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Overview of the application of active/semiactive control to building structures in Japan

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SUMMARY

Perhaps one of the most significant technological innovations in the structural engineering field is the practical application of active and semiactive control to civil structures. A number of structures integrating active, hybrid, and semiactive response control technologies have been constructed in Japan. Most of them are building structures. This paper provides an overview of those building structures, focusing mainly on the types of buildings that are controlled, and on the types of control devices that are implemented. Future directions of structural engineering are also discussed. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: active structural control; active control; semiactive control; hybrid control; mass damper; mass driver

1. INTRODUCTION

Extensive efforts have been devoted to the theoretical and practical development of active structural control. More than 10 years have passed since the completion of the Kyobashi Seiwa Building, the first active structural control building in the world [1, 2]. The construction of this building in Tokyo, Japan in 1989, opened the door to a new stage for innovative earthquake-resistant strategies for civil structures. At this stage, the technologies related to sensor and computer control can be integrated effectively into building structures to enhance safety, performance and serviceability. Moreover, this building caused a dramatic change in people's view of building structures. Before that time, buildings had been regarded as passive structures, even though a number of published research papers had proposed the conceptual philosophy and methodologies for active control of civil structures utilizing the technologies related to modern control engineering (a few of those are References [3–6]).

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Inspired by the Seiwa Building, more than 30 buildings in Japan have implemented various types of active, hybrid, and semiactive control systems. In the remainder of this paper, the term ‘active control’ will be used to cover a broad range of control systems, thus including also hybrid and semiactive control.

Active control technology of civil structures, however, has not yet reached its full potential for innovative earthquake disaster prevention and therefore should be regarded as still being under development. The ultimate goal of active structural control is the enhancement of structural safety during strong earthquakes. However, there still remain a number of significant unsolved issues, particularly with regard to the use of active structural control to ensure safety against severe seismic excitation. With the above background, this paper discusses the current state of the practical applications of active control in Japan.

2. STRUCTURAL CONTROL PRINCIPLES AND ACTIVE CONTROL

Structural control is generally classified into two categories: active control and passive control. In comparison with passive control, active control of structural response is characterized essentially in terms of the following two features: (i) a certain amount of external power or energy is required; and (ii) a decision-making process based on real-time-measured data is involved. In this regard, active control includes a wide range of technologies. There are five fundamental engineering principles for the current strategies of structural control for buildings. These principles are not mutually exclusive ideas. Certain types of control systems follow multiple principles.

The first principle is to transfer the vibrational energy of the main structural system to an auxiliary oscillator system. This is based on the energy transfer philosophy, i.e. the reduction of the motion of the main system is achieved at the expense of increased motion of the auxiliary oscillator. The second is to reduce the flow of input excitation energy into the main structural system. The third is to subject the structure to additional damping. The fourth is to prevent the building from exhibiting resonance due to an external excitation. The fifth is to provide a structural system with computer-controllable forces. The first four of these principles can be applied to both active and passive control strategies, while the fifth principle is apparently only for active control strategy.

The auxiliary oscillator mentioned in the first principle could be a passive-tuned mass damper or an active mass damper/driver (AMD). An AMD is an actively controlled auxiliary oscillator. Base isolation represents a typical passive control technology based on the second principle. The additional damping cited in the third principle could be provided, for example, through the implementation of oil damper systems with passive or semiactive control. As one of the examples for passive control following the fourth principle, base-isolation technology can be counted again. Base-isolated buildings with a natural period of 3–4 s will not exhibit resonance during ordinary earthquakes. A semiactive-controlled variable-stiffness system is also an example of a structural control scheme on the basis of the fourth principle. This system avoids resonant vibration of the structure by selecting the most appropriate stiffness.

From the control-engineering point of view, active control systems consist of four interconnected components or elements. These components are: the plant, the sensors, the control computer or controller and the actuators. Each of them works as a subsystem and is mutually integrated in such a way that the output from one component would be the input to other

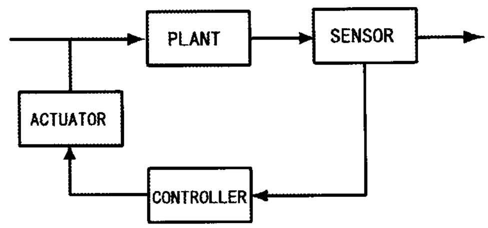

Figure 1. Control system.

component. This relationship between the four components is schematically illustrated in Figure 1.

