The National Science Foundation's Summer Institute in Japan Program

Active Structural Control Research at Kajima Corporation

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Responsible for my placement at the Kobori Research Complex was Dr. Fujino of the University of Tokyo. During my brief stay at the Kobori Research Complex, the complex's expertise, facilities and personnel impressed me. All of the engineers at the complex were willing to give of their time to explain and demonstrate the structural control systems they have helped designed. Many thanks to Dr. Kobori, President of the Kobori Research Complex, and Mitsuo Sakamoto, Deputy Director of the Kobori Research Complex who invited me to conduct research at Kajima. My deepest gratitude goes to my formal hosts, Akihiro Kondo, Research Engineer and Tomohiko Hatada, Senior Research Engineer, who both made every effort to assist me in all aspects of my research. Furthermore, they are great friends who provided me with a deeper understanding of Japanese culture and life.

Introduction

Japan is a nation which has been plagued by earthquakes and other natural disasters such as typhoons since the beginning of time. History shows that Japan experiences an earthquake of magnitude seven or greater every ten years. The Japanese have recognized this fact and they seek to protect themselves from these natural disasters. For well over two decades, Japanese structural engineers have played a significant role in advancing active structural control research. Structural control technology, still nascent in its development, is a technology aimed at reducing vibrations of structures which are caused by strong winds or earthquakes, thus protecting the structures and their inhabitants. The accomplishments by the Japanese researchers and engineers in the field of structural control can be clearly seen. For instance, almost all structural engineering programs at the university level have made active structural control research a top priority. Japanese construction companies such as Kajima Corporation in Tokyo have taken the worldwide lead by developing successful structural control systems for buildings they have designed and constructed. To date, as shown in Table 1, there are well over 20 buildings in Japan which are actively controlled while none exist outside Japan. At the present time, the technology is sufficient to protect structures from winds and moderate earthquakes but current Japanese research is investigating systems which can be used in large earthquakes such as the Hyogoken-Nanbu earthquake (Kobe earthquake). [1]

Through a unique opportunity provided by the Summer Institute in Japan Program organized under the auspices of the National Science Foundation, I spent eight weeks in the Summer of 1998 at Kajima Corporation investigating structural control systems that they have developed and are developing. Of all of the Japanese companies developing such control systems for structures, Kajima has been the most successful with five different active control systems fully developed to date. In addition, my research schedule allowed for professional visits to other Japanese construction companies conducting similar research as well as prestigious Japanese universities. Such an opportunity can only be found in Japan due to the unfortunate fact that the American building industry has not yet considered the use of active structural control for structures. The result has been that American companies have not developed and installed a full scale active structural control system. The engineering community's reluctance in developing active structural control technology is due to the field's conservatism and the lack of widely approved analysis and design procedures. Currently, active structural control research is being conducted only in universities and research laboratories located throughout the United States which have all made significant contributions to the field. The current research trends in the American universities is in the direction of semi-active structural control which has proven to be cost effective and highly reliable. It is inevitable though that American structural engineers will be using active structural control in future designs of structures, especially those in the seismic regions of the United States.[2]

This report is an attempt to review the active structural control systems investigated during my summer at the Kobori Research Complex of Kajima Corporation. First, the summer's itinerary is presented as well as an overview of the Kajima corporation. Second, the terms used in discussing active control systems are introduced followed by an in-depth discussion of Kajima's active structural control systems. The systems investigated date back as far as 1989 when Kajima constructed the Kyobashi Seiwa Building in Tokyo which was the world's first actively controlled building. The five control systems can be classed into two categories, active and semi-active systems. The control systems that Kajima has developed to date include the active mass driver system, the TRIGON system and the DUOX system which are active control systems. There are also the active variable stiffness system and the active variable damping system which are semi-active control systems. The report concludes with a closing discussion on the future direction of control research in Japan and the United States.

Table 1 - Active Structural Control Buildings in Japan

Source: Nishitani, A.. Application of Active Structural Control in Japan. Progress in Structural Engineering and Materials, 1998 Vol 1, pg 301-307.

Building	Type	Stories Above/ Below	Height (m)	Mass of AMD or HMD (t)	Total Mass (t)	Period (s)	Control Type	Target Wind	Response to Large Earthquakes
Kyobashi Seiwa Building, Tokyo, Office, 1989	Steel	11/1	33	5	390	1.1 T 0.76 L	AMD	20 m/s	Stop
Kajima Research Institute, Tokyo, Laboratory, 1990	Steel	3/0	12		400	0.41 T 0.32 L	AVS		Effective
Sendagaya INTES, Tokyo, Office, 1992	SRC Steel	11/1	44	72	3,300		AMD	RP: 5 years	Stop
Applause Tower, Osaka, Hotel/Office, 1992	Steel	34/3	161	480	13,000	4.7 T 4.8 L	AMD	RP: 5 years	Stop
Kansai Airport Control Tower, Osaka, 1992	Steel	7/0	86	10	2,600	1.3 T 1.3 L	HMD	Strong Wind	
Osaka ORC200, Osaka, Office/Hotel, 1992	Steel	50/3	200	200	57,000	4.7 T 4.7 L	HMD	RP: 5 years	Stop
Ando Nishikicho Building, Tokyo, Office, 1993	Steel	14/2	54	24	2,500	1.4 T 1.4 L	HMD	RP: 20 years	Continue Working
Yokohama Landmark Tower, Yokohama, Hotel/Office, 1993	Steel	70/3	296	340	26,0000	6.0 T 6.1 L	HMD	RP: 5 years	Stop
Long Term Credit Bank, Tokyo, Office, 1993	Steel	21/5	129	195	39,000	3.0 T 3.1 L	HMD	Strong Wind	Continue Working
Porte Kanazawa, Kanazawa, Hotel/Office, 1994	Steel	29/2	121	100	27,000	3.2 T 3.4 L	HMD		
Shinjuku Park Tower, Office/Hotel, 1994	Steel	52/5	232	330	120,000	5.2 T 4.5 L	HMD	RP: 5 years	Stop
RIHGA Royal Hotel, Hiroshima, Hotel, 1994	Steel	35/2	150		83,000	3.6 T 3.8 L	HMD	RP: 5 years	Stop
MHI Yokohama Building, Yokohama, Office, 1994	Steel	34/2	152			3.9 T 3.8 L	HMD	RP: 5 years	Stop
Hikarigaoka City Building, Tokyo, Office/Hotel, 1994	Steel	24/3	100	80	29,000	2.2 T 2.3 L	HMD		Stop
Hamamatsu ACT City, Hamamatsu, Office/Hotel, 1994	Steel	46/2	212	180	110,000	4.7 T 4.5 L	HMD	RP: 5 years	Stop
Riverside Sumida, Tokyo, Residential, 1994	Steel	33/2	134	30	52,000	3.5 T 3.5 L	AMD	RP: 5 years	
Hotel Ocean 45, Miyazaki, 1994	Steel	43/2	154	240	80,000	3.6 T 3.9 L	HMD TMD	RP: 5 years	
Osaka World Trade Center, Osaka, Office, 1995	Steel	52/3	252		75,000	5.3 T 5.8 L	HMD	RP: 5 years	Stop
Dowa Kasai Pheonix Tower, Osaka, Office, 1995	Steel	28/3	144	72	27,000	3.8 T 3.6 L	HMD	RP: 5 years	Continue Working
Rinku Gate Tower Building , Osaka, Office, 1995	Steel SRC	56/2	255		75,000	4.4 T 4.4 L	HMD	RP: 5 years	
Hirobe Miyake Building, Tokyo, Office, 1995	Steel	9/0	30	2	270	0.81 T	HMD	RP: 1 year	
Plaza Ichihara, Chiba, 1995	Steel	12/0	61	14	5,760		HMD		
Herbis Osaka, Osaka, Office/Hotel, 1997	Steel	40/5	189			5.1 T 5.1 L	AMD		

RP = Return Period SRC = Steel Reinforced Concrete AMD = Active Mass Damper
AVS = Active Variable Stiffness HMD = Hybrid Mass Damper

Summer Research Itinerary

The Summer Institute Program in Japan is a National Science Foundation sponsored program which invites over forty American Ph.D. students from various backgrounds in the sciences and engineering to conduct research in Japan during the summer. The program is eight weeks in duration of which two are spent in intensive Japanese language training. The remaining six weeks are devoted to research related activities in the host institution. The Kobori Research Complex of Kajima Corporation located in Akasaka, Tokyo accepted to be my host for the summer. My research primarily focused on investigating the design and workings of their five active control systems. An additional objective was to learn about Kajima and the Japanese construction industry. During my stay at the Kobori Research Complex, I was supervised by Mr. Akihiro Kondo and Mr. Tomohiko Hatada, who ensured that I was given full access to every member of the complex and all scholarly publications relative to their control systems. As part of my investigation, Mr. Kondo arranged for tours of buildings employing each active control system under investigation. During the sixth week of the Summer Institute, I was given the opportunity to spend a week at the Kajima Technical Research Institute (KaTRI) in Chofu, Tokyo learning about KaTRI's research facilities and research activities.

