Journal of Japan Association for Earthquake Engineering, Vol.4 No.3 (Special Issue), 2004

ACTIVE AND SEMI-ACTIVE CONTROL
OF
BUILDINGS IN JAPAN

Yoshiki IKEDA

Member of JAEE, Principal Research Engineer, Kobori Research Complex, Kajima Corporation,
Tokyo, Japan, ikeda-yoshiki@kajima.com

ABSTRACT: During the last two decades, active and semi-active control of civil engineering structures has made rapid progress in Japan. This technology has become widely used in earthquake engineering design, and more than 50 control systems have already been applied to buildings in Japan. The 1995 Hyogo-ken Nanbu Earthquake opened a door to positive development of semi-actively-controlled buildings against large earthquakes. This paper reports the state of the art by introducing practical applications, and describes future perspectives.

Key Words: active and semi-active control, building structures, practical applications, future perspectives

INTRODUCTION

During the last twenty years, active and semi-active vibration control of civil engineering structures has attracted growing worldwide interest as an innovative technology in the earthquake engineering field. In Japan, research and development (R & D) has made rapid progress, since the concept of active control was widely expected to exceed the performance limitations of conventional earthquake-resistant structures (Kobori *et al*. 1986). Active and semi-active control has already become a structural design item to be considered for high-rise buildings. The journal of *Earthquake Engineering & Structural Dynamics* published a special issue on “Practical applications of active and semi-active structural control systems to actual civil engineering structures” in November 2001. An overview paper indicated a list of 31 practical applications in Japan from 1989-1998 (Nishitani and Inoue 2001). At present, more than 50 buildings have been equipped with active and semi-active control systems to suppress vibrations under earthquake and wind excitations.

The R & D is categorized in four stages. In the first stage up to the late 1980s, the fundamental dynamic properties of active control were understood theoretically and experimentally from the civil engineering viewpoint. The next stage evidently started in 1989 when an active mass damper system was first applied to a building. The 1995 Hyogo-ken Nanbu Earthquake opened the door to the third stage where buildings can be semi-actively controlled even under large earthquakes. Now, the fourth stage is about to start with the integration of structural control and health monitoring. Reflecting recent research, the Structural Control Sub-committee, the Architectural Institute of Japan (AIJ), published summaries of 43 practical applications in Japan from 1989-2002 and outlined 560 references in journals and conference proceedings (AIJ 2002).

This paper mainly reports the state of the art in Japan by renewing the list of practical applications of active and semi-active control to buildings in Japan and describes future perspectives in earthquake engineering. Many applications can be referred to *Earthquake Engineering & Structural Dynamics* Vol.30 No.11 (2001) and *the Proceedings of the First to the Third World Conferences on Structural Control* (1994, 1998, 2002).

ACTIVE CONTROL

Table 1 indicates 40 practical applications of active control to buildings in Japan. In the control system column, "AMD" means an active mass damper that is not tuned in to a certain natural frequency of an objective structure. "ATMD" means an active tuned mass damper; and "TMD with AMD" means a tuned mass damper on which is mounted an actively controlled mass damper. 39 applications are mass dampers and only one is an active interstructure damper system.

The second research stage started in 1989, when an AMD system was applied to a ten-story office building to suppress lateral and torsional vibrations under small/medium earthquakes and strong wind excitations [1 in Table 1]. This suddenly called our attention to many research items on practical applications such as controller-structural interaction problems, design of full-scale control devices, simultaneous control of vibrations in plural directions, auto-gain control strategies, non-linear control laws, modelling and system identification, failsafe, and maintenance operations. Although mass dampers cannot protect buildings from large earthquakes, they have produced a lot of the R & D on active control. To solve the problem of auxiliary mass scale, two AMD systems first utilize facilities such as heat storage tanks and a heliport on roofs [2 & 3]. Most control systems have been installed to work when objective structures are subjected to not only earthquakes but also wind excitations. By considering only the lowest vibration mode that has the largest amplitude of all modes, the AMD system can be simplified to reduce its external energy supply. The ATMD system has comprised most mass damper applications since two were installed on a fifty-story building [4]. The derivation of ATMD is an active-passive composite TMD, i.e. a TMD with an AMD. The AMD effectively moves the TMD to cope with inharmonic excitations, because the passive TMD cannot react instantaneously. The TMD with the AMD is also thought to save the external energy supply by utilizing resonance. A TMD system with AMD was first applied to a 14-story office building [7]. In addition, two active interstructure dampers have been installed in two bridges among three high-rise buildings to suppress wind-induced vibrations [36]. The maximum control force per damper is 340 kN.

