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AN ENERGY REGENERATION SEISMIC ISOLATION DEVICE USING A TRANSDUCER AS A DAMPER

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ABSTRACT: A damper reduces vibrational response by transducing kinetic energy into thermal energy. In this study, the focus is on the kinetic energy. A power outage often occurs during a large-scale earthquake, and it leads to an electricity shortage. To solve this energy problem, a proposed semi-active seismic isolation device regenerates energy from the kinetic energy as electric energy, which means that the seismic isolation device has a charging function as an additional value. The semi-active seismic isolation device is composed of a stiffness element, a damper element, a rechargeable battery, and a transducer. Its control design is based on a Linear Quadratic Regulator, which gives continuous control force. As the proposed seismic isolation device is semi-active control, only negative value is applied to the system. The structural parameters and the design variables of the control are optimized concurrently using Genetic Algorithm so that it reduces vibrational response and regenerates energy. Through numerical simulation, it is confirmed that the vibration reduction performance of the proposed device is superior to that of the passive seismic isolation device and it can regenerate energy.

1. Introduction

During the 2011 off the Pacific coast of Tohoku Earthquake (March 11), the damage of seismic isolation devices in some server rooms was reported (Japan Data Center Council, 2012). Against such strong vibrations semi-active control can improve the control performance and achieve greater safety. By contrast, it cannot operate as required in the event of a power outage. In fact, a semi-active seismic isolation device did not operate during a large-scale blackout on March 11 (Nakajima, et al., 2012). Thus, it is important to ensure sufficient energy for semi-active control, in addition for emergency power.

As a potential for ensuring energy, the focus is on the regenerated energy from the kinetic energy of a vibration system. A control system which uses regenerated energy from a kinetic system is a well-known strategy for a motor control, named energy harvesting control, e.g. the regenerative brake of a train. For the vibration control of a mechanical system, Suda et al. (1998, 2003) proposed self-powered active control which regenerated energy from vibration and used it for active control. Furthermore, authors applied this concept to an active seismic isolation device (Miura and Takahashi, 2014).

In this study, the objective is a server room where passive seismic isolation devices are commonly used. The proposed semi-active seismic isolation device gives a traditional seismic isolation device a charging function as an additional value and is more effective for response reduction.

(a) Passive Model

(b) Semi-active Model

Fig. 1 – Seismic Isolation Device Models.

2. Seismic Isolation Device Models

In this study, the proposed semi-active seismic isolation device (seismic isolation floor) is compared with a passive one as shown in Fig. 1, where $m = 775$ (kg) is the mass of the isolation device and an equipment (server) placed on it. The passive model is composed of a stiffness element k_{p} and a damper element c_{p}. The semi-active model is composed of a stiffness element k_{sa}, a damper element c_{sa}, a rechargeable battery, and a transducer.

2.1. Passive Model

The motion equation of the passive model shown in Fig. 1 (a) is as follows:

$$m\ddot{x} + c_{\mathrm{p}}\dot{x} + k_{\mathrm{p}}x = -m\ddot{q}_{\mathrm{z}} \tag{1}$$

where x and $\ddot{q}_{\mathrm{z}}$ represent the relative displacement of the isolation layer to the structural floor and the absolute acceleration of the structural floor, respectively.

2.2. Semi-active Model

2.2.1. Structural Design

As shown in Fig. 1 (b), the semi-active seismic isolation device has the rechargeable battery and the transducer. The battery is assumed to be charged in an initial condition. The transducer acts as a generator during deceleration. The transducer changes its viscous damping coefficient c_{ctrl} by changing its resistance, thus c_{ctrl} is a discrete value. In this study, the characteristic of the transducer is assumed to be changed continuously as a foundation examination.

2.2.2. Control Design of the Transducer

The motion equation of the semi-active model shown in Fig. 1 (b) is written as follows:

$$m\ddot{x} + c_{\mathrm{sa}}\dot{x} + k_{\mathrm{sa}}x = -m\ddot{q}_{\mathrm{z}} + u \tag{2}$$

where u is the viscous damping force by the transducer. In this study a Linear Quadratic Regulator (LQR) is applied to the control design. Using the state vector $\mathbf{X} = [x \quad \dot{x}]^{\mathrm{T}}$, absolute acceleration response $\ddot{q}_{\mathrm{z}} + \ddot{x}$ and relative displacement response x are expressed as follows:

$$\ddot{q}_{\mathrm{z}} + \ddot{x} = \mathbf{c}_{\mathrm{a}}\mathbf{X} + \mathbf{d}_{\mathrm{a}}u\ , \tag{3}$$

$$x = \mathbf{c}_{\mathrm{d}}\mathbf{X}\ , \tag{4}$$

$$\mathbf{c}_{\mathrm{a}} = \begin{bmatrix} -\frac{k}{m} & -\frac{c}{m} \end{bmatrix}, \tag{5}$$

