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REDUCTION OF SEISMIC RESPONSE OF MECHANICAL SYSTEM BY FRICTION TYPE BASE ISOLATION SYSTEM

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Reduction of seismic response of mechanical system is important problem for aseismic design. In order to reduce seismic response, two types of devices have been developed. One type is devices which are attached or installed in structures. Tuned mass dampers are representative one. The other type is base isolation systems. Some types of base isolation systems are developed and used in actual base of buildings and floors in buildings. For example, rubber bearing and viscoelastic damper are used for base isolation system. In this paper, a base isolation system utilizing friction and restoring force of bearing is proposed. This bearing is used for reduction of mechanical systems, for example, console of electrical equipment on the floor. This bearing consists of two plates having spherical holes and oval type metal or spherical metal with rubber. One of two plates is on the floor of building (input) and the other is on the base of mechanical system (response).First, effectiveness of the base isolation system is examined experimentally. For fundamental experiment, a weight is set on the plate for the base of mechanical system. The plate on the floor of building is shaken on the shaking table. Acceleration of input and response are measured. Some types of input acceleration are used. The maximum value, squared sum value and Fourier spectrum of input and response are obtained. The maximum value of response is reduced by 50% compared with input. Sum of square of response is about 2% of that of input. Fourier spectrum is significantly reduced in almost of all frequency regions, except for very low frequency region. The plate for the base of mechanical system stopped at original position because restoring force acted.Next, in order to examine reduction of seismic response of actual mechanical system, a console is set on the plate. Acceleration of input and response are measured. The maximum value of response is reduced by 50% compared with input. Squared sum value of response is about 2% of that of input. Fourier spectrum is significantly reduced in almost of all frequency regions, except for very low frequency region. Acceleration of the top of the console is also measured. Acceleration is also significantly reduced.Finally, obtained results of experiment are examined by simulation method. An analytical model considering friction and restoring force is used. Using input same as experiment, response is obtained by numerical method. From simulation method, effectiveness of the proposed base isolation system is demonstrated.

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概 要
ACMDは，マルチボディシステムのダイナミクス，制御，および設計に携わるアジアと欧米の研究者ならびに技術者が一堂に会して情報交流を行うことを目的に，日本機械学会および韓国機械学会が企画した国際会議である．第1回会議はいわき明星大学にて開催され，第2回会議はソウル（韓国）にて開催された．第3回会議となるACMD2006では，下記のトピックスに関する最新の研究成果の発表と，日本および海外の著名な研究者によるキーノートスピーチが予定されている．

トピックス
Multibody system analysis／Rigid and flexible multibody dynamics／Modeling, formalisms, and DAE solution method／High performance formalisms and computation／Kinematics／Vehicle dynamics／Contact, impact, and friction／Rail-wheel contact problems／Control of MBS／Motion and vibration control／Robotics and mechatronics／Biomechanics／Visualization／Dynamic strength evaluation for MBS／Parameter identification／Optimization and sensitivity analysis in MBS／Electro-magnetic interactions in MBS／CFD interactions／Aerospace dynamics

使用言語
英語

REDUCTION OF SEISMIC RESPONSE OF MECHANICAL SYSTEM BY FRICTION TYPE BASE ISOLATION SYSTEM

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ABSTRACT

Reduction of seismic response of mechanical system is important problem for aseismic design. Some types of base isolation systems are developed and used in actual base of buildings and floors in buildings for reduction of seismic response of mechaninical system. In this paper, a base isolation system utilizing bearing with friction and restoring force of bearing is proposed. Friction bearing consists of two plates having spherical concaves and oval type metal or spherical metal with rubber. First, effectiveness of the base isolation system is examined experimentally. Using artificial time histories, the isolated table is shaken on the shaking table. The maximum value of response is reduced and sum of squares of response is significantly reduced. Fourier spectrum is significantly reduced in almost of all frequency regions, except for very low frequency region. Next, in order to examine reduction of seismic response of actual mechanical system, a console rack is set on the isolated plate. Seismic response is also significantly reduced. Finally, obtained results of experiment are examined by simulation method. An analytical model considering friction and restoring force is used. From simulation method, effectiveness of the proposed base isolation system is demonstrated.