In general, active control systems are designed on the Linear Quadratic Regulator (LQR) theory or H-infinite control theory, and the state feedback control laws are converted into output feedback ones. Non-linearity and transmissibility of control systems are considered in controller-structural interaction models in detailed design. In designing many mass dampers, we learn their general behavior under small/medium earthquakes and frequent wind excitations (AIJ 2002). The equivalent damping ratio in the objective vibration mode is approximately 4 % to 15 %. When the mass ratio is defined as the total auxiliary mass weight to the total building weight, the ratio for the ATMD is 0.06 % to 1.85 % and the average except for No.18 is 0.32 %. The ratio for the TMD with the AMD is 0.16 % to 0.85 % and the average is 0.35%.

There are four main methods for verifying the installed active control systems. Both free vibration tests and forced vibration tests are often conducted just before completion of a building to compare the controlled response with the uncontrolled one and to estimate the equivalent natural frequencies and the corresponding damping ratios. Earthquake observation is utilized to identify a controller-structural model. After the identification, the uncontrolled response is estimated only through a structure model. The fourth method is to estimate the equivalent damping ratios through the poles of ARX models or the frequency transmissibility. These verification methods are similarly applied to semi-active control.

Table 1 Practical applications of active control to buildings in Japan

(* indicates the 1st modal effective weight)

Completion date		Objective buildings (Use, City)	Main structure	Story	Height (m)	Total weight (t)		Control system
						Bldg.	Damper	
1989	1	Kyobashi Center Bldg. (office, Tokyo)	S	10	33	400	5.4	2 AMDs
1991	2	Sendagaya INTES (office, Tokyo)	S	11	58	*3,280	72	2 AMDs
1992	3	Appluase Tower (hotel, office & theater, Osaka)	S	34	162	*13,940	480	AMD
	4	ORC 200 Bay Tower (hotel, office & residence, Osaka)	S	50	200	56,680	200	2 ATMDs
	5	Kansai Airport Control Tower (control tower, Osaka)	S	5	86	2,570	10	2 ATMDs
1993	6	NTT Cred Motomachi Bldg. (hotel & store, Hiroshima)	SRC,S	35	150	82,900	80	ATMD
	7	Nishimoto Kosan Nishikicho Bldg. (office, Tokyo)	S	14	68	2,600	22	TMD with AMD
	8	Long Term Credit Bank (office, Tokyo)	S	21	130	39,800	195	ATMD
	9	Porte Kanazawa (hotel & office, Kanazawa)	S	30	131	*10,150	100	2 AMDs
	10	Yokohama Landmark Tower (hotel, office & store, Yokohama)	SRC, S	70	296	260,600	340	2 ATMDs
1994	11	J City Tower (office, Tokyo)	S	24	100	25,390	44	2 ATMDs
	12	Shinjuku Park Tower (hotel & office, Tokyo)	S	52	233	130,000	330	3 ATMDs
	13	Hamamatsu ACT Tower (hotel, office & store, Hamamatsu)	S	45	213	107,530	180	2 ATMDs
	14	Hirobe Miyake Bldg. (office & residence, Tokyo)	S	9	30	273	2.1	ATMD
	15	Hotel Ocean 45 (hotel, Miyazaki)	S	43	154	83,650	240	2 ATMDs
	16	MHI Yokohama Bldg. (office & store, Yokohama)	S	34	152	61,800	60	ATMD
	17	Riverside Sumida Central Tower (office & residence, Tokyo)	S	33	134	52,000	30	2 AMDs
1995	18	Osaka World Trade Center Bldg. (office,Osaka)	S	55	255	*28,000	100	2 ATMDs
	19	Nissei Dowa Sonpo Phoenix Tower (office, store & hall, Osaka)	S	29	145	26,800	42	2 TMDs with AMD
	20	Plaza Ichihara (hall, Chiba)		12	58	5,760	14	2 ATMDs
1996	21	Rinku Gate Tower Bldg. (hotel, office & hall, Osaka)	S	56	255	65,000	160	2 ATMDs
1997	22	The Itoyama Tower (office & residence, Tokyo)	CFT, S	18	90	9,030	27	ATMD
	23	Nisseki Yokohama Bldg. (office, Yokohama)	S	30	133	53,000	100	2 ATMDs
	24	Herbis Osaka (hotel & office, Osaka)	S	40	190	*22,750	320	2 AMDs
1998	25	Oita Oasis Tower (hotel, Oita)	S	21	101	20,940	49	2 ATMDs
	26	OTIS Shibayama Test Tower (elevator test, Chiba)	S	39	154	6,880	35	ATMD
	27	Odakyu Southern Tower (hotel, office & store, Tokyo)	CFT, S	36	151	50,000	60	2 ATMDs
	28	Kaikyo Messe Yume Tower (observation, Shimonoseki)	S	11	153	5,400	100	ATMD
	29	Bunka Gakuen (school, Tokyo)	CFT, S	20	93	43,490	24	2 ATMDs
	30	Yokohama Bay Sheraton Hotel & Towers (hotel, Yokohama)	S	27	115	33,000	122	2 ATMDs
1999	31	JR Central Towers (Nagoya): Office Tower	CFT, S	51	245	300,000	150	2 ATMDs
		Hotel Tower	CFT, S	53	226	(Total)	240	4 ATMDs
	32	Shinagawa Intercity Bldg. (office, Tokyo)	S	32	144	50,000	150	2 ATMDs
	33	Century Park Tower (residence, Tokyo)		54	170	124,540	440	4 ATMDs
2001	34	Osaka Airport Control Tower (control tower, Osaka)	S	5	69	3,600	10	2 ATMDs
	35	Cerulean Tower (hotel & office, Tokyo)	S	41	184	65,000	110	2 ATMDs
	36	Office Towers, Triton Square, Harumi Island (office & store, Tokyo) Tower X	S	45	195	*27,300	-	2 Active Interstruct. Dampers (Max.force 340 kN)
		Tower Y	S	40	175	*24,500		
		Tower Z	S	34	155	*24,000		
2001	37	Hotel Nikko Bayside Osaka (hotel, Osaka)	S	33	138	37,000	124	2 ATMDs
	38	Dentsu Head Office Bldg. (office, Tokyo)	S	48	210	130,000	440	2 TMDs with AMD
2003	39	Shiodome Tower (hotel & office, Tokyo)	CFT, S	38	172	53,200	100	2 TMDs with AMD
	40	Shiodome Media Tower (hotel, office, Tokyo)	S	34	172	44,700	100	2 TMDs with AMD

