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A preliminary study on an active aseismic control system for large structures

Kato, M.[1], Watanabe, Y.[1], Kato, A.[1], Tomura, H.[2], Shirahama, K.[2], Kageyama, M.[2]
1) The Japan Atomic Power Company, Tokyo, Japan
2) Obayashi Corporation, Tokyo, Japan

1 INTRODUCTION

This paper presents and discusses the concepts of an active aseismic control system for large structures such as a nuclear reactor building. Active control systems currently studied to be adopted for buildings are mostly for wind-induced responses, not for earthquake responses, mainly because of its control power capacity and efficiency. On the other hand, passive control systems such as base-isolation units have been used in some existing buildings, though such systems' performance depends on input motion characteristics of the structural system.

The concept of an active aseismic control system for a large structure, which is the main theme of this paper, is established towards the so-called "site-free design" which implies a structural design free from aseismic design conditions such as design response spectra. Therefore, a structure where the system applied may get benefits in both structural safety and costs.

2 CONCEPT OF SUPER QUAKE FREE CONTROL SYSTEM (SQFC)

Firstly, a feasibility study on an effective active control system for seismic excitations is carried out. Namely, Active Mass Damper (AMD), Variable-Stiffness System (VSS), and Super Quake-Free Control System (SQFC) are compared in terms of their efficiency and power requirement. These three systems are compared by a parametric study using SDOF lumped mass models. As a result of the analysis, AMD and SQFC show less response acceleration than that of VSS, and SQFC shows less control power than that of AMD. From these results, the best system for an active aseismic control system for large structures is SQFC because of its performance and control power requirement.

The SQFC has actuators at the bottom of the structure, connecting a ground surface and the base mat. The base mat of the structure is also isolated from the ground surface by some bearing system such as laminated rubber bearings. The actuators apply counter forces to the seismic ground motion, so that the response of the entire structure above the base mat can be reduced.

3 ANALYSIS METHOD AND RESULTS

3.1 *Model*

The SQFC system is modified for a heavy structure (the target weight is 180,000 tons) using a dynamic analyses of the controlled structure. In this section, an analytical model of the SQFC system is used as shown in Fig.1. The analytical model has three lumped mass : an upper structure, an internal basemat and a lower basemat, each of which has three degree of freedoms (horizontal, vertical and rotational); thus, the model has nine degree of freedoms. An control actuator is located between the base mat and the ground surface. The upper structure itself is supported by two alternative bearing systems. One is a group of laminated rubber bearings generally used in seismic isolation structures with its natural frequency of approximately 2.0 seconds. The other is a group of flat steel roller bearing systems whose natural frequency is expected to be approximately 10.0 seconds. The soil, its velocity of secondary wave is 1500m/sec., is described as a pair of a spring and a viscous damper based on an analytical modeling.

3.2 *Method*

The equation of motion of the model takes the following forms:

$$M\{\ddot{x}\}+C\{\dot{x}\}+K\{x\}=E\ddot{y}_0+Ff_0\cdots\cdots(1)$$

$$M\{\ddot{x}+\ddot{y}\}+C\{\dot{x}+\dot{y}\}+K\{x+y\}=C\{\dot{y}\}+K\{y\}+Ff_0\cdots\cdots(2)$$

$$\ddot{y}+2h\omega_0\dot{y}+\omega_0{}^2=\ddot{y}_0\cdots\cdots(3)$$

where, $\{x\}$ is a displacement vector of the system, $\{y\}$ is a ground motion vector, and y_0 is a stroke vector of the actuator. M is a lumped mass vector, K is a stiffness matrix. E is a mass matrix for acceleration applied by the actuator, F is a matrix for applied force of the actuator.

The optimal control force to the system is calculated by a modern control theory to get the optimal gain matrices solving the Riccati Equation. Then the analytical model get the control force to reduce the seismic responses.

3.3 *Input motion*

Fig. 2 shows response spectra of applied ground motions in this analysis. It is an artificial wave especially designed for design base of seismic isolation system of nuclear plants. The values of horizontal velocity response spectrum over longer periods than 1.0 sec. are approximately 200 Kine.

3.4 *Results*

As a numerical example, a dynamic response analysis using the above theory to the lumped mass model is done. Applied ground motion is the artificial wave shown in the Fig. 2. One parameter is the level of applied control force: Type-1, 2 and 3 reduce the acceleration response of the structure as 2/3, 1/2 and 1/3 of that of non-controlled structure respectively. The other parameter is the type of bearing system: here, a laminated rubber bearing system and a roller bearing system are compared.

Fig. 3 shows the results of response analyses of the controlled structures. The results show that the roller bearing system needs much less control power than the laminated rubber bearing system. The main reason of the difference may be caused by the difference of their natural frequency: that of the roller bearing system is extra originally long (approximately 10 seconds or more).