In the structural control system depicted in Figure 1, the plant is the building whose response is to be controlled so as to provide a desired response. This building responds to the input excitation, and the sensors installed on the selected floors in the building measure this response (in some cases, together with the input ground acceleration) and send it to a control computer or controller in the real time. Having the measured responses and following a specified control algorithm, the control computer then determines what control signal should be given to the actuators. After receiving the control signal, the actuators accomplish the specific control action, for example, driving an AMD mass. There are a variety of types of actuators and control actions for active control of building structures. An overview will be given in the following sections.

Active structural control can be discussed from the following viewpoints: (i) What type of building is considered? (ii) What kind of control algorithm is employed? (iii) What kind of response is measured and fed back to the controller? and (iv) What kind of actuators is implemented? These four viewpoints may be closely related to each other. To give a single example, the control algorithm could strongly influence what type of responses should be measured and fed back to the controller. This paper, focusing mainly on the first and fourth viewpoints, presents an overview of the practical applications of active, hybrid, and semiactive control to building structures in Japan and also discusses future directions of active structural control. The other papers in this special issue, on the other hand, enter into more detailed discussions with respect to each specific active-, hybrid- or semiactive-controlled building. They address such questions as what the target external excitation is, what responses are fed back, what the employed control algorithm is, what kind of actuator accomplishes the required control operation, etc.

3. OVERVIEW OF BUILDINGS

Most of the practical applications of active control to civil structures are found in Japan. Presenting such practical applications of active structural control, Housner *et al.* [7] in 1997 discussed the general view of structural control. In addition, Spencer and Sain [8] in 1997 and Nishitani [9] in 1998 presented overviews of the application of active control to actual buildings in Japan. Since these papers were published, several more active-controlled buildings have been completed in Japan. Table I provides an updated list of active-controlled buildings

Table I. Active/semiactive controlled buildings in Japan. (The mass of building in parentheses indicates the first modal effective mass.)

Name	City	Completion date	Main structure	Bldg use	Storey	Height (m)	Mass (t) Bldg.	Mass (t) Mass damper	Type
Kyobashi Seiwa Bldg.	Tokyo	1989	Steel	Office	11	33	400	4.4	AMD
Kajima Research Institute No. 21 Bldg	Tokyo	1990	Steel	Laboratory	3	12	400	—	AVS
Sendagaya INTES	Tokyo	1992	Column:SRC Beam:steel	Office	11	44	(3300)	72	AMD
Applause Tower	Osaka	1992	Steel	Hotel, office theatre	34	161	(13 000)	480	AMD
Kansai Airport Control Tower	Osaka	1992	Steel	Control tower	7	86	2600	10	HMD
Osaka ORC200	Osaka	1992	Steel	Hotel, office	50	200	57 000	200	HMD
Ando Nishikicho Bldg.	Tokyo	1993	Steel	Office	14	54	2500	24	HMD
Yokohama Landmark Tower	Yokohama	1993	Steel	Hotel, office	70	296	260 000	340	HMD
Long Term Credit Bank	Tokyo	1993	Steel	Office	21	129	39 000	195	HMD
Porte Kanazawa	Kanazawa	1994	Steel	Hotel, office	29	121	27 000	100	HMD
Shinjuku Park Tower	Tokyo	1994	Steel	Hotel, office	52	232	120 000	330	HMD
RIHGA Royal Hotel	Hiroshima	1994	Steel	Hotel	35	150	83 000	80	HMD
MHI Yokohama Bldg.	Yokohama	1994	Steel	Office	34	152	61 800	60	HMD
Hikarigaoka J City Bldg.	Tokyo	1994	Steel	Hotel, office	24	100	29 000	80	HMD
Hamamatsu ACT City	Hamamatsu	1994	Steel	Hotel, office	46	212	110 000	180	HMD
Riverside Sumida	Tokyo	1994	Steel	Residential	33	134	52 000	30	AMD
Hotel Ocean 45	Miyazaki	1994	Steel	Hotel	43	154	80 000	240	HMD
Osaka World Trade Center Bldg.	Osaka	1995	Steel	Office	52	252	75 000	100	HMD
Dowa Kasai Phoenix Tower	Osaka	1995	Steel	Office	28	144	27 000	72	HMD
Rinku Gate Tower Bldg.	Osaka	1995	Steel	Hotel, office	56	255	75 000	160	HMD
Hirobe Miyake Bldg.	Tokyo	1995	Steel		9	30	270	2	HMD
Plaza Ichihara	Chiba	1995			12	61	5760	14	HMD
HERBIS Osaka	Osaka	1997	Steel	Hotel, office	40	189		316	AMD
Nisseki Yokohama Bldg.	Yokohama	1997		Office	30			50,60	HMD
Itoyama Tower	Tokyo	1997	Steel	Office, residential	18	89			HMD
OTIS Elevator Tower	Chiba	1998	Steel	Laboratory	39	154	6900	35,27	HMD
Odakyu Southern Tower	Tokyo	1998	Steel	Hotel, office	36	151	50 000	62	HMD
Bunka Fukuso Gakuin	Tokyo	1998	Steel	School	20	93	24 000	24	HMD
Oita Oasis Plaza 21	Oita	1998	Steel	Hotel, office	20	101		25	HMD
Kajima Shizuoka Bldg.	Shizuoka	1998	Steel	Office	5	19	1100		AVD
Shinagawa Inter City Bldg.	Tokyo	1998	Steel	Office	32	145			HMD