$$\mathbf{d}_{\mathrm{a}} = \frac{1}{m}\ , \tag{6}$$

$$\mathbf{c}_{\mathrm{d}} = \begin{bmatrix} 1 & 0 \end{bmatrix} . \tag{7}$$

A cost function J for the LQR is then formulated as:

$$J = \int_0^{\infty} \left[\left(\ddot{q}_{\mathrm{z}} + \ddot{x} \right)^2 + qx^2 + ru^2 \right] dt = \int_0^{\infty} \left(\mathbf{X}^{\mathrm{T}} \mathbf{Q} \mathbf{X} + 2\mathbf{X}^{\mathrm{T}} \mathbf{S} u + Ru^2 \right) dt \ , \tag{8}$$

$$\mathbf{Q} = \mathbf{c}_{\mathrm{a}}^{\mathrm{T}} \mathbf{c}_{\mathrm{a}} + q \mathbf{c}_{\mathrm{d}}^{\mathrm{T}} \mathbf{c}_{\mathrm{d}} \ , \tag{9}$$

$$\mathbf{S} = \mathbf{c}_{\mathrm{a}}^{\mathrm{T}} \mathbf{d}_{\mathrm{a}} \ , \tag{10}$$

$$R = \mathbf{d}_{\mathrm{a}}^{\mathrm{T}} \mathbf{d}_{\mathrm{a}} + r \ , \tag{11}$$

where q and r represent design variables. Transforming Eq. 2 into a state space form $\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}u$, the optimal control force u_{opt} is obtained as follows:

$$u_{\mathrm{opt}} = -R^{-1} \left(\mathbf{S}^{\mathrm{T}} + \mathbf{B}^{\mathrm{T}} \mathbf{P} \right) \mathbf{X} \ , \tag{12}$$

where $\mathbf{P}$ is a symmetric positive definite solution to the following Riccati equation:

$$\mathbf{P} \left(\mathbf{A} - \mathbf{B} R^{-1} \mathbf{S}^{\mathrm{T}} \right) + \left(\mathbf{A} - \mathbf{B} R^{-1} \mathbf{S}^{\mathrm{T}} \right)^{\mathrm{T}} \mathbf{P} - \mathbf{P} \mathbf{B} R^{-1} \mathbf{B}^{\mathrm{T}} \mathbf{P} + \mathbf{Q} - \mathbf{S} R^{-1} \mathbf{S}^{\mathrm{T}} = \mathbf{O} \ . \tag{13}$$

As the transducer only acts during deceleration, the control force $u(t)$ by the transducer is given as follows:

$$u(t) = u_{\mathrm{opt}}(t) \qquad (u(t)\dot{x}(t) \le 0), \tag{14}$$

$$u(t) = 0 \qquad (u(t)\dot{x}(t) > 0), \tag{15}$$

where the relation between $u(t)$ and $c_{\mathrm{ctrl}}(t)$ is:

$$u(t) = -c_{\mathrm{ctrl}}(t)\dot{x}(t) \tag{16}$$

3. Optimization of the Structural Parameters and the Design Variables of Control

The structural parameters (the damper elements c_{p} and c_{sa}, and the stiffness elements k_{p} and k_{sa}) and the design variables of control (q and r) are optimized using Genetic Algorithm.

First, these parameters are represented as c_{p} or $c_{\mathrm{sa}} = s_1 \times 10^{s_2}$, k_{p} or $k_{\mathrm{sa}} = s_3 \times 10^{s_4}$, $q = s_5$, and $r = s_6 \times 10^{s_7}$. Then $s_1 \sim s_7$ are set as the genes for Genetic Algorithm. The parameters of Genetic Algorithm are shown in Table 1, where the range constraints are determined by explorative analyses.

Second, each set of genes is evaluated using ten excitations $\ddot{q}_{\mathrm{z}i}$ ($i = 1, \ldots, 10$) by 'Kokuji waves', which are based on the design acceleration response spectrum for Level 2 as defined in Notification No. 1461 of the Japanese Ministry of Construction in 2000. A sample of Kokuji waves is shown in Fig. 2. The duration time of Kokuji waves is $T = 120$ (s).

Requirements for the both passive and semi-active seismic isolation devices are that the displacement responses $|x_i(t)| < 0.200$ in order not to hit the frame with the isolation floor and that the acceleration responses are minimized. In addition to them, the semi-active one has a requirement of generation capacity. About vibration power generation, a device which generation capacity is 0.1 mW is proposed. Thus, in this study the minimum requirement of generation capacity is assumed to be $0.1T = 1.2 \times 10^{-2}$ (J) at $T = 120$ (s), where the charged energy $E(T)$ is derived as follows:

$$E(T) = -\int_0^T u(t)\dot{x}(t)\,dt\,. \tag{17}$$

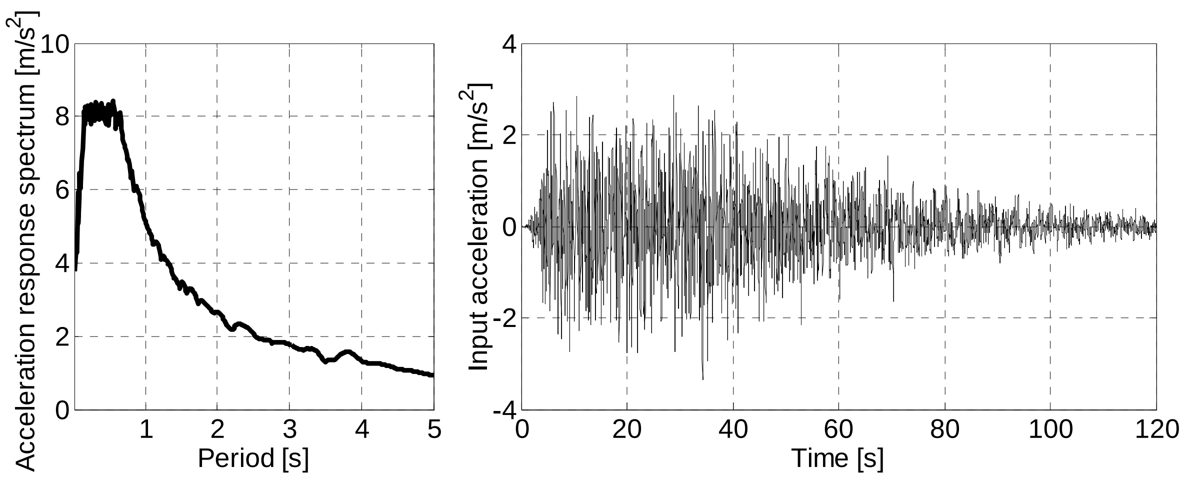
When these requirements are met, a following fitness function f which reduces the absolute acceleration response $\ddot{q}_z + \ddot{x}$ is calculated:

$$f = \frac{1000}{\sum_{i=1}^{10} \max_t |\ddot{q}_{zi}(t) + \ddot{x}_i(t)|} \qquad (|x_i(t)| < 0.200\,,\, E(T) > 1.2\times 10^{-2}). \tag{18}$$

The optimized parameters are shown in Table 2, where ‘Mass’ is the mass of the isolation device and an equipment (server) placed on it.

Table 1 – Parameters of Genetic Algorithm.

Parameter	Gene	Value
Damping coefficient (c_p or c_{sa})	s_1	1.0, …,9.9
	s_2	-2, …, 2
Stiffness coefficient (k_p or k_{sa})	s_3	1.0, …,9.9
	s_4	2, …, 6
Design variable q	s_5	0.1, …, 100
Design variable r	s_6	1.0, …,9.9
	s_7	-6, …, -3
Population size	–	30
Generation number	–	100
Crossover rate	–	0.80
Mutation rate	–	0.35



(a) Acceleration Response Spectrum (b) Acceleration

Fig. 2 – A Sample of Kokuji Waves.

Table 2 – Parameters of the Devices.

Parameter	Passive Model	Semi-active Model
Mass	7.75×10^2 kg	
Damping coefficient	9.22×10^2 Ns/m	5.38×10^2 Ns/m
Stiffness coefficient	3.83×10^3 N/m	5.67×10^2 N/m
Design variable q		3.52×10
Design variable r		1.31×10^{-5}

Table 3 – Performance of the Devices.

Performance	Passive Model	Semi-active Model
Input acceleration	3.55 m/s^2	
Acceleration response	1.03 m/s^2	0.830 m/s^2
Displacement response	0.167 m	0.175 m
Regenerated energy (power)		847 J (7.06 W)

4. Validation Analyses

To verify the effectiveness of the proposed device, arithmetic averages of the responses excited by the 100 Kokuji waves are shown in

Table 3, where the ten Kokuji waves for the optimization in Sections 3 and the 100 Kokuji waves for validation in Section 4 are different waves sets.

First, about performance of vibration reduction, the relative displacement responses are less than 0.200 m, which is the design requirement.

According to quake-resistance standards in several PC company, a server can operate under the 2.5 m/s^2 acceleration. In both devices, the absolute acceleration responses are reduced to less than 2.5 m/s^2. Although the passive device seems to be safe sufficiently, ground motions may be amplified double or triple-fold in a building, so that the responses in the passive device have the potential to exceed 2.5 m/s^2.

About charge performance, as shown in

Table 3, the proposed semi-active seismic isolation device regenerates 847 J by 120 seconds. It means that the device has about 7.06 W generation capacity, so that the proposed device has a realistic property. In this regard, an actual regenerative ratio may depend on vibration properties such as predominant frequencies of an excitation and natural frequencies of the device. Thus it is needed to verify its performance by experiment.

5. Conclusion

In this study, the semi-active seismic isolation device which regenerates energy from the kinetic energy as electric energy is proposed. The vibration reduction performance of the proposed device is superior to that of the passive seismic isolation device and it can regenerate certain energy.

In future studies, we will verify its performance by experiment.

6. Acknowledgements

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