1. INTRODUCTION

Reduction of seismic response of mechanical system is important problem for aseismic design. In order to reduce seismic response, two types of devices have been developed. One type is devices which are attached or installed in structures. Tuned mass damper is representative one (Soong and Dargush 1997). The other type is base isolation systems. Some types of base isolation systems are developed and used in actual base of buildings and floors in buildings. For example, rubber bearing and viscoelastic damper are used for base isolation system (Chen et al. 2004).

In this paper, a base isolation system utilizing friction and restoring force of bearing is proposed. This bearing is used for reduction of mechanical systems, for example, console of electrical equipment on the floor. This bearing consists of two plates having spherical concaves and oval type metal or spherical metal with rubber. One of two plates is on the floor of building (input) and the other is on the base of mechanical system (response).

First, effectiveness of the base isolation system is examined experimentally. For fundamental experiment, a weight is set on the plate for the base of mechanical system. The plate on the floor of building is shaken on the shaking table. Acceleration of input and response are measured. Some types of input acceleration are used. The maximum value, sum of squares and Fourier spectrum of input and response are obtained. The maximum value of response is reduced and sum of squares of response is significantly re duced. Fourier spectrum is significantly reduced in almost of all frequency regions, except for very low frequency region. The table for the base of mechanical system stopped at original position because restoring force acted.

Next, in order to examine reduction of seismic respons e of actual mechanical system, a console r a c k is set on the plate. Acceleration of input and response are m easured. The maximum value of response is reduced and s um of squares of response is significantly reduce d. Fourier spectrum is significantly reduced in almost of all frequency regions, except for very low frequency region.

Finally, obtained results of experiment are examined by simulation method. An analytical model considering friction and restoring force is used. Using input same as experiment, response is obtained by numerical method. From simulation method, effectiveness of the proposed base isolation system is demonstrated.

2. EXPERIMENT USING OVAL METAL

For reduction of seismic response, bearing is used. This bearing consists of two plates having spherical concaves and oval type metal.

2.1 Friction Bearing

Figure 1 shows friction bearing. This bearing consists of two plates having spherical concaves and oval type metal (marble plate). One of two plates is fixed on the shaking table and the other is fixed under the table for the base of mechanical system (isolated table). Shape of plate is square and length of 250mm and thickness of edge is 40mm. Radius of concave is 250mm. Figure 2 shows a marble plate. Height of the center of plate is 35mm and width is 96mm. Height of edge of plate is 5mm. In this system, marble plate slides between two plates and vibration of the shaking table is transmitted to the isolated plate via marble plate. Natural frequency of the system depends on radius of concaves and restoring force is generated in case of uplift of marble plate. Then, marble plate returns to the original position.

2.2 Experimental Setup

Size of the shaking table is 1600mm length, 860mm width and 60mm thickness. Friction bearings are set on the four corners. Isolated table is set on the four friction bearings. Size of isolated table is same as shaking table. Acceleration of shaking table, that is, input earthquake excitation and that of isolated table are measured by accelerometers.

2.3 Input Earthquake Excitation

As input excitation, an artificial time history is used. Input excitation is given as acceleration record. Figure 3(a) shows time history of input acceleration. Figure 3(b) shows

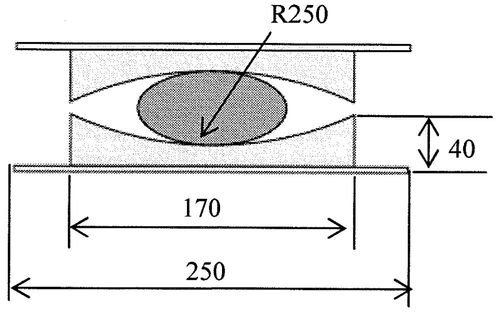


Fig. 1 Friction bearing (mm)

(Spherical plate and marble plate)

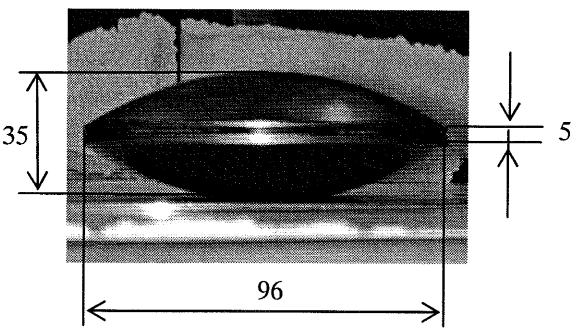


Fig. 2 Marble plate (mm)

Fourier spectrum of input excitation. The aim of the study is reduction of seismic response of mechanical systems. Then Fourier spectrum of input excitation has the peak at about 10Hz. The natural frequency of actual mechanical system is about near 10Hz.