in Japan. Since active structural response control technology, as already mentioned, is still at a quite early stage, some applications of control systems to certain buildings might be viewed as research-and-development activities. Table I includes also those cases, showing fundamental information about the active-controlled buildings, such as the numbers of storeys, the heights, the locations, and the type of actuators.

The first active-controlled building, the Kyobashi Seiwa Building, is an 11-storey steel building constructed in Tokyo, Japan, in 1989, which was designed by Kobori *et al.* [1, 2]. His proposal for the seismic-response-control philosophy dates back to the late 1950s and the early 1960s. As early as 1956 and 1958, Kobori [10, 11] proposed the philosophical strategy of incorporating automatic control philosophy into seismic-resistant design of structures for the purpose of enhancing safety against severe earthquake. In addition, Kobori and Minai [12, 13] in 1960 comprehensively presented a number of fundamental ideas for accomplishing seismic-response control, and proposed the Japanese expression exactly equivalent to the English term 'seismic-response control' or 'seismic-response-controlled structure'. In this regard, his idea, including the Japanese naming of seismic-response control, was the earliest proposal for structural control. However, control engineering in those days was not ready to bring about automatic control buildings during a seismic event, in terms of either theoretical or practical development. Following the many technological developments in control engineering in the 1960s, Yao [3] published his seminal paper in 1972, demonstrating the idea and practical schemes for active control of civil engineering structures. His paper presented feedforward and feedback control of civil structures and inspired many researchers in the civil engineering field, especially in the United States, to work on the application of control theory to structural engineering. Numerous research papers were subsequently published on active structural control.

Going back to the discussion of the active-controlled buildings in Table I, many of these structures are more than 60 m high. Under the Building Standard Law of Japan effective as of April 2000 [9], buildings with heights of over 60 m are categorized as high-rise buildings and have to obtain special permission from the Minister of Construction for their design and construction. These high-rise buildings receive special treatment at the design stage. Ordinary seismic design codes and guidelines do not apply to such structures. Less design base shear can be employed by taking into account the dynamic characteristics of structures, which are likely to be more flexible structures with a relatively long natural period. As a building gets higher, on the other hand, wind loads are likely to become larger. Therefore, high-rise buildings may have poor performance and serviceability during strong winds, even though safety is not endangered, resulting in the buildings occupants feeling uncomfortable. With the implementation of structural control, whether it is of the passive or active type, high-rise buildings may have better performance and serviceability.

Besides the above-mentioned general background of high-rise buildings, many of the high-rise buildings listed in Table I have other reasons for implementation of active structural control. For example, many of these buildings have luxury hotels in the upper storeys. Such luxury hotels should be comfortable even during strong winds and moderate earthquakes. Active control is expected to achieve more flexible and effective control performance against unpredictable external disturbances such as earthquakes and wind storms than comparable passive control can achieve. Buildings with hotel facilities includes: the Applause Tower (completed in 1992), the Osaka ORC 200 (completed in 1992), the Yokohama Landmark Tower (completed in 1993); the Porte Kanazawa (completed in 1994); the Shinjuku Park

Tower (completed in 1994); RIHGA Royal Hotel (completed in 1994); the Hikarigaoka J City Building (completed in 1994); Hamamatsu ACT City (completed in 1994); Hotel Ocean 45 (completed in 1994); the Rinku Gate Tower Building (completed in 1995); the HERBIS Osaka (completed in 1997); Odakyu Southern Tower (completed in 1998); and the Oita Oasis Plaza 21 (completed in 1998).