The United States Panel on Structural Control partly funded and organized professional visits for the American students conducting research in the area of active structural control. These trips were organized by Professor Spencer of the University of Notre Dame who was the panel's representative in Japan overseeing the students who are interested in active structural control. A U.S.-Japan Seminar on Structural Control at University of Tokyo was held on July 8 where students presented their current Ph.D. research work. On August 7, a Student Symposium on Structural Control was held at Waseda University where a presentation of each student's summer activities was given. Numerous trips were also scheduled during the program. In particular, a trip was arranged to the Hanshin area from July 22 to July 25. This trip included a tour of the Akashi Kaikyo Suspension bridge, the longest suspension bridge in the world, as well as a tour of the new elevated Hanshin Expressway in Kobe which was destroyed during the Hyogoken-Nanbu earthquake (Kobe earthquake) in 1995. An opportunity was given to see the active mass damper system of the Herbis Osaka Building designed by Takenaka in Osaka city. The trip concluded with a tour of Kyoto University's excellent structural testing facilities where some very interesting active structural control research is underway on full scale structures.

The following schedule clearly delineates my activities during the course of the eight weeks spent in Japan. See Table 2 and Table 3.

Table 2 - Schedule of Summer Institute in Japan 1998 Program (June 23 to July 26, 1998)

Note: Yellow Box Denotes NSF Mandatory Event and Gray Box Indicates US Panel on Structural Control Group Event

	Monday	Tuesday	Wednesday	Thursday	Friday	Sat/Sun
	June 22	**June 23**	**June 24**	**June 25**	**June 26**	**June 27, 28**
Week 1		Depart New York JFK for Japan	Arrive in Narita Airport Shuttle Bus to Hotel in Narita	Summer Institute in Japan 1998 Orientation in Narita Summer Institute in Japan 1998 Orientation in Narita	Bus Departs for Tsukuba Summer Institute in Japan 1998 Orientation in Tsukuba	
	June 29	**June 30**	**July 1**	**July 2**	**July 3**	**July 4, 5**
Week 2	Japanese Language Training - Tsukuba Japanese Language Training - Tsukuba	Japanese Language Training - Tsukuba Japanese Language Training - Tsukuba	Japanese Language Training – Tsukuba Japanese Language Training – Tsukuba	Japanese Language Training - Tsukuba Japanese Language Training - Tsukuba	Japanese Language Training - Tsukuba Japanese Language Training - Tsukuba	
	July 6	**July 7**	**July 8**	**July 9**	**July 10**	**July 11, 12**
Week 3	Japanese Language Training - Tsukuba Japanese Language Training - Tsukuba	Japanese Language Training - Tsukuba Bus Departs for Tokyo	Japanese Language Training - Tokyo Seminar on Structural Control at University of Tokyo	Japanese Language Training - Tokyo Introduction to Kobori Research Complex (KRC)	Visit Shinjuku Park Tower Visit Ishikawajima-Harima Heavy Industries	
	July 13	**July 14**	**July 15**	**July 16**	**July 17**	**July 18, 19**
Week 4	Japanese Language Training Tour of KI Building Introduction to Active Control (Hatada-san)	Japanese Language Training Visit to Kajima Technical Research Institute (KaTRI)	Japanese Language Training Visit to Kyobashi Seiwa Building (Sasaki-san)	Research Meeting of Advance Structural Engineering Dept. of KRC Visit to Ando Nishikicho Building (Orui-san, Kondo-san)	NSF Trip to Nikko NSF Trip to Nikko	NSF Trip to Nikko NSF Trip to Nikko
	July 20	**July 21**	**July 22**	**July 23**	**July 24**	**July 25, 26**
Week 5	National Holiday	Introduction to Active Variable Stiffness (Nasu-san) Dynamic Analysis of High Rise Buildings (Orui-san)	Tour of Akashi Kaikyo Suspension Bridge in Kobe Tour of Kobe's Hanshin Expressway	Tour of AMD System of Herbis Osaka Building in Osaka Tour of Disaster Prevention Research Institute of Kyoto University	Tour of Kyoto University Sight Seeing in Kyoto	Sight Seeing in Kyoto Kabuki Theater in Tokyo

<u>Table 3 - Schedule of Summer Institute in Japan 1998 Program (July 27 to August 21, 1998)</u>

Note: Yellow Box Denotes NSF Mandatory Event and Gray Box Indicates US Panel on Structural Control Group Event

	Monday	Tuesday	Wednesday	Thursday	Friday	Sat/Sun
Week 6	**July 27**	**July 28**	**July 29**	**July 30**	**July 31**	**August 1, 2**
	KaTRI - Introduction and Shaking Table (Igarashi-san) KaTRI - Earthquake Hazard Mitigation (Kohiyama-san)	KaTRI - Analysis with Computers (Horikoshi-san) KaTRI - Analysis with Computers (Horikoshi-san)	KaTRI - Base Isolation (Iizuka-san) KaTRI - Base Isolation (Iizuka-san)	KaTRI - Structural Control Research (Tagami-san) KaTRI - Structural Control Research (Tagami-san)	KaTRI - Soil Structure Interaction (Matsumoto-san) KaTRI - Soil Structure Interaction (Matsumoto-san)	
Week 7	**August 3**	**August 4**	**August 5**	**August 6**	**August 7**	**August 8, 9**
	Research Work Shaking Table Test Discussion (Nakayama-san)	Research Work Introduction to Active Variable Damping System (Kurata-san)	Research Work Introduction to Kajima Computer System	Research Work Discussion of AMD System (Ikeda-san)	Student Symposium at Waseda University Student Symposium at Waseda University	
Week 8	**August 10**	**August 11**	**August 12**	**August 13**	**August 14**	**August 15, 16**
	National Holiday Obon Week	National Holiday Obon Week	National Holiday Obon Week	National Holiday Obon Week	National Holiday Obon Week	
Week 9	**August 17**	**August 18**	**August 19**	**August 20**	**August 21**	**August 22**
	Final Presentation to Kobori Research Complex Research Work	Research Work Research Work	Research Work Research Work Farewell Party at Kajima	Bus Departs for Tsukuba Speech Contest Closing Ceremony	Bus Departs for Narita Airport Return to New York JFK	

Kajima Corporation and The Kobori Research Complex

Kajima Corporation is one of Japan's oldest and largest construction firms which was founded in 1840 by Iwakichi Kajima. It was not until 1860 that Kajima became a leader in its field by constructing Japan's first European-style building in Yokohama. Since its early beginning over one hundred and fifty years ago, Kajima has grown into a large public company of well over 13,000 employees. As is typical of Japanese construction firms, Kajima is divided into numerous divisions which incorporate all facets of the building industry. Currently, Kajima Corporation's business activities can be divided into five categories; planning, design and engineering, construction, business real estate development, and research and development. [3]

Kajima was the first Japanese construction firm to establish a research and development division with the creation of The Kajima Technical Research Institute (KaTRI) in 1949. In its fifty years of existence, this institute has been active in conducting research in the civil and structural engineering fields. In the realm of structural engineering, KaTRI can conduct testing of scaled model structures in its two wind tunnels, test structural members in the large-size structural testing laboratory, and test the seismic behavior of scaled structures with its 5m x 5m six degree of freedom shaking table. The institute has been an extremely important component of Kajima Corporation because its research has led to Kajima's ability to undertake new and revolutionary projects which employ new materials, new designs and new construction methods. Many passive control technologies have been developed at KaTRI including the Honeycomb Damper which is an elasto-plastic steel damper as well as the HiDAM oil damper. KaTRI has also had great success in developing earthquake and microtremor isolation systems for buildings. See Appendix A. [4]

In 1986, a sister research group to The Kajima Technical Research Institute was created called The Kobori Research Complex. This complex, under the direction of Dr. Takuji Kobori, is responsible for research specifically focused upon technology to protect structures from earthquakes and strong winds. Since its creation, the Kobori Research Complex has been very successful in developing active control devices as well as numerous passive damping devices for structures which are subjected to large vibration responses. The Kobori Research Complex has assisted in the design of 6 buildings with active and semi-active control systems. Utilizing the Honeycomb Damper, the complex has designed 28 new buildings and utilized the technology in 6 retrofit projects. Using the HiDAM oil damper, Kobori has designed 6 buildings. Additional information regarding these projects can be found in Table 4. [5]

Table 4 - Kobori Research Complex Structural Control Projects since 1986

Source: Mitsuo Sakamoto, General Manager of Advanced Structural Engineering Department of Kobori Research Complex. 1998.