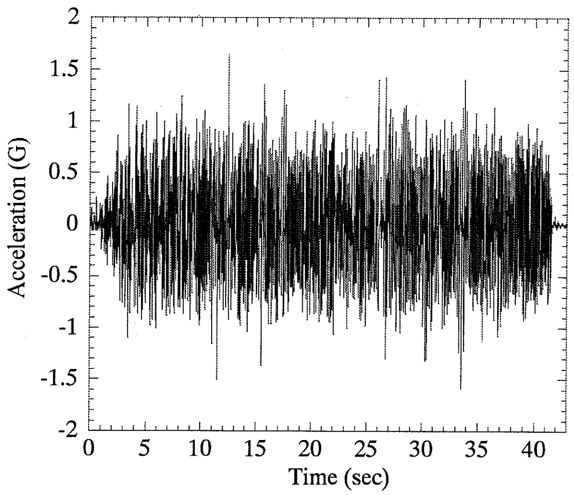
2.4 Conditions of Experiment

The system is shaken horizontally. Effect of grease on reduction of seismic response is examined. In order to simulate actual mechanical system, 8 weights of which length is 600mm, width is 300mm and thickness is 100mm and weight is 280kg are put on the center of the isolated table.

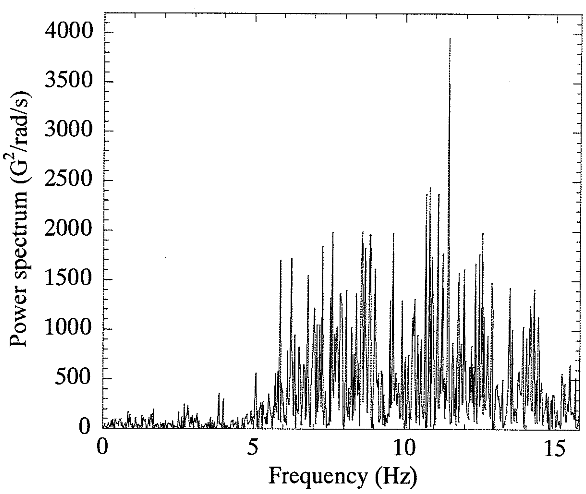
2.5 Results of Experiment

In Figure 4(a), time history of response of the isolated table without grease is shown. Figure 4(b) shows Fourier spectrum of time history shown in Fig.4(a). Comparing Fig.3(a) with Fig4(a), acceleration of response is much less than input excitation. Comparing Fig.3(b) with Fig.4(b), Fourier spectrum of the response is much less than that of input excitation except in low frequency range. In low frequency range, Fourier spectrum of the response is same as that of input excitation.

In Table 1, the maximum values of response and input are shown. In Table 2, sum of squares of response and input are shown. From those tables, the maximum response and sum of squares of response are significantly reduced