In addition to the technological reasons mentioned above, there are economical reasons why active control has mainly been applied to high-rise buildings. Active structural control, at the current stage, is rather expensive, whether for high-rise or low-rise buildings. In other words, active control implementation is, in a relative sense, less expensive in high-rise buildings than in low-rise buildings.

4. OVERVIEW OF ACTUATORS

A variety of actuators for active control of buildings have been installed in the buildings listed in Table I. The term 'actuators' herein means computer-operated devices to execute certain physical control operations. They include the active mass damper/driver (AMD) system, the hybrid mass damper (HMD) system, the active variable-stiffness (AVS) system, the semiactive variable damping (SAVD) system, etc. The most commonly employed actuator is the AMD or HMD. As mentioned previously, the AMD is an active-controlled auxiliary oscillator system. 'Hybrid' in the term HMD means any combination of active and passive systems. Hybrid control covers a wide range of control systems and typically requires less power to achieve efficient control operation. In most cases, HMD means an active-controlled tuned mass damper (ATMD). In the following, each of the actuators is discussed.

4.1. Active mass damper and hybrid mass damper

The inertia force of an active mass damper (AMD) provides a building with control force (i.e. the fifth principle). The AMD also works as an auxiliary oscillator that can reduce the motion of the main structural system over a wider range of frequencies than the tuned mass damper (TMD) (i.e. the first principle for structural control). Furthermore, the AMD can be considered as a control system having the effect of providing additional damping (i.e. the third principle).

The AMD system in the Kyobashi Seiwa Building was installed on the top floor. This AMD system comprises two auxiliary masses, which are controlled in such a way as to reduce not only the response in the transverse direction but also the torsional response. The total mass of the two AMDs in this building is 4.4 t, equal to 1.1 per cent of the building structural mass of 400 t.

For AMD-based structural control, as mentioned already, the inertia force resulting from the movement of AMD provides a building with a dynamic control force. Larger mass or larger acceleration of the AMD would produce larger inertia forces and thus larger control forces. A larger AMD mass ratio therefore would accomplish more effective control performance. In this regard, if certain necessary heavy equipments are utilized as the AMD mass, larger AMD mass ratios and hence larger control forces may be obtained. In some buildings, essential facilities for building operation have been effectively used as AMDs. The Sendagaya INTES Building (completed in 1992), the second building implementing an AMD system, manipulates

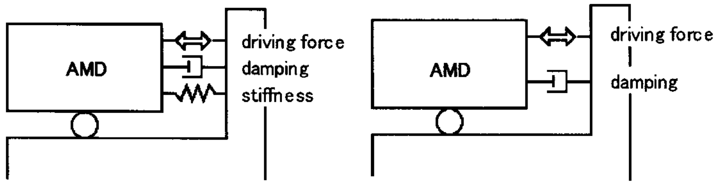

Figure 2. AMD systems.

two ice-generating heat-storage tanks on the roof with a total mass of 72 t as the AMD mass. The AMD mass ratio to the first modal effective mass of 3300 t is around 2 per cent in the INTES Building. The same type of heat-storage tank has been installed in the HERBIS Osaka Building (completed in 1997) as the AMD mass. The Applause Tower Building (completed in 1994) has utilized its heliport of 480 t on the top floor as the AMD mass. In this case, the AMD mass ratio to the first modal effective mass of 13 000 t is 3.7 per cent.

The Riverside Sumida Building (completed in 1994) has employed a unique type of AMD. The AMD for this building is of a non-pendulum type. The equation of motion for an ordinary AMD of the pendulum type is represented by

$$m(\ddot{x} + \ddot{x}_R + \ddot{x}_g) + c\dot{x} + kx = f \tag{1}$$

in which m is the mass of AMD, c the damping of AMD, k the stiffness of AMD, x the displacement of AMD relative to the floor on which it is attached, x_R the displacement of the floor on which the AMD is attached relative to the ground, x_g the earthquake ground displacement, and f the driving force applied to the AMD under the direction of controller. On the other hand, the equation for AMD of non-pendulum type is given by making $k = 0$ in Equation (1):

$$m(\ddot{x} + \ddot{x}_R + \ddot{x}_g) + c\dot{x} = f \tag{2}$$

These two different types of AMD, pendulum and non-pendulum types of AMD, are schematically illustrated in Figure 2.