Fig. 4 shows other results of the analyses (required control power and response accelerations). Here, the three types of the level of applied control force show a trade-off relationship between the control force and response reduction. The more the control power becomes, the less response of the structure is expected. An optimal combination of these may be selected depending on a case of a structure.

However, the roller bearing system is apt to have a larger displacement, and main cause of the control power is due to the large stroke of the actuator. Therefore, further study may be needed to modify the system to be better one. Table 1 shows the number of actuators needed in the case of 180,000 ton building with the roller bearing system.

These numbers indicate that the system will be feasible. Fig. 5 shows time histories of an acceleration, a displacement and a control force obtained by the analysis. As shown in Fig.6, the horizontal acceleration response spectrum implies relatively little accelerations effectively in a short period domain (0.1 to 0.3 sec.).

4 VERTICAL RESPONSE CHARACTERISTICS AND ITS REDUCTION

The analysis model also shows the vertical response characteristics of the SQFC with the roller bearing system. Fig. 7 shows the vertical response acceleration spectrum of the analytical model. As the roller bearing system has high stiffness, the vertical response characteristics of the structure may be similar to that of conventional aseismic building. It shows approximately 4G to 5G accelerations in a short period domain. To establish a site-free design, the vertical response of the structure should also be reduced.

Different from the horizontal isolation, the vertical isolation cannot avoid the gravity force; therefore very low natural frequency (equals to very low stiffness) as that of horizontal isolation system can hardly be applied. In this study, a passive control system consisting steel springs and viscous dampers between upper basemat and superstructure is presented. Parametric studies are carried out to get an optimal design of the springs and dampers. Fig. 8 is the results of the studies, showing the best frequency (0.5 seconds) and damping coefficient (20%). By using this system, the peak horizontal acceleration response spectrum (h=0.01) reduces to 3 G and the displacement response of the vertical control layer to 10 cm.

5 PROPOSAL OF A THREE DIMENSIONAL SQFC SYSTEM

Combining the horizontal and vertical aseismic control systems, a 3D-SQFC system is proposed. Fig. 10 shows a schematic view of the proposed system. Fig. 9 shows the area of input motion levels where the system can maintain its control performance and the concept of site-free design can be expected. In terms of applying the artificial wave, maximum horizontal acceleration of 1000 gals (1G) and vertical acceleration of 850 gals are the range of allowable levels. Considering the fact that the artificial wave has large velocity in relatively long period components, the range seems to be beyond the maximum value of earthquakes reasonably considered in Japan. Even for such a large ground motion, the proposed SQFC system can work well and reduce the response of the structure.

6 CONCLUDING REMARKS

A concept of three-dimensional Super Quake-Free Control System (3D-SQFC) based on the results of this study is presented. The presented system can be effective even an artificial ground motion, which is considered to be a maximum one in Japan, is applied. Therefore, the "site-free" concept for heavy structures under large input motions is expected.

REFERENCE

Shirahama, K., Watanabe, Y. et al. 1994. A Conceptual Study on Active Seismic Control System for Large Structures (Part 1: A Parametric Study on Control Methods): *Summaries of Technical Papers on Annual Architectural Institute of Japan, Structures I*: 1709-1710.

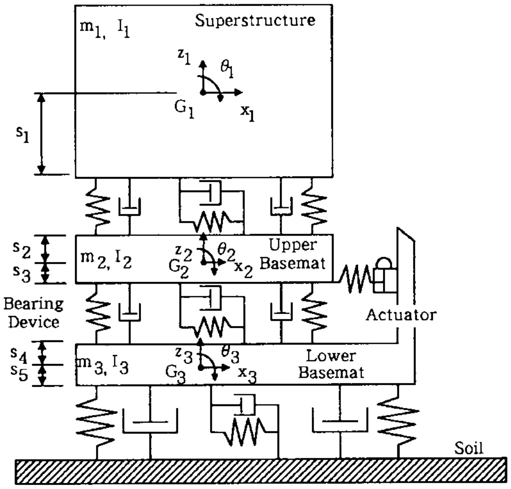
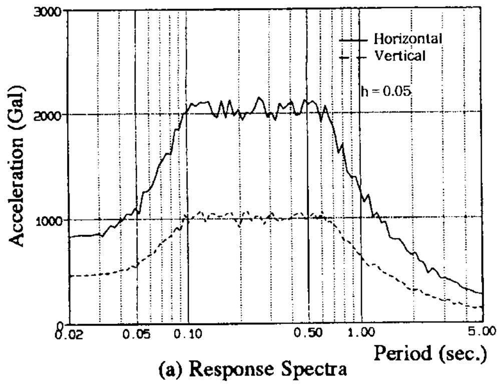
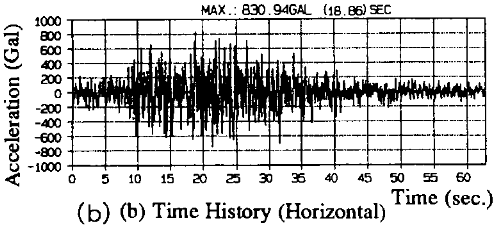


