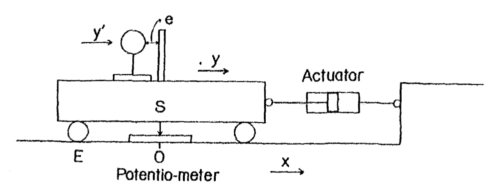
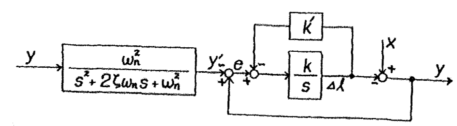


FIG. 18A SCHEMATIC DIAGRAM OF SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE (WITH NEUTRAL COMPENSATION)



K': GAIN CONSTANT OF NEUTRAL DETECTOR

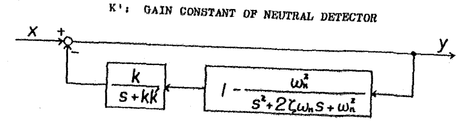
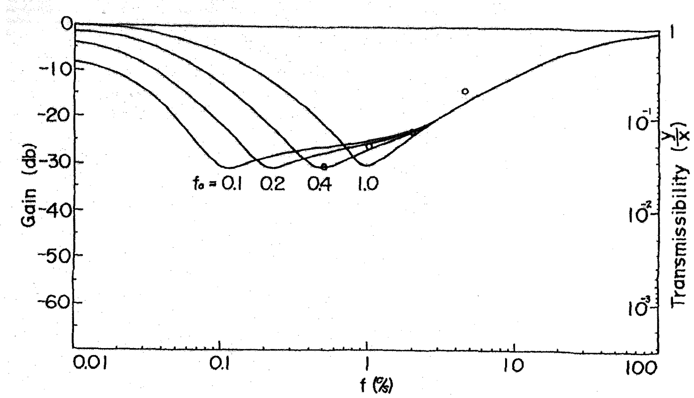


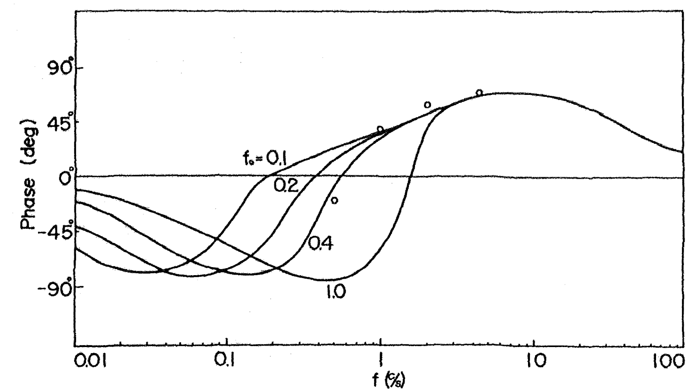
FIG. 18B BLOCK DIAGRAM



f_o = 0.1, 0.2, 0.4, 1.0 %, ζ = 0.42, K = 215, K′ = 0.047,

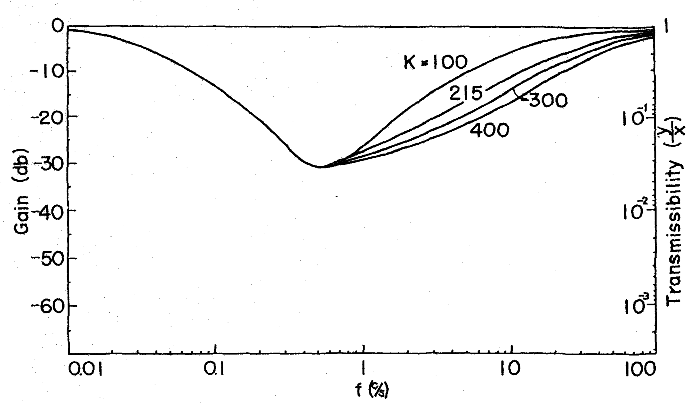
FIG. 19. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE (WITH NEUTRAL COMPENSATION)

EFFECT OF FREQUENCY OF SEISMOGRAPH



f_o = 0.1, 0.2, 0.4, 1.0 %, ζ = 0.42, K = 215, K′ = 0.047

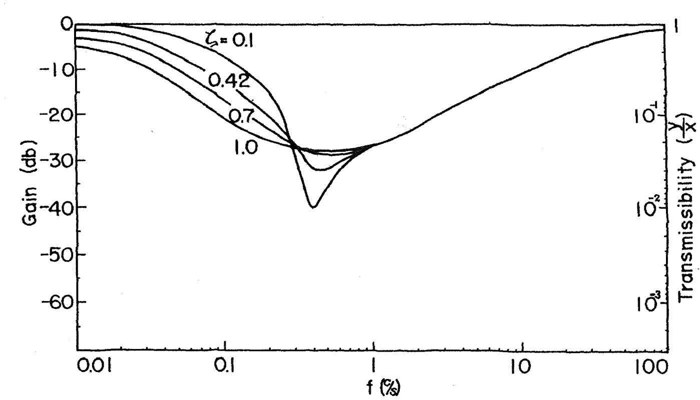
FIG. 20. FREQUENCY RESPONSE OF PHASE LAG IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON STRUCTURE (WITH NEUTRAL COMPENSATION)



f_o = 0.4 %, ζ = 0.42, K = 100, 215, 300, 400, K′ = 0.047,

FIG. 21. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE (WITH NEUTRAL COMPENSATION)