Table Applied Buildings of Structural Control System

Kobori Research Complex Inc. / Kajima Corporation. 8.1998

Control System			Name of Building	Client	Location	Structure	Story	Height(m)	Total Fl. Area(m²)	Usu ob Building	Compl.
Active & Semi-Active	Auxiliary Mass	Active Mass Driver	Kyobashi Seiwa Bldg.	Seiwa Jisho Corp.	Chuou-ku Tokyo	S	11,B1	32.8	423	Office	1989
		Active Passive Composite Tuned Mass Damper(DUOX)	Ando-Nishikicho Bldg.	Ando Shouten Corp.	Chiyoda-ku Tokyo	S	14,B2	53.55	4,928	Office	1993
			Dowa Kassai Phoenix Tower	Dowa Kasai Marine & Fire Ins.	Kita-ku Osaka	S	29,B3	145.45	30,370	Office, Concert Hall	1995
		Hybrid Mass Damper(TRIGON)	Shinjuku Park Tower	Tokyo Gas Corp.	Shinjuku-ku Tokyo	S	52,B5	226.5	264,129	Office, Hotel, Showroom	1994
	Variable Stiffness	Active Variable Stiffness(AVS)	Vibration Test Facility of KaTRI	Kajima Corp.	Chofu-shi Tokyo	S	3	12	465	Labolatory	1990
	Variable Damping	Active Variable Damping(AVD)	Kajima Shizuoka Bldg.	Kajima Corp.	Shizuoka-shi Shizuoka	S	B1,5	19.75	1,685	Office	1998
Passive	Auxiliary Damping for Story Drift	Honeycomb Damper (Elasto-Plastic Steel Damper)	Oji Papaper Co. Headquaters Bldg.	Oji Paper Corp.	Chuou-ku Tokyo	S	15,B4	68.4	18,616	Office, Event Hall	1991
			Sea Fort Tower	Mitsubishi Shouji Corp.	Shinagawa-ku Tokyo	S+SRC	29,B1	93.65	148,885	Hotel, Housing	1992
			Kamogawa Grand Tower	Kamogawa Grand Hotel Corp.	Kamogawa-shi Chiba	RC	33,B1	99.55	30,494	Hotel	1992
			Aeon Tower	Aeon Group Corp.	Mihama-ku Chiba	S	26,B1	112.55	52,566	Office	1994
			Granpark Heights	NTT Urban Develop. Corp.	Minato-ku Tokyo	RC	28,B4	88.35	19,594	Housing	1996
			Shin-Kobe Apartments	Takesu Corp.	Chuou-ku Kobe	SRC	14,B1	43.9	10,428	Housing	1997
			Asule Esaka	Nippon Lease Corp.	Suita-shi Osaka	SRC	14	39.25	3,166	Housing	1997
			Garden City Nishi-Umeda Bldg.	Rail City West Devlop.Corp.	Kita-ku Osaka	S	21,B3	75.54	31,785	School	1998
			Hiroshima East Bldg.	Kajima Corp.	Minami-ku Hiroshima	S	19,B1	77.63	24,691	Office, Shop	1998
			Ginza Sawamoto Bldg.	Sawamoto Shouten Corp.	Chuou-ku Tokyo	S	8,B2	27.7	2,237	Office	1997
			Shiba Center Bldg.	Orix Corp.	Minato-ku Tokyo	S	18,B1	70	21,529	Office	1998
			Kobe KIMEC Center Bldg.	Kobe City	Chuou-ku Tokyo	S	11,B1	48.95	17,396	Office	1998
			Toshiba Fukoku Insurance Bldg.	Toshiba Corp. & Fukoku Life Ins.	Naka-ku Tokyo	S+SRC	11,B1	43.7	15,793	Office	1997
			Kaetsu Gakuen High School	Kaetsu Joshi Gakuen	Chiyoda-ku Tokyo	S+SRC	7,B1	28.9	14,930	School	1998
			Shakujii Kouen Residential Bldg.	Redevelopment Partnership	Nerima-ku Tokyo	SRC	33,B2	100	52,368	Housing	2000
			Taisho Life Insurance Kogyo Bldg.	Redevelopment Partnership	Aoba-ku Sensai	S	12,B1	46.1	9,184	Office	1998
			Inotech Headquaters Bldg.	Inotech Corp.	Kouhoku-ku Yokohama	S	14,B1	56.2	29,929	Office	1998
			Asahi Insurance Niigata Bldg.	Asahi Life Ins. Corp.	Niigata-shi Niigata	S+SRC	10	40.65	7,996	Office	1998
			Kajima Shizuoka Bldg.	Kajima Corp.	Shizuoka-shi Shizuoka	S	B1,5	19.6	1,685	Office	1998
			Kokusai Kogyo Fukuoka K Bldg.	Kokusai Kogyo Corp.	Fukuoka-shi Fukuoka	S+SRC	7	27.7	6,916	Office	1998
			Kashiwa West Redevelopment Bldg.	Redevelopment Partnership	Kahiwa-shi Chiba	S	15,B2	62.65	20,431	Office, Hotel, Hall	2000
			Sanshin Muromachi Bldg.	Mitsui Trust Bank Corp.	Chuou-ku Tokyo	S+SRC	9,B2	34.78	6,185	Office	1999
			Nippon Paper Co. R&D Center	Nippon Paper Corp.	Kita-ku Tokyo	S+ CFT	10,B1	41.7	9,249	Office	1999
			Maruito Sapporo Bldg.	Maruito Corp.	Sapporo-shi Hokkaidou	S+SC	22,B3	86.97	54,088	Office, Hotel	2000
			Higashi Shinagawa Redevelop. A1 Bldg.	*Nippon Tobacco Corp. & Kajima*	*Shinagawa-ku Tokyo*	*S+CFT*	*23,B2*	*90*	*84,400*	*Office*	*2001*
			Higashi Shinagawa Redevelop. A2 Bldg.	*Nippon Tobacco Corp. & Kajima*	*Shinagawa-ku Tokyo*	*S+ CFT*	*23,B2*	*90*	*(A1+A2)*	*Office*	*2001*
			Kintetsu Investment Minatomchi Bldg.	*Kintetsu Investment Corp.*	*Naniwa-ku Osaka*	*S*	*21,B1*	*80.9*	*23,877*	*Office*	*2001*
			Nippon Media System Bldg.	*Nippon Media System Corp.*	*Higashi-ku Nagoya*	*S+SRC*	*9,B1*	*30.98*	*6,200*	*Office*	*1999*
		Honeycomb Damper (Seismic Retrofitting)	Taisho Permaceutical Co. Bldg.	Taisho Seiyaku Corp.	Toshima-ku Tokyo	S+SRC	9,B1	38.6	16,700	Office (1977 Compl.)	1996
			Koito Shizuoka Factory C6 Bldg.	Koito Seisakusho Corp.	Shimizu-shi Shizuoka	S	3	10.25	4,739	Office, Factory (1969 Compl.)	1997
			Hokuriku Postal Office, MOPT	MOPT	Kanazawa-shi Ishikawa	RC	5,B1	19	10,157	Office (1958 Compl.)	1997
			Keio Bldg.	Keio Corp.	Shinjuku-ku Tokyo	S	11,B2	42.96	80,571	Department Store (1964 Compl.)	1998
			Fukushima Yamashitacho Apartment	Fukushima Pref.	Fukushima-shi	SRC	10,11	30.85	10,707	Housing (1976 Compl.)	1998
			Katsushika Govermenal Office Bldg.	Katsushika Ward.	Katsushika-ku Tokyo	RC	4	14.82	10,411	Office (1962 Compl.)	2000
		HiDAM (Oil Damper)	Atsugi Axst Main Tower	Redevelopment Partnership	Atsugi-shi Kanagawa	S	26,B1	108.1	57,116	Office, Shop	1995
			JAL Building	Ryokou Souko Corp. & JAL	Shinagawa-ku Tokyo	S+SRC	26,B1	118.8	83,279	Office, Shop, Hall	1996
			Koito Technical Center	Koito Seisakusyo Corp.	Shimizu-shi Shizuoka	S+SRC	10	43.85	21,297	Labolatory, Office	1997
			Aichi Kikai Headquaters Bldg.	Aichi Kikai Industry Corp.	Nagoya-shi Aichi	S+SRC	8,B1	30.8	9,230	Office	1997
			Kobe KIMEC Center Bldg.	Kobe City	Chuou-ku Kobe	S	11,B1	43.7	17,396	Office	1998
			Chubu Electric Power Co.Gifu Bldg.	*Chubu Electric Power Corp.*	*Gifu-shi Gifu*	*S*	*11,B1*	*45*	*24,140*	*Office*	*2001*
	Control for Adjacent Building	Joint Damper (Bell, Hourglass, Alley & Oil Damper)	Kajima KI Bldg.	Kajiama Corp.	Minato-ku Tokyo	S+SRC	5+9	34.3	29,553	Office	1989
			La-La Port Indoor Ski Dome 'SSAWS'	Mitsui Fudosan Corp.	Funabashi-shi Chiba	S	3	96.91	112,852	Ski Dome	1993
			Lex Garden Saidaiji	Kanematsu Urban Develop. Crp.	Nara-shi Nara	RC	5+5	13.75	4,484	Housing	1996
			Kaetsu Gakuen High School	Kaetsu Joshi Gakuen	Chiyoda-ku Tokyo	S+SRC	7,B1	28.9	14,930	School	1998
			Kyoritsu Joshi Gakuen University	*Kyouritsu Joshi Gakuen*	*Chiyoda-ku Tokyo*	*S*	*23,B1*	*100*	*40,381*	*School*	*2000*

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Introduction to Active Control Systems

Civil engineering structures located in environments where earthquakes or large wind forces are common will be subjected to serious structural vibrations during their life spans. These vibrations can range from harmless to severe with the later resulting in serious structural damage and potential structural failure. For a moment, imagine a world in which structures have the ability to reduce these vibrations resulting in a structure that is damage proof during earthquakes and strong winds. Even though engineers can not design this type of building yet, the field is getting closer to attaining this goal. Structural control is one area of current research which looks promising in attaining the goal.