SEMI-ACTIVE CONTROL

In the third research stage, objective structures can be semi-actively controlled even under large earthquakes. Semi-active control requires an extremely small amount of external energy to produce a large control force, because it dynamically changes the structural damping coefficient/stiffness by merely regulating parameters of a control device such as an actuator. It is recognized as one of the solutions to highly efficient active control. Strictly speaking, there is not yet any clear definition of the amount of energy to distinguish semi-active control from active control.

The first application of semi-active control was an active variable stiffness (AVS) system installed in three-story experimental facility [1 in Table 2]. Based on the nature of an input earthquake, the AVS system selects on-line one of three structural stiffness types to establish a non-resonant state. Since the 1995 Hyogo-ken Nanbu Earthquake, semi-active control has been regularly applied to actual building structures. In 1998, a semi-active oil damper system was installed in a five-story office building [2]. Each oil damper produces a maximum force of 1,000 kN with an electric power of only 70 W. The system continuously changes the damping forces by adjusting the opening of valves that the confined oil flows through. The control law is based on the LQR theory. An on/off type semi-active damper [5] follows this development by simplifying the controller. In most cases, a semi-active damper is installed in a structure equipped with braces. The on/off type damper utilizes the fact that the Maxwell model constrains its force-displacement hysterisis loop within a certain limited area by its stiffness values. Each damper measures a cylinder rod's stroke and two oil pressures (supply and demand) in each built-in controller to establish a decentralized autonomous system. On/off type oil dampers have already been applied to nine buildings. Three systems [5, 6, 11] work with passive oil dampers and one system [9] works with two passive-active composite TMDs [39 in Table 1].

TMD and base isolation have also adopted the principal of semi-active control. A semi-active TMD [3] is usually set at the optimal damping factor to operate as a passive TMD to reduce wind-induced vibrations. It changes the damping capacity by switching the electromagnetic valve to keep the auxiliary mass within the stroke limitation. Base isolation with semi-active oil damper [4] selects one of five damping coefficients by changing the valve opening.