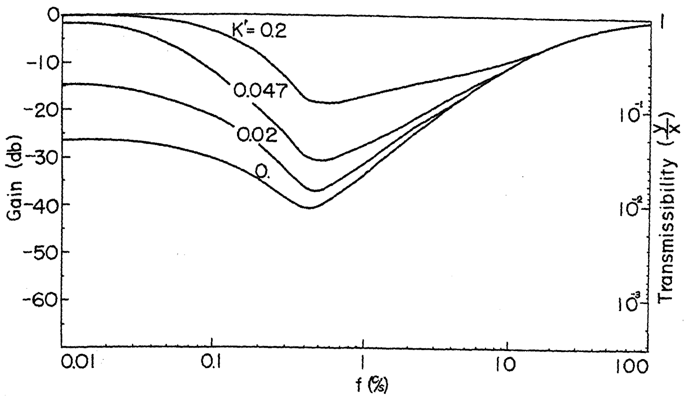
EFFECT OF K



f_o = 0.4 %, ζ = 0.1, 0.42, 0.7, 1.0, K = 215, K′ = 0.047,

FIG. 22. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE (WITH NEUTRAL COMPENSATION)

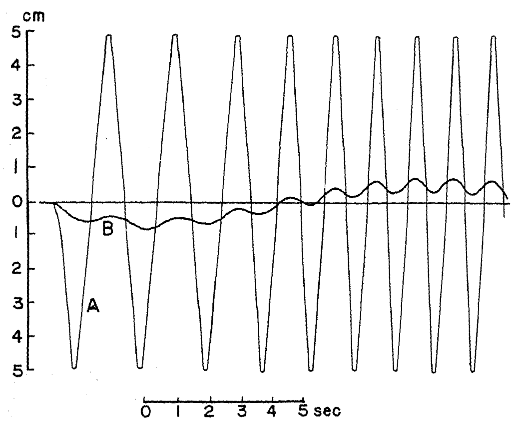
EFFECT OF ζ



f_o=0.4c/s, ζ =0.42, K=215, K'=0, 0.02, 0.047, 0.2.

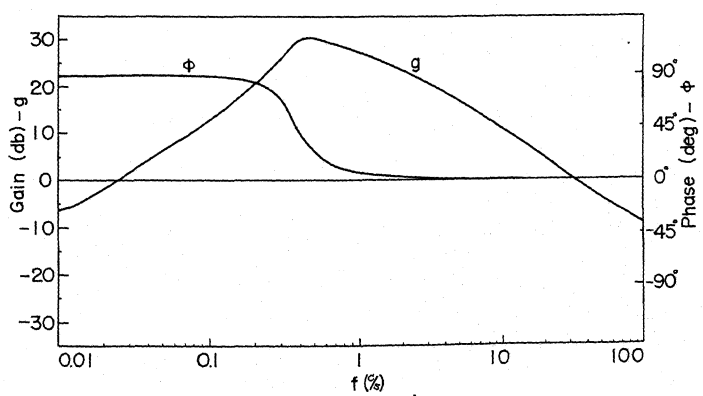
FIG. 23. RESPONSE DIAGRAM OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE (WITH NEUTRAL COMPENSATION)

EFFECT OF K'



A - Shaking Table (f = 1c/sec, Amplitude = ±5 cm)
B - Earthquake Isolated Table
$K = K_e \times K_a \times K_h = 215$, $f_o = 0.4$ c/sec
$K' = \frac{K_n \times K_b}{K_e \times K_a} = 0.03$, $\zeta = 0.42$

FIG. 24 RESPONSE OF DISPLACEMENT OF THE ISOLATED TABLE AGAINST SHAKING TABLE HAVING AMPLITUDE 10 CM AND FREQUENCY 1 C/SEC.
DRIFTING IS LITTLE RECOGNIZED



f_o=0.4c/s, ζ=0.42, K=215, K'=0.047,

FIG. 25. BODE DIAGRAM OF LOOP TRANSFER FUNCTION OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON THE STRUCTURE (WITH NEUTRAL COMPENSATION)