Structural control is defined as a mechanical system which is installed in a structure to reduce structural vibrations during loadings such as strong winds and earthquakes. The purpose of such a structural control system is to enhance the safety as well as improve the habitability of structures during these loading scenarios. The structural control system can be divided into two parts, with the first part being the actual control device and the second the control algorithm. It is common for the structural control system to be classified by its device type resulting in three general control types: passive, active and semi active. If the system is an active or semi-active structural control system, then the control algorithm can be used to further classify the system as either feed forward or feed backward. [6]

A passive control system is one in which structural vibrations are reduced from a passive control device imparting a force upon a structure in response to the motion of the structure. Passive control has many benefits associated with it. First, no external power is required for the passive device to work. This makes a passive device an economical solution. In addition, the device will generally be smaller in size than an active control device. Furthermore, passive devices have been in existence for well over 50 years and have been thoroughly researched and tested resulting in a highly reliable product. However, there is a negative aspect to the passive device, in that only limited amount of control can be attained. Even in light of this fact, they are still considered a very cost effective solution to controlling the vibrations of structures. Examples of passive control devices include base isolation, tuned mass dampers, viscous dampers, elasto-plastic dampers, metallic yield dampers and friction dampers.

An active control system is a much more complex system than the passive control systems. External power is employed to power actuators located in the structure in order to apply forces which can put in or take out energy from the system. In order for the actuators to properly apply the desired forces, sensors need to be placed within the structure in order to measure structural response. These sensors relay response information to a central computer which then uses this information to calculate the desired actuator forces. The advantage of an active control system is that the system attains excellent control results. However, there are many drawbacks to using an active control system. They are very expensive systems to design and are expensive to operate due to the large amounts of power they need. Furthermore, they tend to take up more space than passive control devices. Some examples of active control devices include the active mass driver system , the active tuned mass system, and the active-passive composite tuned mass damper.

The last broad category of control is semi-active control. Semi-active control falls between passive and active on the control spectrum. A semi-active control system is similar to an active system in that the system operates on external power but the semi-active control device does not add energy to the structure in any way. In this system, mechanisms are used to control or assist a passive control device. The inherent benefit of a semi active control device is that the mechanism used does not require large amounts of external power. Many semi active devices are able to be powered by batteries protecting them from sudden power loss during earthquakes. Furthermore, semi-active control devices are less complex mechanically than active devices making the semi-active device highly reliable. Semi-active systems are more aggressive than passive systems and usually obtain control results close to that of an active control system. Because of these benefits, many structural control researchers feel that semi-active control systems will be the structural control systems of the future. An active variable stiffness system as well as the active variable damping system are both considered semi-active systems.[7]

Active and semi-active control systems can be further categorized as a feed forward system or a feed backward system. The feed backward system is the most common control algorithm type which uses information from sensors measuring the structure's behavior to determine actuator forces. In control theory, such a system is also termed a closed loop system. In a feed forward system, the input disturbance on the structure is measured and is used to determine actuator forces. Again, in control theory, this type of system is an open loop system.

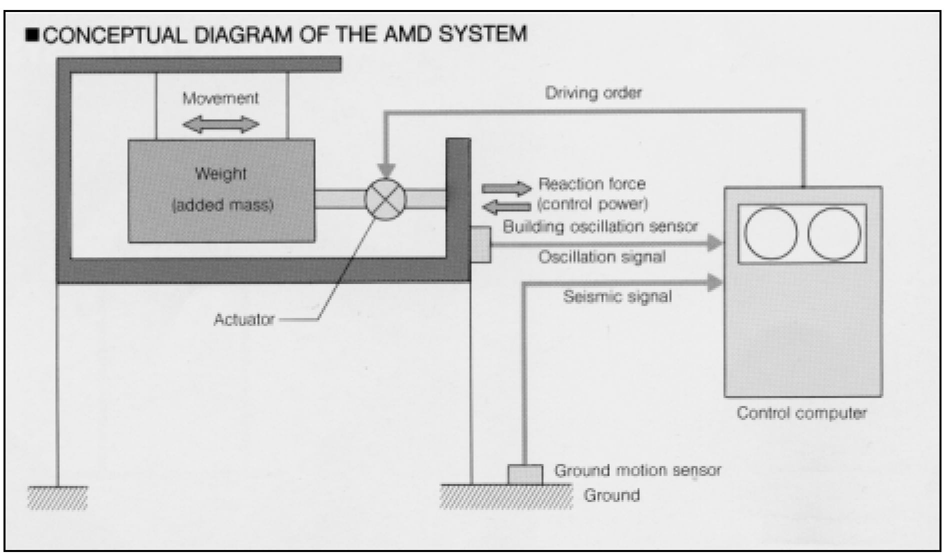
Kajima's Control Systems

AMD - Active Mass Driver System

The active mass driver (AMD) system was the first active control system developed by The Kobori Research Complex in the late 1980's after the complex's founding. In principle, it is a very simple active control system to understand. The AMD device is composed of a large mass whose motion (displacement, velocity and acceleration) in one direction is controlled by a turn screw actuator. The mass is suspended like a pendulum allowing the mass to move without having to overcome bearing surface friction. See Figure 1. Depending upon the application at hand, the AMD device can be designed with various mass sizes to obtain various control effects. More than one AMD device can be installed in a structure to allow engineers to control more complex oscillations by the precise interaction of the numerous AMD devices. Realistically speaking, the AMD device's size is controlled by two factors. First, the AMD can only be placed in the space available in a structure. Second, the actuator is powered by an external power source with more electricity used for larger AMD mass. These two limiting factors prevent the AMD system from being designed as an active control system targeting the vibrations induced by large earthquakes. In addition, if power was to be lost in a large earthquake, the devices would cease operation. The AMD device is used to control a building during large winds and small to moderate earthquakes. [8]

Figure 1 - Concept of the AMD Device

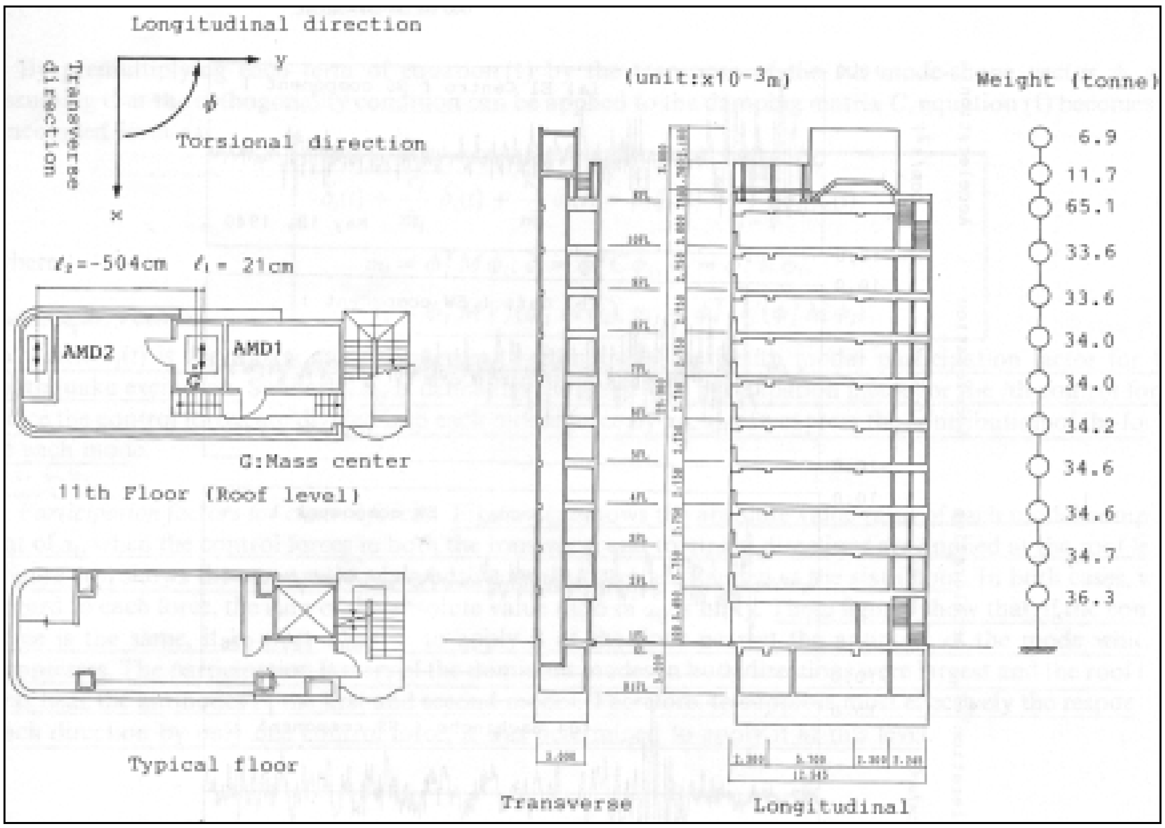
Source: Kajima Corporation. Seismic Response Control Series: AMD - Active Mass Driver System. Kajima Technical Pamphlet 91-63E, Tokyo. 1991.