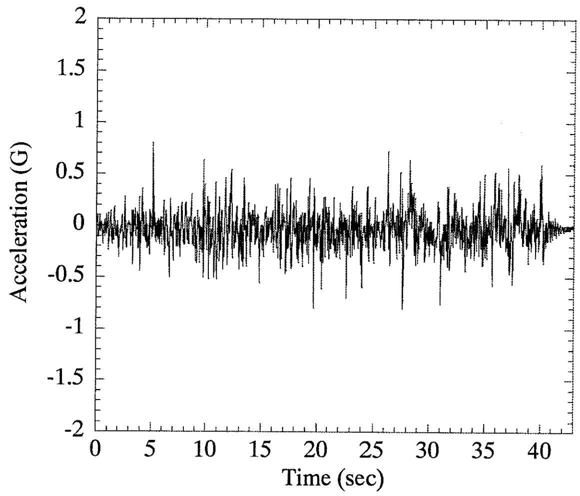


(a) Time history

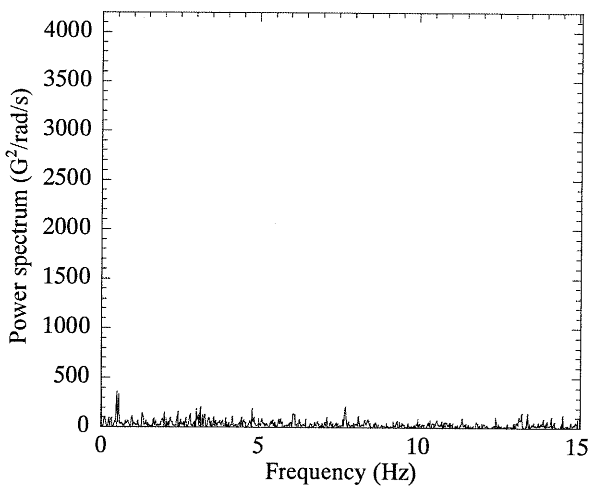


(b) Fourier spectrum

Fig.3 Input earthquake excitation



(a) Time history



(b) Fourier spectrum

Fig.4 Response of isolated plate

Table 1 Maximum acceleration

	Non-grease	Grease
Input (G)	1.80	1.80
Response (G)	0.80	2.56
Response/Input	0.44	1.42

Table 2 Sum of squares of acceleration

	Non-grease	Grease
Input (secG^2)	410	410
Response (secG^2)	43.9	451
Response/Input	0.11	1.1

using the system without grease compared with those of input. However, for the system with grease, reduction effect is not obtained.

3. EXPERIMENT USING SPHERICAL METAL

For reduction of seismic response, the other type of bearing is used. This bearing consists of two plates having spherical concaves and spherical metal surrounded by rubber.

3.1 Friction Bearing

Figure 5 shows friction bearing. This bearing consists of two plates having spherical concaves and spherical metal surrounded by rubber. Shape of plate is square and length of 250mm and thickness of edge is 19mm. Radius of concave changes from 300mm to 500 continuously. Diameter of spherical metal is 36.5mm. Inner diameter of rubber is 36mm and outer diameter is 80mm. In this system, spherical metal slides between two plates and vibration of the shaking table is transmitted to the isolated plate via spherical metal. Natural frequency of the system depends on radius of concaves and restoring force is generated when