Table 2 Practical applications of semi-active control to buildings in Japan

Completion date		Objective buildings (Use, City)	Main structure	Story	Height (m)	Bldg. weight (t)	Max.force per damper (kN)	Control system
1990	1	Kajima Research Institute, Bldg. No.21 (laboratory, Tokyo)	S	3	12	400	700	AVS (6 on/off devices)
1998	2	Kajima Shizuoka Bldg. (office, Shizuoka)	S	5	20	1,100	1,000	8 oil dampers (contin.)
1999	3	Laxa Osaka (hotel & office, Osaka)	S	24	97	*11,150	1,300	2 oil dampers for 2 TMDs (2TMDs: 330t)
2000	4	House of Creation & Imagination, Keio Univ. (school, Yokohama)	SRC, CFT, S	7	29	25,460	640	8 oil dampers for base isolation
2001	5	Chuden Gifu Bldg. (office, Gifu)	S	11	56	18,000	1,500	42 oil dampers (on/off)
2003	6	Bandaijima Bldg. (hotel & office, Niigata)	CFT, S	31	141	22,500	1,500	72 oil dampers (on/off)
	7	Tokyo Head Office Bldg., Matsushita Electric Works (office, Tokyo)	CFT, S	25	120	37,500	1,500	38 oil dampers (on/off)
	8	Roppongi Hills Mori Tower (art museum, office & store, Tokyo)	CFT, S	54	241	290,000	2,100	356 oil dampers (on/off)
	9	Shiodome Tower (hotel & office, Tokyo)	CFT, S	38	172	53,200	1,500	88 oil dampers (on/off)
	10	Toppan Forms Bldg. (office, Tokyo)	CFT, S	19	100	18,400	2,100	27 oil dampers (on/off)
	11	Head Office Bldg., Nippon Express (office, Tokyo)	CFT, S	28	137	32,500	1,500	60 oil dampers (on/off)
2004	12	Higashi Shinagawa Office Bldg. (office, Tokyo)	CFT, S	23	100	29,000	1,500	28 oil dampers (on/off)
	13	Tokyo Prince Park Tower (hotel, Tokyo)	CFT, S	30	105	34,700	2,100	66 oil dampers (on/off)

Semi-active control affects conventional seismic-resistant structures and passively controlled structures, since it can be approached from either passive control or active control. In the past, the terminology "structural control" usually meant active control. Now, structural control includes not only active and semi-active control but also passive control. In other words, vibration problems in civil engineering are examined again from the standpoint of control engineering.

FUTURE PERSPECTIVES

Experience in practical applications is now leading us to the fourth stage of this attractive technology. Future perspectives of active and semi-active structural control will be based on the knowledge obtained in the last two research stages (Yang, J.N. and Dyke, S.C. 2002). (1) Structural control should follow economic principles with development of inexpensive control devices. It is scientifically important to divide intrinsic and essential properties from extrinsic and inessential properties *to develop highly efficient control systems*. (2) Researchers and engineers have recognized the necessity to reach a consensus on *evaluation criteria for structural control*. (3) *Integration of structure and controller designs* is required so that the dynamics of the control cooperates rather than competes with the structure dynamics. Simultaneous design of structure and controller can require a smaller amount of control energy to attain the same performance. (4) *Long-term accumulation of earthquake observation records* verifies active and semi-active control systems especially under large earthquakes. (5) *Maintenance of control devices* should be carefully considered in design to widely spread active and semi-active control. Maintenance and replacement always exists with unpredictable accidents in serving controllers. (6) *Integration of structural control, system identification and health monitoring* effectively utilizes sensors in active/semi-active control systems. The integration is expected to be one of new technologies in usual building management. Observation data in closed loop and high damping make controller-structural systems less sensitive to external disturbances. This advantage makes system identification using observation records difficult. Item (6) contains not only Items (4) and (5) but also various problems on active and semi-active structural control.

CONCLUSIONS

The state of the art in Japan on active and semi-active structural control is reported by introducing practical applications, and future perspectives are described on present research progress.

REFERENCES

AIJ (2002). *References and practical applications of active and semi-active structural control* (Books for Symposium on Active Control), Architectural Institute of Japan (AIJ), JAPAN (in Japanese).

Kobori, T. *et al*. (1986). "New philosophy of aseismic design: Approach on dynamic intelligent building system." *Summaries of technical papers of annual meeting, Architectural Institute of Japan*, Vol.B-1, 837-838 (in Japanese).

Nishitani, A. and Inoue Y. (2001). "Overview of the application of active/semi-active control to building structures in Japan." *Earthquake Engineering & Structural Dynamics*, Vol.30, 1565-1574.

Yang, J.N. and Dyke, S.J. (2002). "Future perspectives on structural control." for Kobori Panel Discussion, *Proc. of Third World Conference on Structural Control*, Vol.3, 279-286

(Submitted: March 19, 2004)
(Accepted: June18, 2004)