Figure 1 Analytical Model

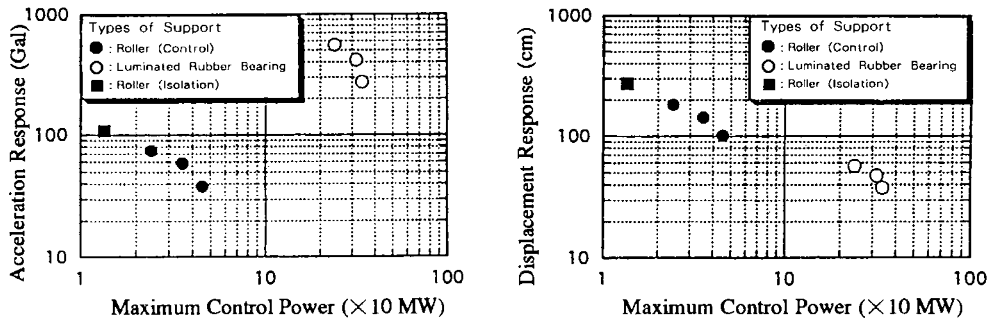


(a) Response Spectra



(b) (b) Time History (Horizontal)

Figure 2 Artificial Input Motion



(a) Structure (Horizontal)

(b) Isolated Layer (Horizontal)

Figure 3 Relationship between Responses of Structure and Maximum Control Power

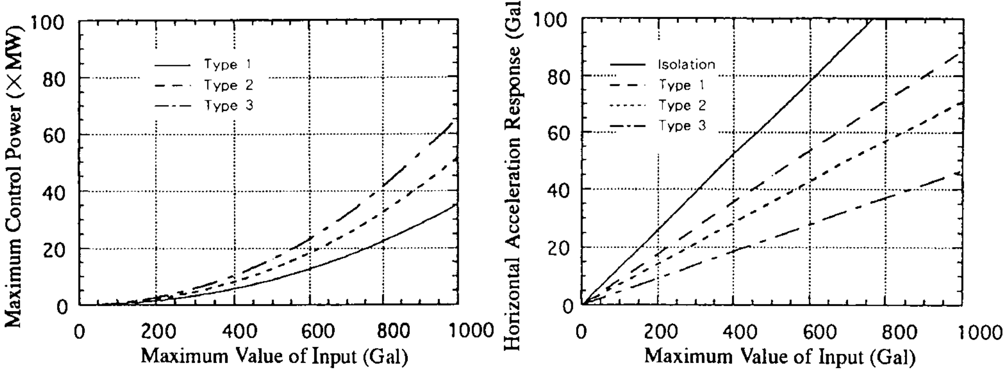
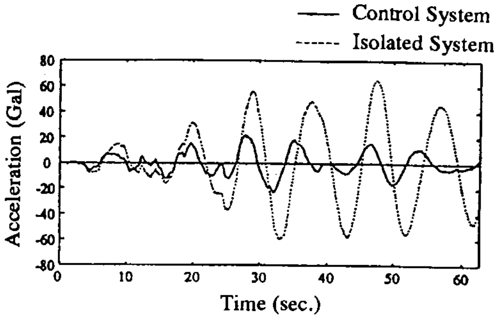


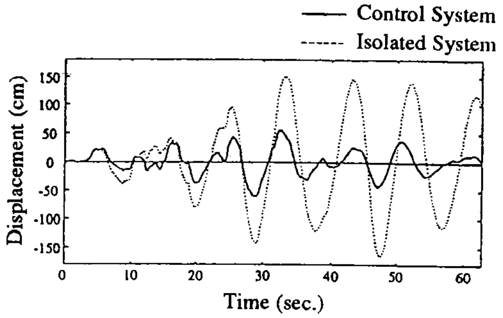
Figure 4 Relationships between Maximum Control Power and Input Motion, and between Responses of Structure and Input Motion

Table 1 Required Maximum Control Power

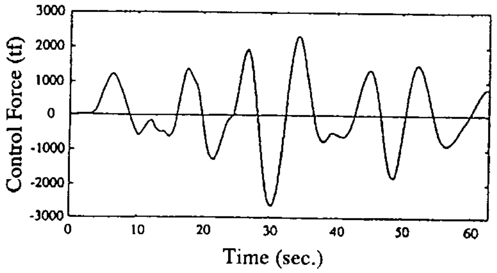
Method	Type 1	Type 2	Type 3
Required Maximum Control Power (MW)	24	36	45
Required Units of 0.6 MW-Actuators	40	60	75
Required Units of 3 MW-Actuators (such as Tadotsu)	8	12	15