The AMD device was designed to be installed within the Kyobashi Seiwa Building. The Seiwa building is located in Tokyo, Japan and because of this location is subjected to typhoons and earthquakes. The building is 10 stories tall and its height to width ratio is 9.5 making it quite vulnerable to transverse and torsional displacements. See Figure 2. The Seiwa building is a steel structure whose lateral resistance is provided by rigidly connected steel frames. Structurally, the building is designed to take all lateral loads safely. However, to enhance occupant's comfort, an AMD control system was designed to reduce vibrations during strong winds and moderate earthquakes. Due to a lack of available space in the building, the control device was placed upon the roof.[9]

Figure 2 - The Kyobashi Seiwa Building

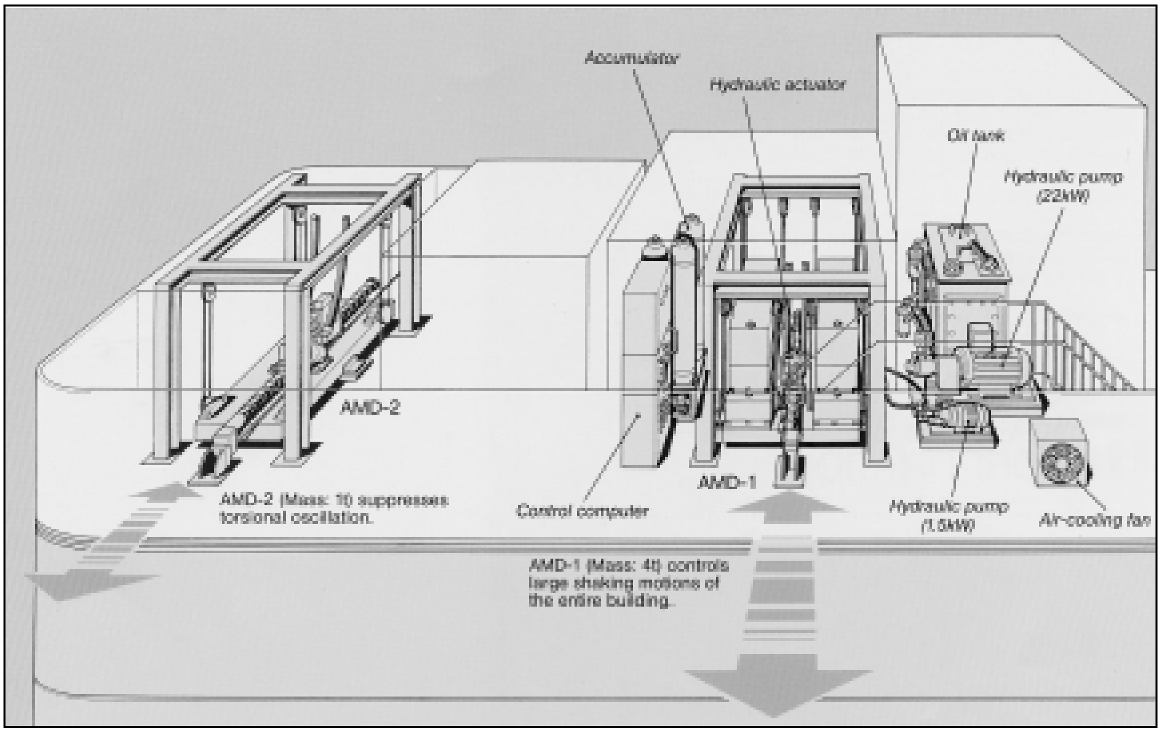
Source: Kobori, T., et. al. Seismic Response Controlled Structure with Active Mass Driver System - Part 1: Design. Earthquake Engineering and Structural Dynamics, Vol 20, 133-149. 1991.



Eigenvalue analysis of the structure shows that the first dominant mode of vibration is in the transverse direction with a period of 1.13 seconds. The second mode is in the torsional direction with a period of 0.97 seconds while the third mode is in the longitudinal direction with a natural period of 0.76 sec. The primary objective of the AMD system is to control the first two modes. To control the transverse vibrations, one AMD device, termed AMD1, is placed as close to the roof's center of mass as possible. To control torsional vibrations, a second AMD device, termed AMD2, was placed an eccentric distance from the center of mass. Provided an adequate eccentricity, the mass of the second AMD device can be significantly less than the mass of the primary AMD device. The mass of AMD1 was 4.2 metric tons and the mass of AMD2 was 1.2 metric tons. The total mass of the AMD system represents only 1% of the buildings superstructure weight. With a maximum stroke of $\pm$ 25 centimeters for both devices, the capacity of AMD1 is a control force of 3.4 metric tons while AMD2's capacity is a control force of 2.2 metric tons. From the center of mass, AMD1 was located 0.8 meters in the direction of the back of the building. AMD2 was placed 4.45 meters from the center of the roof in the direction of the front of the building. See Figure 3.[10]

Figure 3 - Layout of the AMD Devices

Source: Kajima Corporation. Seismic Response Control Series: AMD - Active Mass Driver System. Kajima Technical Pamphlet 91-63E, Tokyo. 1991.

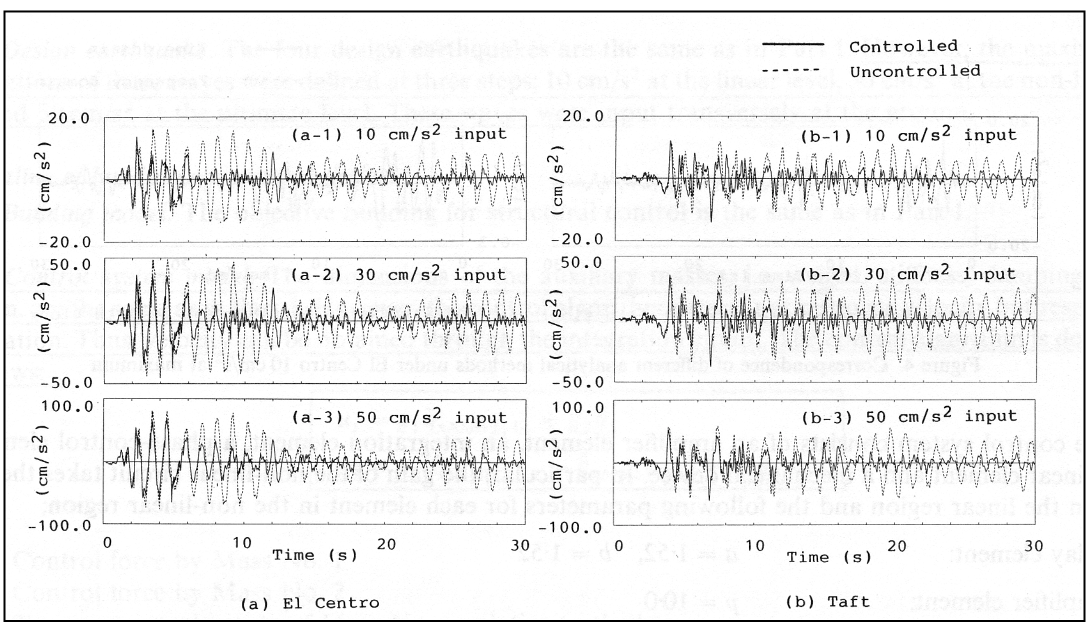


The AMD devices are only part of the control system; just as important are the sensors and controller. To measure the vibrations of the Seiwa building, accelerometers are located on the basement, 6th and roof levels. The sensor on the roof is the only sensor whose measurements are used to compute control forces. The remaining two accelerometers are used only for validation purposes. The roof's sensor transmits its information to the control computer which is also located on the roof level. The computer then uses an acceleration feed back algorithm, meaning the control force calculated for each AMD is directly proportional to the acceleration of the roof level. To achieve this control force, the controller determines the desired movement of the masses. Two interesting points should be made about the control algorithm. The first is that it is an algorithm based on discrete time steps. The time step for the system is 5 msec. which is small enough to avoid serious time lag problems. The second point is that the algorithm employs a nonlinear element so that the mass of the AMD is prevented from going to the end of its stoke. However, after installation, the building experienced significant long-periodical excitations which ultimately drifted the mass to the stoke limit. [11]

The AMD system's design considered four different earthquake records, El Centro, Taft, Sendai and Hachonohe. Each earthquake record was scaled to a maximum input motion of 10 cm/s^2, 30 cm/s^2 and 50 cm/s^2. Wind was not considered in the design since these earthquake scenarios far exceed the worst wind case. The control target was to reduce the building's displacement by 1/3 to 1/2 in the 10 cm/s^2 case and 1/4 to 1/3 in the 30 cm/s^2. If the initial maximum response of the building is considered, then the initial targets were not met. If this maximum is ignored, then the targets were met. See Figure 4. In almost all control systems, the initial response is very difficult if not impossible to reduce. In terms of equivalent damping per mode, in the first mode, 20% damping increase was gained while in the second and third modes 5% damping was gained. This is a significant gain. The first mode gains most of the benefit because the first mode is the easiest to measure given only one sensor at the roof level. The higher modes have anti-nodes in their mode shapes at points below the roof level which are difficult to measure with only one sensor. [12]

Figure 4 - Control Performance under El Centro and Taft

Source: Kobori, T., et. al. Seismic Response Controlled Structure with Active Mass Driver System - Part 2: Verification. Earthquake Engineering and Structural Dynamics, Vol 20, 151-16. 1991



A price is paid for the very good control results gained using the AMD system. The AMD system is always on and operating on electricity. Mr. Sasaki of the Kobori Research Complex puts the monthly electricity cost of the system at roughly 10,000 yen. Furthermore, the initial cost of research and development of the AMD system was very high with Kajima absorbing most off this cost. However, it is projected that if an AMD system was to be designed today for a structure, then the capital cost of the system would equate to roughly 1% of the total construction cost. After the Kyobashi Seiwa Building, Kajima has not designed an AMD system since. The Kobori Research Complex recognized that improvements could be made upon the system resulting in the TRIGON and DUOX control systems. However, many of Kajima's competitors have designed many AMD systems which also exhibit some very exciting innovations. Most impressive are Takenaka's AMD systems which use the HVAC equipment as the mass used in the AMD device. See Appendix C for further details. [13]