Many of the active-controlled buildings listed in Table I have employed HMD systems. The hybrid mass damper integrates certain active control operation into passive mass damper movement. Thus, there are a number of variations for HMD systems.

The most common HMD is an ATMD. The TMD is an auxiliary mass oscillator which is tuned so that its increased motion should decrease the motion of the main structure, usually at the natural frequency of the structure. The ATMD can work more effectively employing a smaller driving force. The Osaka ORC 200 Building (completed in 1992), a 50-storey building with a height of 200 m, was the first building employing the ATMD type of HMD. The mass damper consists of two masses of total 200t weight, each supported by multiple-layered rubber bearings. It works as a TMD in the longitudinal direction, while in the transverse direction it is manipulated as an ATMD with variable feedback gain. The mass of the building structure is 57 000 t, and the mass ratio is 0.35 per cent. A similar mass damper system is employed in the Hotel Ocean 45 (completed in 1995). This hotel building is unique in that the planview of the floors has the shape of an isosceles triangle. The mass damper system works as an ATMD with variable feedback gain in the perpendicular direction to the base of the triangle

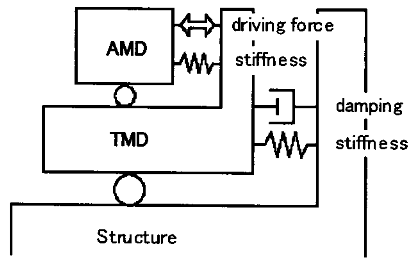

Figure 3. HMD system.

as long as its stroke does not exceed specified limits. In the direction parallel to the base, the mass damper works as a TMD.

A number of other ideas have been employed in HMD systems. A unique type of HMD system has been implemented in two buildings: the Ando Nishikicho Building (completed in 1993) and the Dowa Kasai Phoenix Tower Building (completed in 1995). This system has a smaller mass driver installed on a larger TMD. The relation between the smaller mass driver and the TMD is schematically depicted in Figure 3. The upper mass driver is computer-operated in such a way as to excite the lower TMD. The movement of the TMD leads to more effective control operation than the ordinary passive TMD. In this system, an active mass driver is utilized to excite the lower TMD, not to directly suppress the oscillation of the building.

Most of the AMD and HMD systems were designed to stop operation during a severe seismic event. This is partially because most of the active-controlled buildings were designed in such a way as to maintain their safety without the need for active control operation, and partially because the active structural control technology at the current level must solve several issues to reach its ultimate goal of presenting an innovative scheme for earthquake disaster mitigation. These issues include availability of sufficient reserve power to accomplish control operation under a severe earthquake excitation, construction of highly reliable schemes that will be operational during large earthquakes, etc.

4.2. Semiactive control

Considering the feasibility of enhancing the safety for buildings against severe seismic excitation, fully active control schemes do not appear to be very promising at the current level of technology. Fully active control schemes would require a large amount of energy or power to counteract severe seismic excitation. In this regard, semiactive control is regarded as one of the most promising schemes. Although a clear definition of semiactive control has not yet been established in the field of structural control, semiactive control herein indicates a control system in which the actuator needs power only on specific occasions, not throughout the entire operation. Only when the characteristics or state of the actuator is changed, a limited amount of energy will be needed.

As of April 2000, according to our investigation, semiactive control has been applied to three buildings. They are: the No. 21 Building of Kajima Research Institute (completed in 1990); the Kajima Shizuoka Building (completed in 1997); and a new building in Keio

University School of Science and Engineering (completed in early 2000 and not listed in Table I).

The No. 21 building employed an active variable stiffness (AVS) system. This is only one practical example for the AVS system. In this three-storey building, two braces in each storey, six braces in total, are controlled to be either full-on or full-off in such a way as to have the most appropriate stiffness for the building (and thus the most appropriate natural frequency for the building). This on-off control operation is accomplished by using the measured and predicted ground shaking information. Since the control operation in this system is just conducted by opening or closing the valve of the device, only limited energy is needed even for the case of counteracting a severe earthquake excitation. The principle of this AVS system is basically not to allow structural resonance to occur with the external excitation (i.e. the fourth principle).