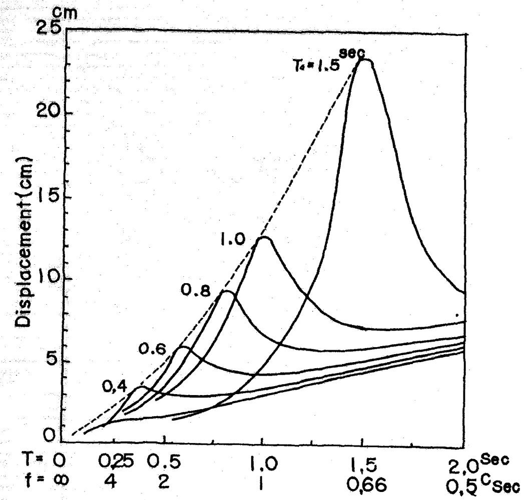


FIG. 26. THE SPECTRUM OF STRONG EARTHQUAKE MOTION AT GROUND SURFACE (BY KIYOSHI KANAI)

T_0 : PREDOMINANT PERIOD OF GROUND OF RICHTER MAGNITUDE 8 AND EPICENTRAL DISTANCE 50 KM

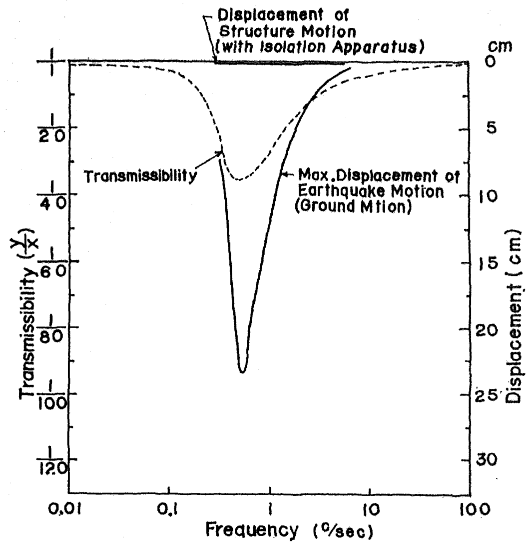
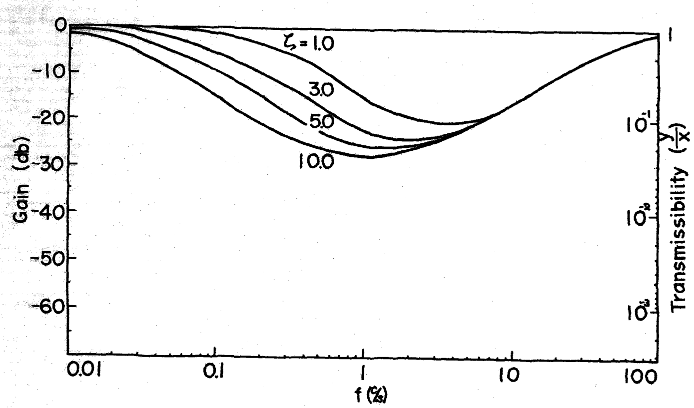
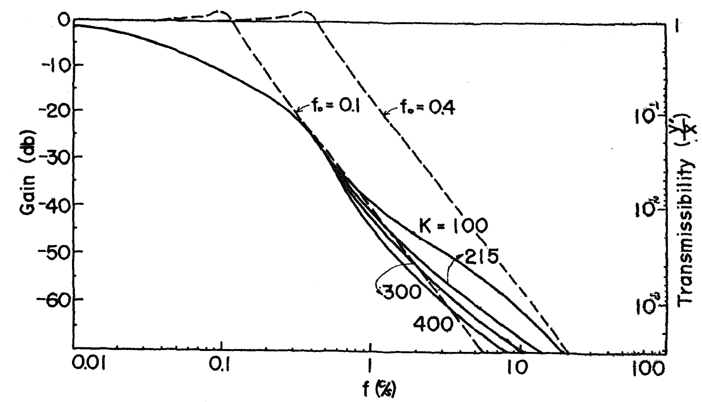


FIG. 27. ONE EXAMPLE OF ISOLATION RESULT OF STRONG EARTHQUAKE MOTION.



f_0 = 10.0 c/s, ζ = 1.0 , 3.0 , 5.0 , 10.0 , K = 400 , K' = 0.035 ,

FIG. 28. FREQUENCY RESPONSE OF Y IN THE SYSTEM CONTROLLED BY THE BOB OF ACCELEROGRAM SET ON STRUCTURE (WITH NEUTRAL COMPENSATION)



f_0 = 0.4 c/s, ζ = 0.42 , K = 100 , 215 , 300 , 400 , K' = 0.047 ,

FIG. 30. FREQUENCY RESPONSE OF Y' IN THE SYSTEM CONTROLLED BY THE BOB OF SEISMOGRAPH SET ON STRUCTURE (WITH NEUTRAL COMPENSATION)