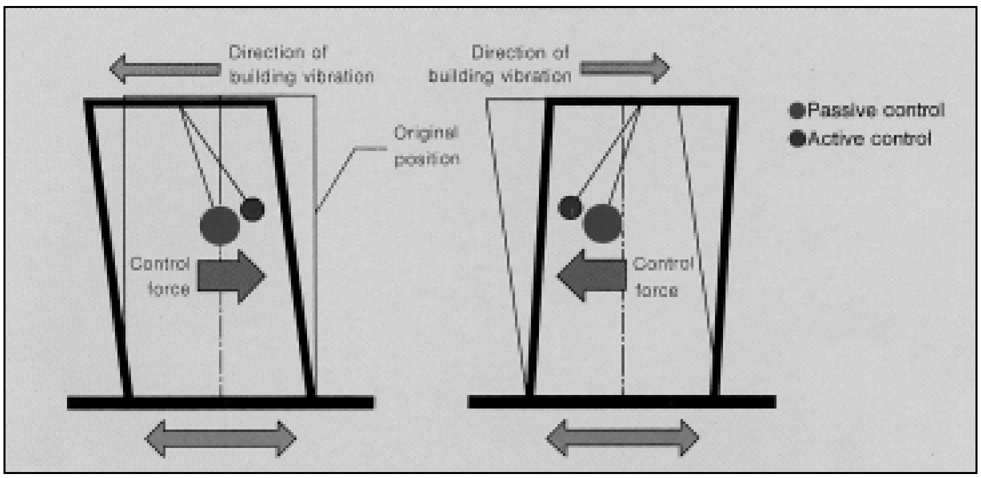
Kajima's Control Systems

TRIGON- Active Tuned Mass Damper

Shortly after the completion of the AMD system, Kajima sought to develop a better active control system using less external power. The TRIGON system was one such active system that resulted in early 1990's. In principle, the device is similar to a suspended mass which behaves as a tuned pendulum except that an actuator is attached to the pendulum which can dynamically extend the amplitude of the pendulum. This extended amplitude creates a greater control force upon the structure in which it is located. See Figure 5.

Figure 5 - Concept of the TRIGON Device

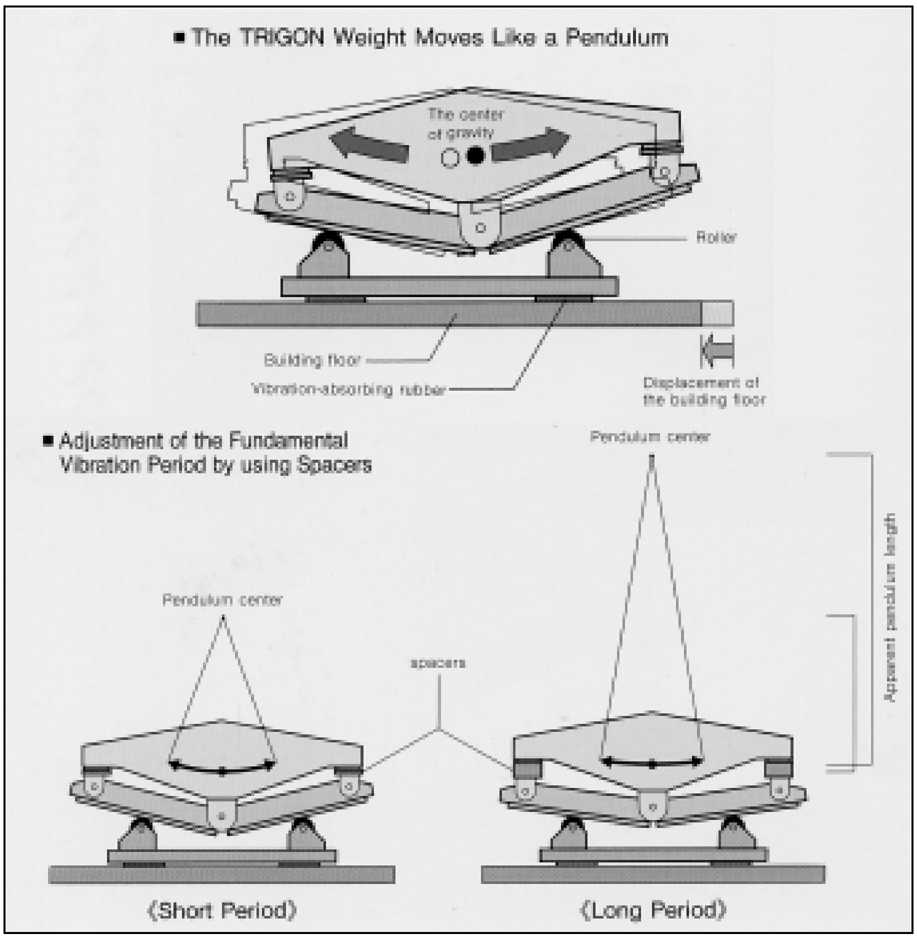
Source: Kajima Corporation. Seismic Response Control Series: TRIGON - Weight Driven hybrid Seismic Response Control System. Kajima Technical Pamphlet 93-80E, Tokyo. 1993.



In the TRIGON device, the mass is not suspended but is mounted upon a V-shaped rail which can roll on rollers. By eliminating the suspension of the mass, the TRIGON device is significantly smaller than a suspended mass allowing it to be installed in a room of a building (TRIGON's dimensions are 7.6 x 4.4 x 3.5 meters). The V-shape rails allow the mass to oscillate in a pendulum like fashion with a maximum stroke of $\pm$ 1 meter. TRIGON has been designed so that it can be installed in any building scenario. In order for the device to be effective in structures of various stiffness, a way to change the period of the mass is available. The V-shape rail's angle can be adjusted to increase or shorten the apparent pendulum length which respectively increases or shortens the mass's period. The period can be adjusted from 3.7 to 5.8 seconds depending upon the application. See Figure 6. The control force is placed directly upon the TRIGON mass via an electric motor with reduction gearing and rack & pinion mechanisms. The mass's inertial force in turn becomes a control force upon the structure. The mass can not move freely without the assistance of the actuator due to bearing surface friction between the mass and the rollers. Therefore, the mass of TRIGON was limited to 110 metric tons so that adequate control gain can be attained using this device in an electrically efficient manner. It should be noted that given the size of the TRIGON device, it has been designed as a device used for controlling structures during strong winds and moderate earthquakes but not large earthquakes. The advantage of the TRIGON device is that it is a modular unit that can be installed in groups within a structure giving greater desired control forces. [14]

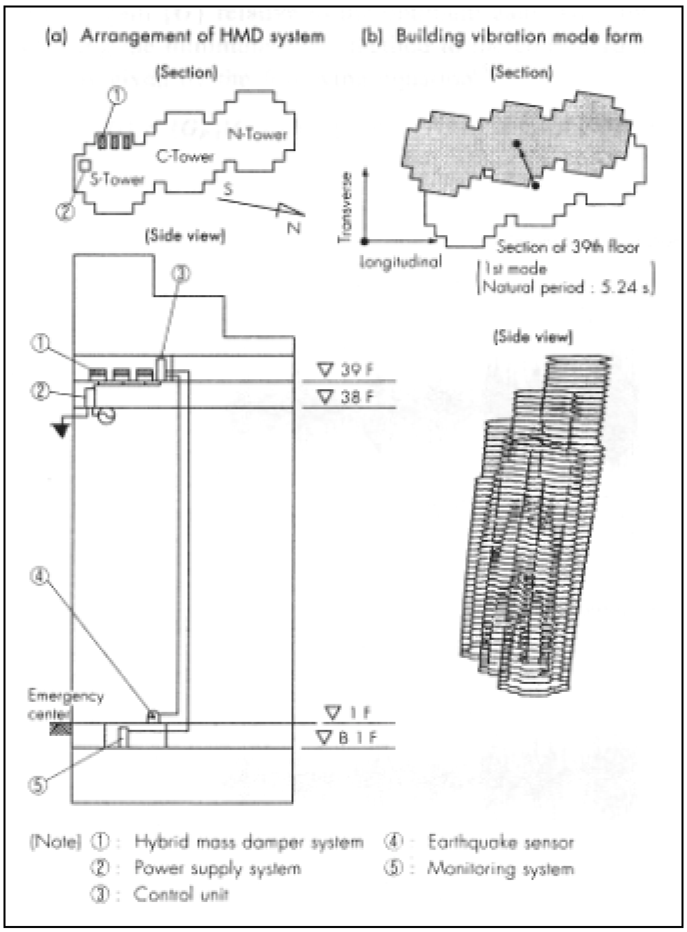
Figure 6 - TRIGON's Pendulum Motion

Source: Kajima Corporation. Seismic Response Control Series: TRIGON - Weight Driven hybrid Seismic Response Control System. Kajima Technical Pamphlet 93-80E, Tokyo. 1993.