(a) Acceleration Response



(b) Displacement Response



(c) Control Force

Figure 5 Time Histories of Response (Type 3)

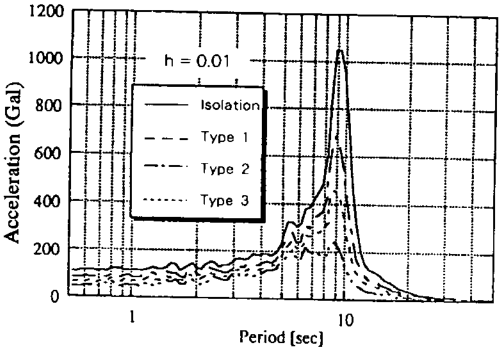


Figure 6 Response Spectrum (Horizontal)

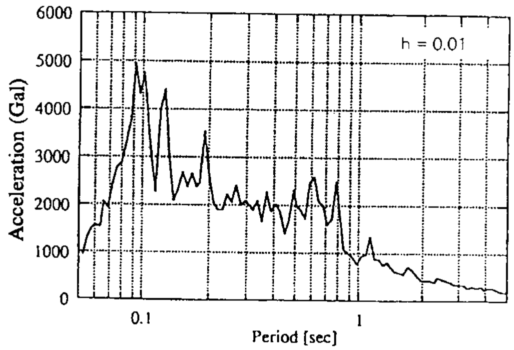


Figure 7 Response Spectrum (Vertical)

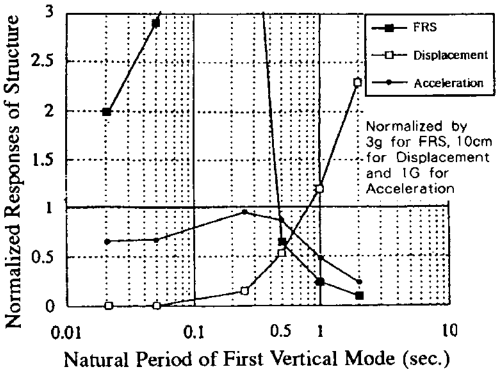


Figure 8 Relationship between Normalized Responses and Natural Periods of First Vertical Mode of Structure

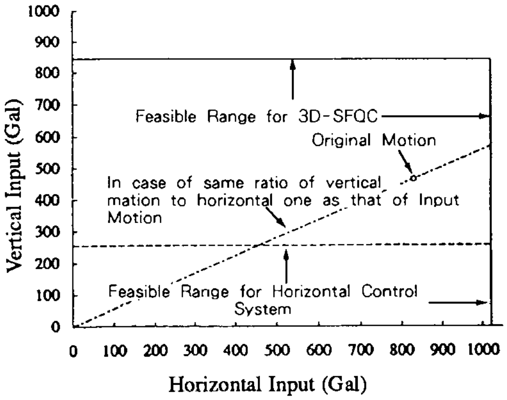


Figure 9 Feasible Range for Active Aseismic Control System

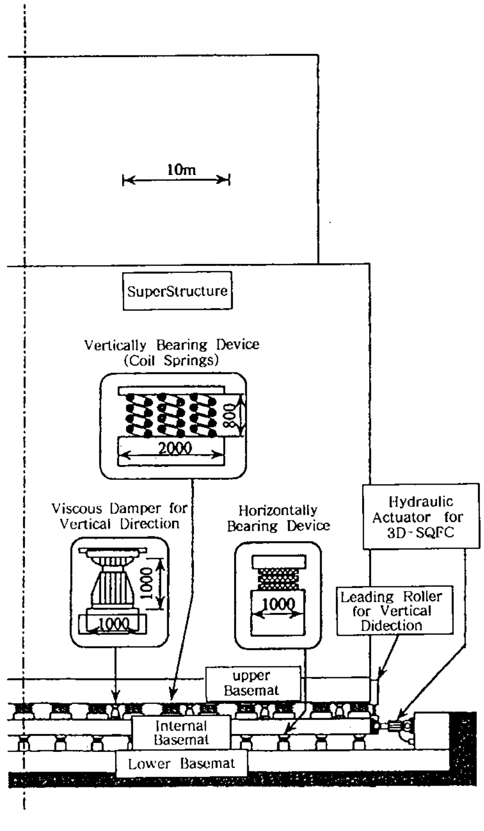


Figure 10 Schematic View of Active Aseismic Control System