In the Kajima Shizuoka Building, a semiactive variable damping system has been employed. This building obtains the optimal control force by means of damping force (the fifth principle). The controller determines the optimal control force and controls the damping coefficient of oil dampers so as to produce such an optimal control force. In a way, this control system is also regarded as adding damping to the building (the second principle).

The new building of Keio University, just completed in early 2000, employs a semiactive-controlled base isolation system. The basic principle of base isolation is to reduce the energy flow into the main structure above the isolation system by allowing large deformation of the isolators. In this scheme, the damping incorporated into the isolation system is significant. Large damping would prevent the isolators from having large enough deformation, while small damping would cause such large response displacement as to exceed the clearance between the building and retaining walls. In view of this, the variable damping concept is practical. Variable damping is obtained by controlling the damping coefficient of oil dampers.

5. FUTURE DIRECTIONS AND CLOSURE

Since the Hyogoken-Nanbu earthquake (Kobe earthquake) in January 1995, Japanese people have been deeply concerned about the seismic safety of buildings and civil infrastructural systems. Reflecting upon this fact, the number of base isolation buildings in Japan has shown an enormous increase with accelerating speed, now with more than 700 base isolation buildings in total already constructed or having received construction permits.

On the contrary, the increase in the number of active-controlled buildings slowed after the Kobe earthquake, while nearly 20 active-controlled buildings had been constructed prior to this event. This is partially because after the Kobe earthquake the Japanese structural engineering community has been seeking immediate solutions to the problem of how to establish disaster mitigation strategies for severe earthquakes. In this regard, the current level of active structural control technology is not ready to immediately provide such a strategy. Most of the active-controlled buildings are aimed at response reduction against strong winds or moderate earthquakes, not against strong earthquakes.

More advanced active control strategies with the principle of less energy and better performance should be urgently developed for the purpose of enhancing safety against severe earthquakes. In this respect, semiactive control strategies seem to be one of the most promising schemes for structural control, with the expectation that it will mark the opening of the next-generation computer-controlled structural protective systems.

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REFERENCES

1. Kobori T, Koshika N, Yamada K, Ikeda Y. Seismic-response-controlled structure with active mass driver system. Part 1: Design. *Earthquake Engineering and Structural Dynamics* 1991; **20**:133–149.
2. Kobori T, Koshika N, Yamada K, Ikeda Y. Seismic-response-controlled structure with active mass driver system. Part 2: Verification. *Earthquake Engineering and Structural Dynamics* 1991; **20**:151–166.
3. Yao JTP. Concept of structural control. *Journal of Structural Division, ASCE* 1972; **98(ST7)**:1567–1574.
4. Yang JN. Application of optimal control theory to civil engineering structures. *Journal of Engineering Mechanics Division, ASCE* 1975; **101(6)**:819–838.
5. Masri SF, Bekey GA, Caughey TK. On-line control of nonlinear flexible structures. *Journal of Applied Mechanics ASME* 1982; **49**:877–884.
6. Chang JCH, Soong TT. Structural control using active tuned mass dampers. *Journal of Engineering Mechanics Division ASCE* 1980; **106(EM6)**:1091–1098.
7. Housner GW *et al*., Structural control: past, present, and future. *Journal of Structural Engineering*, *ASCE* 1997; **123(9)**:897–971.
8. Spencer Jr. BF, Sain MK. Controlling buildings: a new frontier in feedback. *IEEE Control Systems Magazine*: *Special Issue on Emerging Technologies* (T. Samad, Guest Ed.), 1997; **17(6)**:19–35.
9. Nishitani A. Application of active structural control in Japan. *Progress in Structural Engineering and Materials* 1998; **1(3)**:301–307.
10. Kobori T. Quake resistant and nonlinear problems of the structural vibrations to violent earthquake. *Journal of Kyoto University Disaster Prevention Laboratory*; *5th Anniversary Edition* 1956; 116–124 (in Japanese).
11. Kobori T. The direction of earthquake resistant engineering. *Journal of Architecture and Building Science* 1958; **73**:5–9 (in Japanese).
12. Kobori T, Minai R. Analytical study on active seismic response control: seismic-response-controlled structure 1. *Transactions of Architectural Institute of Japan* 1960; **66**:257–260 (in Japanese).
13. Kobori T, Minai R. Condition for active seismic response control: seismic-response-controlled structure 2. *Transactions of Architectural Institute of Japan* 1960; **66**:253–256 (in Japanese).