By 1994, the TRIGON device was fully developed and ready to be placed in an actual structure. TRIGON is used to control The Shinjuku Park Tower which is a 52 story skyscraper in Shinjuku, Tokyo. Shinjuku Park Tower is one of Japan's largest buildings with a total floor area of well over 264,000 square meters and standing 233 meters tall. The first 37 floors are used as office space while the remaining floors at the top of the tower are occupied by The Park Hyatt Hotel. The building is composed of three connecting towers each of a square shape measuring 32 meters by 32 meters. See Figure 7. To provide the landlord with wide open rentable interior spaces, the building is constructed of 4 steel mast-columns at the four corners of the three square shapes. Each mast column is composed of four steel I-sections bound together by very deep and stocky beams. Medium sized columns between the mast columns carry some additional load. The medium columns' location along the building's exterior face changes on the 37th floor where the office floors end and the hotel begins. To accommodate the discontinuity of the medium columns and to give the building greater stiffness, the structure has a belt truss on the 37th floor.[15]

Figure 7 - The Shinjuku Park Tower
Source: Kurokawa, Y., et. al.. Structural Design and Vibration Control of A Complex High-Rise Building. 1994.



Given the 122 meter by 70 meter narrow floor plan of the building, it is clear that it is susceptible to transverse and torsional displacements during strong winds and earthquakes. Dynamic analysis of the Shinjuku Tower revealed that the building's first mode is a transverse displacement with a natural period of 5.24

seconds and the second mode's displacement was 45 degrees off of the transverse direction with a natural period of 4.5 seconds. Finally, the third mode exhibited torsional displacements with a natural period of 3.98 seconds. The building is designed to structurally withstand typhoons or earthquakes and remain structurally safe without any control measures taken. However, with the Hyatt on the top half of the tower, the transverse and torsional displacements of the tower are most noticeable to residents of the hotel. This was unacceptable to the landlord and a control system employing the TRIGON device was designed by the Kobori Research Complex to remedy this situation. [16]

The TRIGON control system is quite similar to that of the AMD system of the Kyobashi Seiwa Building. In the Shinjuku Park Tower, one TRIGON device would not provide ample control forces necessary to reduce the building's displacements. The control system used three identical TRIGON devices totaling to 330 metric tons, roughly 0.25% of the total superstructure weight. Given the high price of rent in the Shinjuku Park Tower, very limited space was available to the designers. The optimum location is upon the roof of the building, but the hotel's restaurant and pool facility occupied these atrium spaces. The TRIGON devices were placed upon the 39th floor on the south side of the building 45 meters from the center of mass. The eccentricity is intended to gain a slight increase in the control effect for the torsional mode's displacements. See Figure 7. The TRIGON devices operate without cacophonous noise so its close proximity to the hotel was not an issue. The devices were easy to install with installation lasting only 2 days. The total cost of the device and installation, excluding research and development costs was only 0.5% of the total buildings cost. [17]

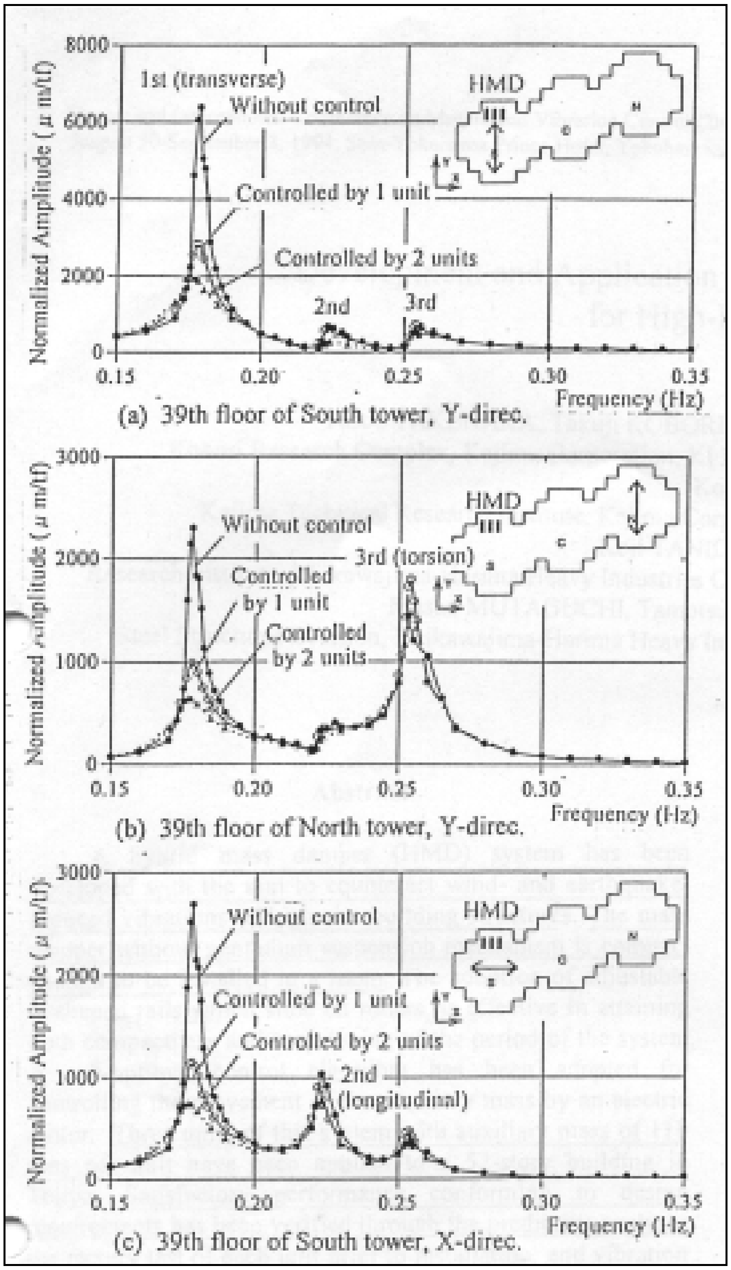
Within the tower are accelerometers which measure the acceleration of the building at all times. These sensors are located upon the 1st, 10th, 20th, 30th, 39th and 52nd floor but only the sensor on the 39th floor is used to calculate the necessary control force to reduce structural vibrations. The other sensors send their measurements to the basement of the tower where this data is used for validation purposes. The sensor on the 39th floor sends its acceleration measurements to the control computer, also on the 39th floor, to be used in an acceleration feedback algorithm. The controller in turn sends its instructions to the TRIGON devices' actuators. The entire TRIGON system only operates when the displacements of the structure are beyond a threshold value representing a value noticeable by humans. When the displacements are below this value, the TRIGON devices are off and braked, thus saving electricity. The system has a built in fail safe monitoring device which will emergency stop the TRIGON masses if it detects an abnormality in their operation. Unfortunately, the annual electricity costs of the system were not known at the Kobori Research Complex. [18]

Since the system's installation in 1994, excellent control results have been obtained. The system was designed with the goal of reducing the 52nd floor displacements by 1/2 during a wind of 28.0 m/sec with a 5 year expected return period. In a predictive analysis conducted by the designers, the 5 year wind was applied to a model of the tower with control and without. In the model without control, the 52nd floor's maximum acceleration was 6.80 gals. With control imposed, the maximum acceleration is reduced to 3.44 gals. In this model, the mass's maximum displacement was 45.2 cm which is well within the TRIGON's stroke limit of 1 meter. In terms of displacements, a 33% to 50% reduction is seen at the top floor. [19]

After installation, a free vibration test was conducted upon the tower. One TRIGON unit was used to excite the building with a sinusoidal force. After exciting the structure, the unit was braked, and the TRIGON units were allowed to control the structure. In one test, only one TRIGON is used, while in subsequent tests only two and then all three units are allowed to operate. With no TRIGON units controlling, the damping of the building is 1.14%. With one unit, damping is increased to 2.38%. With two units, structural damping becomes 3.76% and with all three units in operation the building has an equivalent damping of 4.94%. Similarly, a forced vibration test was also conducted upon the structure. One TRIGON device was used to excite the structure with frequencies ranging from 0.15 Hz to 0.35 Hz. The results obtained show that the first resonance peak of the resonance curve is reduced to approximately one third of the uncontrolled case through the use of three TRIGON units. This clearly illustrates that the system targets the first mode of vibration with damping increased in this mode. The second, third and higher modes are only slightly affected. See Figure 8. Although no earthquake records were considered in the analysis, it is certain that the system will also be effective during earthquakes. [20]

Figure 8 - Forced Vibration Test Results of The Shinjuku Park Tower

Source: Takenaka Y., et. al.. Development and Application of V-Shaped Hybrid Mass Damper for High Rise Buildings. Proceedings of Second International Conference on Motion and Vibration Control, Yokohama, Japan. August 30 - September 3, 1994.