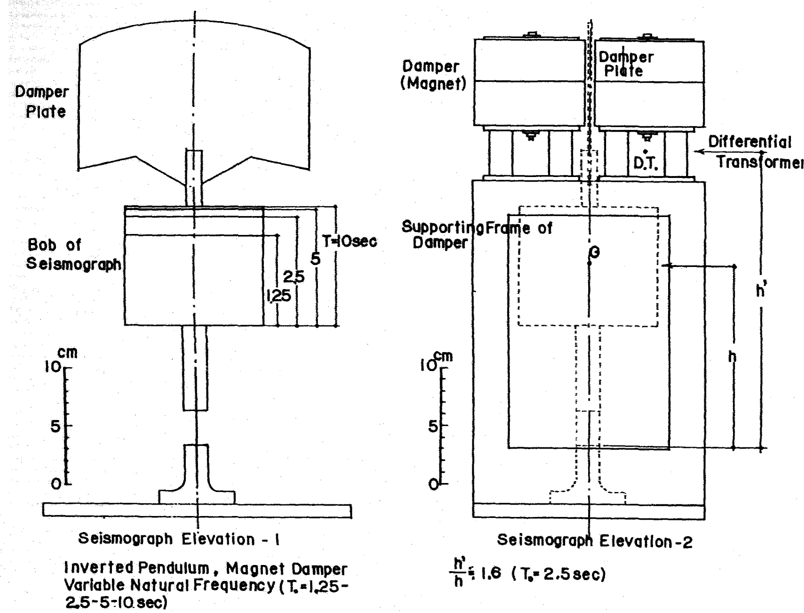


FIG. 29 TESTED SEISMOGRAPH

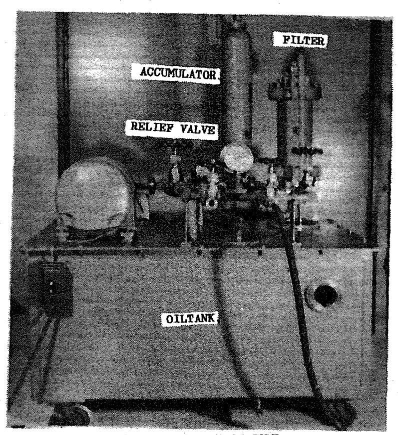


PHOTO. 1 TESTED PUMP.

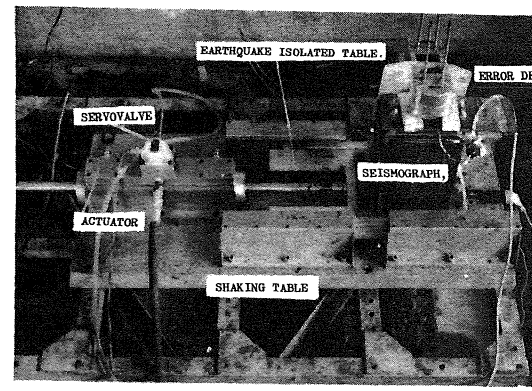


PHOTO 2 TESTED EARTHQUAKE ISOLATION APPARATUS BY THE HIGH SPEED ELECTRO-HYDRAULIC SERVOMECHANISM

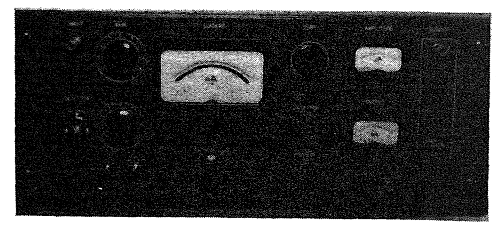


PHOTO. 3 AMPLIFIER OF ERROR DETECTOR, NEUTRAL DETECTOR AND TORQUEMOTOR OF SERVOVALVE

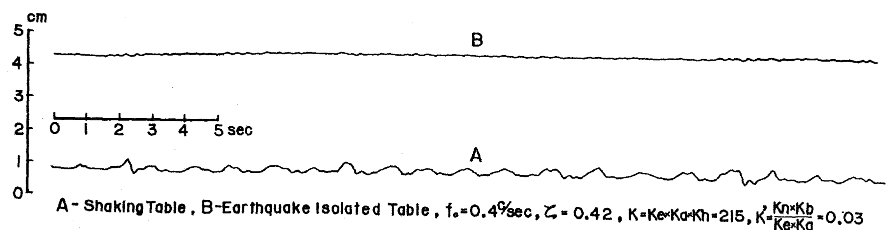


FIG. 31 RESPONSE OF DISPLACEMENT OF ISOLATED TABLE AGAINST SHAKING TABLE HAVING IRREGULAR MOTION