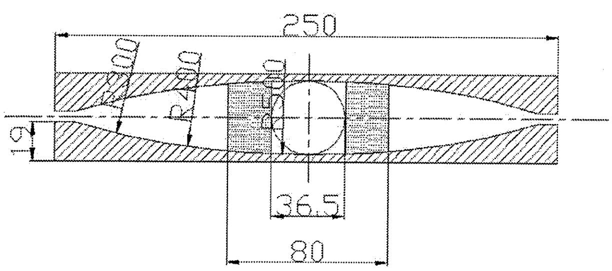


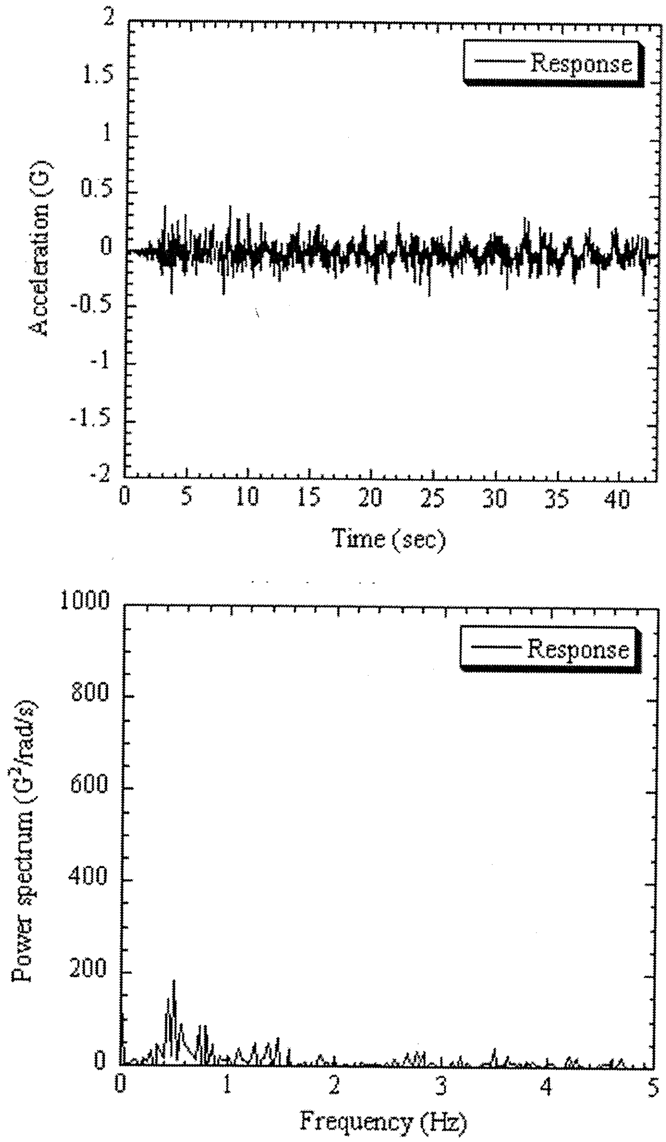
Fig.5 Friction bearing (mm)
(Spherical metal and rubber)

uplift of spherical metal. Then, spherical metal returns to the original position.

Experimental setup, input earthquake excitation and condition of experiment are same as chapter 3.

3.2 Results of Experiment

Figure 6(a) shows time history of response of the isolated table. Figure 6(b) shows Fourier spectrum of time history shown in Fig.6(a). Comparing Fig.3(a) with Fig6(a), acceleration of response is much less than input excitation. Comparing Fig.3(b) with Fig.6(b), Fourier spectrum of the response is much less than that of input excitation except in



(b) Fourier spectrum

Fig.6 Response of isolated plate

low frequency range. In low frequency range, Fourier spectrum of the response is same as that of input excitation.

In Table 3, the maximum values of response and input are shown. In Table 4, sum of squares of response and input are shown. From those tables, the maximum response and sum of squares of response are significantly reduced using the system.

4. EXPERIMENT FOR ACTUAL SYSTEM

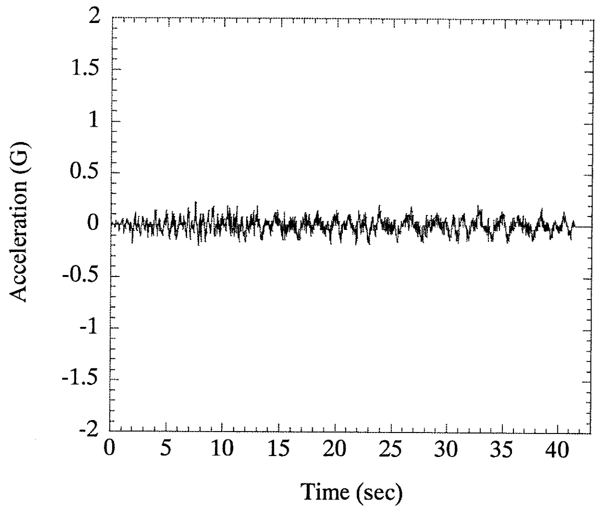
In order to examine reduction of seismic response of actual mechanical system, a console rack is used. Effect of friction bearing on reduction of response of the rack is examined.

Fig.7 Console rack

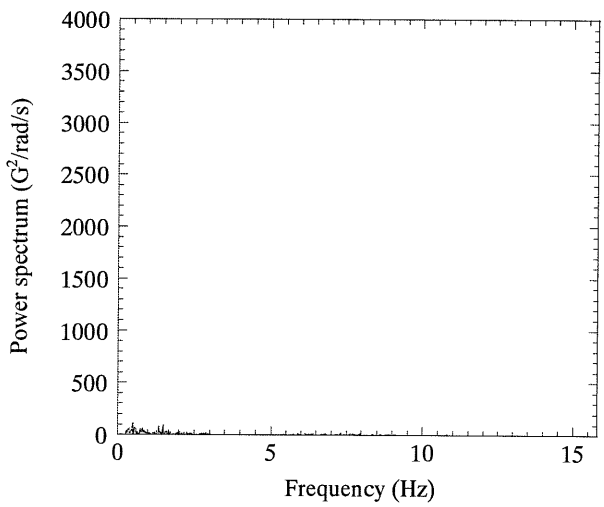
4.1 Experimental Setup

A console rack is set on the isolated table. Fig.7 shows shape and size of console rack. Height is 1850mm, width is 600mm and length is 1000mm. Weight is 210kg. Friction bearings made of spherical metal surrounded by rubber are used.

4.2 Results of Experiment



(a) Time history



(b) Fourier spectrum

Fig.8 Response of console rack

Table 3 Maximum acceleration

Input (G)	1.80
Response (G)	0.38
Response/Input	0.21

Table 5 Maximum acceleration (G)

Height of accelerometer (mm)	200
Input	1.80
Response	0.22
Response/Input	0.12

Table 4 Sum of squares of acceleration

Input (secG^2)	410
Response (secG^2)	12.0
Response/Input	0.03

Table 6 Sum of squares of acceleration (G^2s)

Height of accelerometer (mm)	200
Input	410
Response	5.94
Response/Input	0.014

Figure 8(a) shows time history of response of the isolated table. Figure 8(b) shows Fourier spectrum of time history shown in Fig.8(a). Comparing Fig.3(a) with Fig8(a), acceleration of response is much less than input excitation. Comparing Fig.3(b) with Fig.8(b), Fourier spectrum of the response is much less than that of input excitation except in low frequency range. In low frequency range, Fourier spectrum of the response is same as that of input excitation.

In Table 5, the maximum values of response and input are shown. In Table 6, sum of squares of response and input are shown. From those tables, the maximum response and sum of squares of response are significantly reduced using the system.

5. SIMULATION METHOD

Obtained results of experiment are examined by simulation method. An analytical model considering friction and restoring force is used. Analytical model and analytical method are shown.

5.1 Analytical Model

An analytical model shown in Fig.9 is used. In this model, the system is modeled as single-degree-of-freedom system. m is mass, c is damping coefficient, k is stiffness, x is absolute displacement of the isolated table. And, y is absolute displacement of the shaking table, F_r is friction force.

Equations of motion with respect to relative displacement of the isolated table to the shaking table z and is derived. When the isolated table moves to the shaking table, equations of motion is given as:

$$\ddot{z} + 2\zeta\omega_n\dot{z} + \omega_n^2 z + f = -\ddot{y} \qquad (1)$$

where $\zeta\left(= \frac{c}{2\sqrt{mk}}\right)$ is the damping ratio, $\omega\left(= \sqrt{\frac{k}{m}}\right)$ is the natural circular frequency. As friction characteristic, Coulomb friction characteristic as shown in Fig.10 is introduced. $f_r(= F_r / m)$ is acceleration corresponds to friction force. f is given as:

$$f = f_r \frac{\dot{z}}{|\dot{z}|} \qquad (2)$$

Equation (1) is given when absolute acceleration of the shaking table $\ddot{y}$ is greater than f_r. When this condition is not satisfied, the condition where the isolated table does not move to the shaking table should be considered. In this case,

$$\dot{z} = 0 \text{ and } |\ddot{y}| < f_r \qquad (3)$$

where $\ddot{y}$ is input excitation. And,

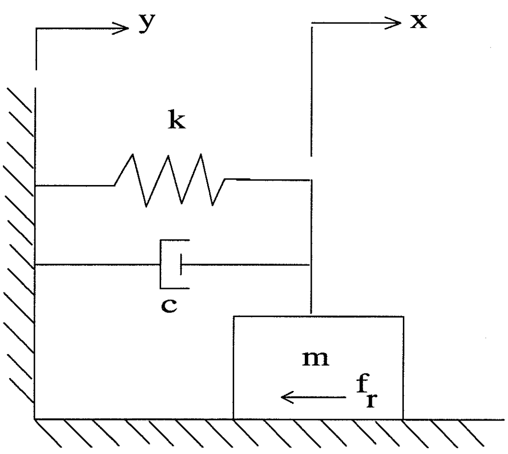


Fig.9 Analytical model

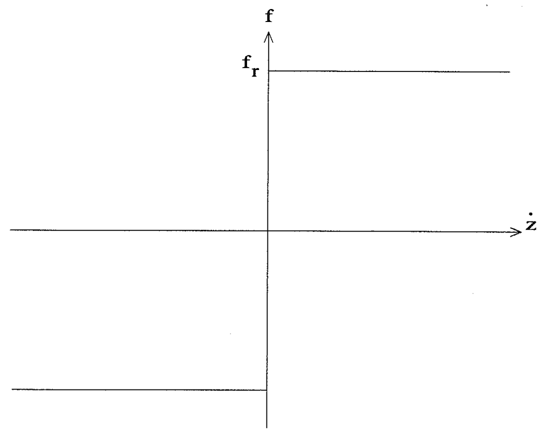


Fig.10 Coulomb friction model

$$\left.\begin{array}{l}\ddot{x}=\ddot{y}\\ \dot{z}=0\\ z=z_{st}\end{array}\right\} \qquad (4)$$

where z_{st} is displacement when Eq.(3) is satisfied. The is olated table begins to move to the shaking table when each of the following equations is satisfied.

$$\left.\begin{array}{l}\left|\ddot{y}-\omega_n{}^2 z_{st}\right| > f_r \ ;\ z_{st} > 0\ ,\ \ddot{y} > 0 \text{ or } z_{st} < 0\ ,\ \ddot{y} < 0\\ \left|\ddot{y}+\omega_n{}^2 z_{st}\right| > f_r \ ;\ z_{st} < 0\ ,\ \ddot{y} > 0 \text{ or } z_{st} > 0\ ,\ \ddot{y} < 0\end{array}\right\} \qquad (5)$$

From Eq.(5), when the isolated table is subjected to earthquake motion from the condition $z = 0$, the isolated t able does not move to the shaking table until the condition $|\ddot{y}| > f_r$ is satisfied. Thus, f_r is determined by the maximum response of the linear system without friction characteristic $|\ddot{y}|_{max}$ as follows:

$$f_r = \xi|\ddot{y}|_{max} \qquad (6)$$

where ξ is normalized friction force and $0 \le \xi \le 1$.

Friction force is often defined using friction coefficient μ as follows.

$$f_r = \mu g \qquad (7)$$

where g is gravitational acceleration. Relation between ξ and μ is given as

$$\xi = \mu / K \qquad (8)$$

Table 7 Maximum acceleration (G)

ξ	0.3
Input	3.80
Response	1.25
Response/Input	0.33

Table 8 Sum of squares of acceleration (G^2s)

ξ	0.3
Input	1377
Response	1146
Response/Input	0.83

where

$$K = |\ddot{y}|_{max} / g \qquad (9)$$

5.2 Results of Simulation

As input excitation, white noise is used. Damping ratio ζ is assumed to be 0.01. From Fig.4(b), Fig.6(b) and 8(b), the natural frequency of the system is 0.5Hz. Table 7 and Table 8 show an example of result of simulation. In Table 7, the maximum values of response and input are shown. In Table 8, sum of squares of response and input are shown. From those tables, the maximum response and sum of squares of response are reduced using the system.

6. CONCLUSION

A base isolation system utilizing bearing with friction and restoring force of bearing is proposed. This bearing consists of two plates having spherical concaves and oval type metal or spherical metal with rubber. First, effectiveness of the base isolation system is examined experimentally. Using artificial time histories, the isolated table is shaken on the shaking table. Acceleration of input and response are measured. The maximum value, sum of squares and Fourier spectrum of input and response are obtained. The maximum value of response is reduced and sum of squares of response is significantly reduced. Fourier spectrum is significantly reduced in almost of all frequency regions, except for very low frequency region. Next, in order to examine reduction of seismic response of actual mechanical system, a console rack is set on the isolated table. Acceleration response is also significantly reduced in this case. Finally, obtained results of experiment are examined by simulation method. An analytical model considering friction and restoring force is used. From simulation method, effectiveness of the proposed base isolation system is demonstrated.

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