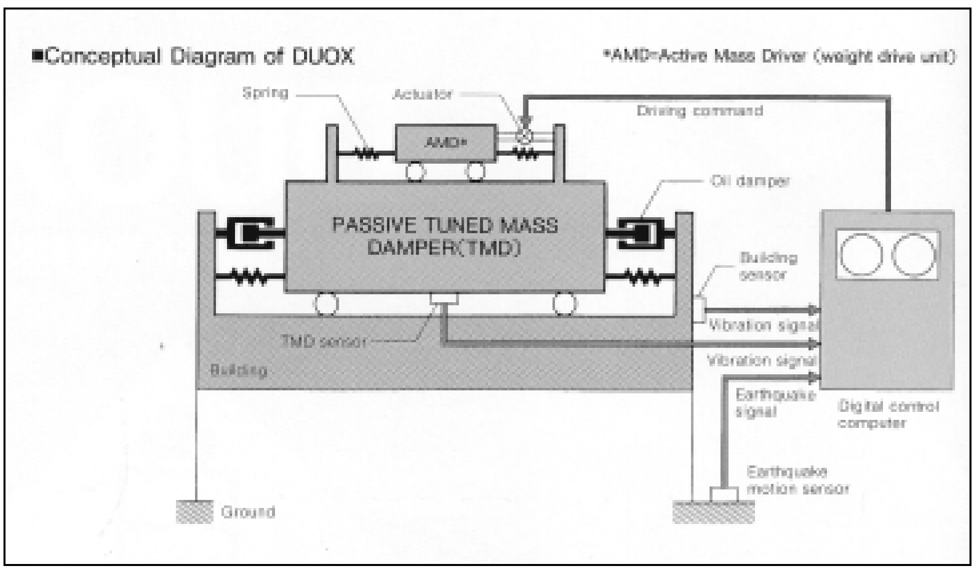
Kajima's Control Systems

DUOX - Active-Passive Composite Tuned Mass Damper

The active-passive composite tuned mass damper, also termed DUOX, is the second system to result from Kajima seeking to improve upon the AMD system. The device is exactly what its name implies, a passive tuned mass damper upon which sits an active mass driver system. An actuator is used in this device to control the active mass driver portion whose inertial force controls the tuned mass damper. See Figure 9. Generally speaking, a tuned mass damper is sluggish in its behavior. When a building is excited by an external load, the tuned mass damper takes time before its motion is significant in assisting in the structure's motion. In a similar fashion, after the load has been removed from the building, the TMD is slow in braking itself, thus applying unnecessary control force to the unloaded structure. The active mass driver atop the tuned mass provides the force necessary to speed up the tuned mass's motion at the start of the loading and provides a braking force at the end of the loading scenario. For the same reasons discussed in the sections describing the AMD and TRIGON systems, the size of the DUOX device is limited and is therefore used to control a building during moderate earthquakes only or very strong winds. [21]

<u>Figure 9 - Concept of the DUOX Device</u>

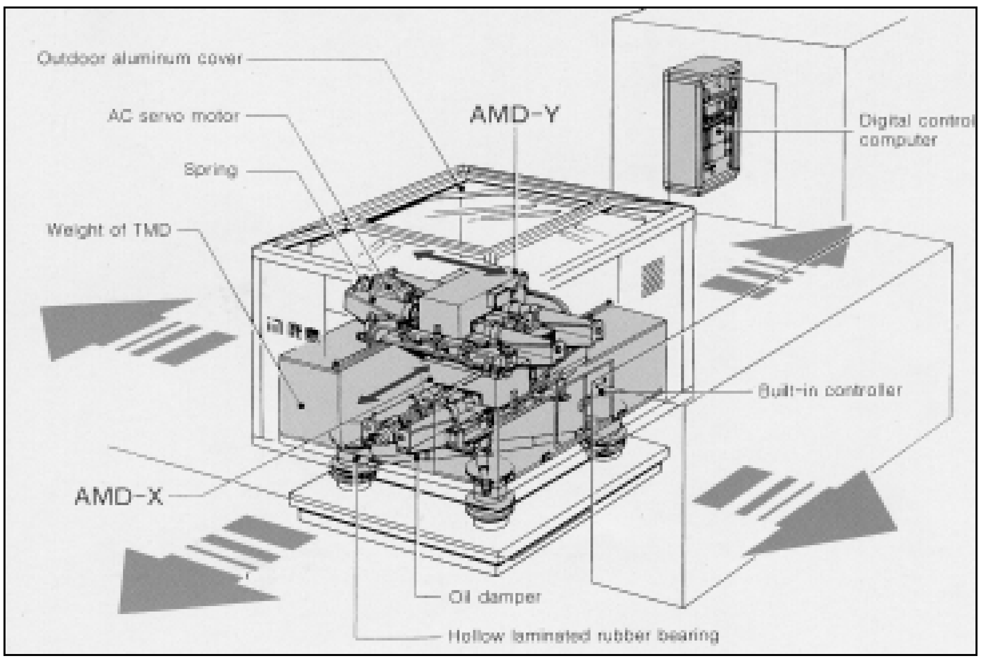
Source: Kajima Corporation. <u>Seismic Response Control Series: DUOX - Active Passive Composite Tuned Mass Damper</u>. Kajima Technical Pamphlet 93-82E, Tokyo. 1993.



The conceptual diagram shown in Figure 9 simplifies the DUOX device, however, the device is a bit more sophisticated in its design. The AMD component of the system is divided into two AMD devices each weighing 2 metric tons. The two devices are orthogonal to each other so that control can be attained in the X and Y directions. DUOX's AMD devices are similar to the AMD device used in the Kyobashi Seiwa Building in that the mass is controlled by a turn screw actuator. The devices sit upon the TMD mass which is 20 metric tons. Together, the composite device is housed within an aluminum housing which also adds to the TMD mass. The housing is then placed upon laminated rubber bearings which provide stiffness to the TMD and oil damping pistons which provide damping for the TMD. The laminated rubber bearings allow the DUOX device to displace in any direction. The TMD and AMD's strokes are 25 cm and 50 cm respectively. See Figure 10. With the aluminum housing, the DUOX device can be placed upon the roof of a building and be subjected to the elements. The DUOX device is very compact and can be installed easily within a building. Furthermore, more than one DUOX device can be used to effectively control a structure in transverse and torsional directions. [22]

Figure 10 - Diagram of the DUOX Device

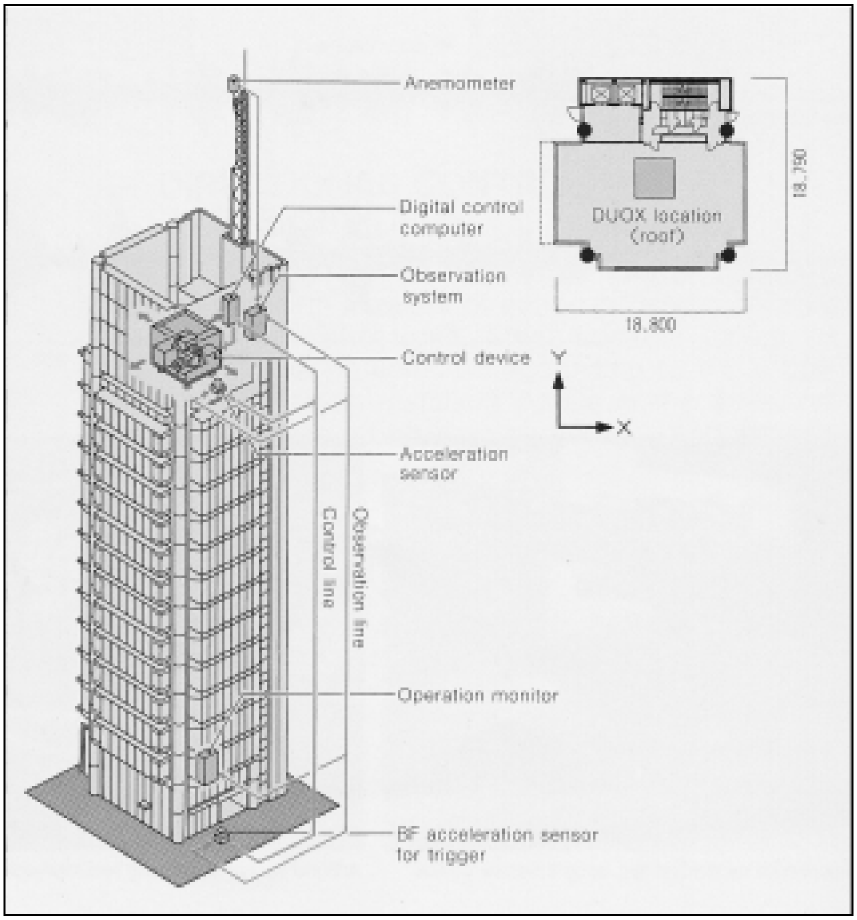
Source: Kajima Corporation. Seismic Response Control Series: DUOX - Active Passive Composite Tuned Mass Damper. Kajima Technical Pamphlet 93-82E, Tokyo. 1993.



By 1993, the DUOX device was ready to be used as part of a structural control system. The DUOX device and a complementary system was installed in the Ando Nishikicho Building. The building is located in Chiyoda-ku, Tokyo and is 14 stories tall, making it the tallest building in the low rise area. The building is primarily a steel structure with four partially reinforced concrete columns at the corners of its square floor plan which are sufficient in resisting lateral loads. See Figure 11. The building is rented as office space so occupant comfort is of great concern. In order to reduce displacements of the building during strong winds, one DUOX device was installed upon the roof of the building at the roof's center of mass. The above ground weight of the building is 2,600 metric tons so the DUOX device represents roughly 1% of the mass. The building's two predominate modes of displacement are in the transverse and longitudinal directions with natural frequencies of 0.68 Hz and 0.72 Hz. The DUOX device is intended to control displacements in these two directions. [23]

Figure 11 - The Ando Nishikicho Building

Source: Kajima Corporation. Seismic Response Control Series: DUOX - Active Passive Composite Tuned Mass Damper. Kajima Technical Pamphlet 93-82E, Tokyo. 1993.



The control system for the DUOX device is similar to that for the TRIGON device. The controller computer is also located on the roof adjacent to the device. An accelerometer is located on this level which sends its measurements to the control computer. The control computer considers the structure's velocity in computing the required control force using a velocity feedback algorithm. Also considered in this algorithm is the TMD's stroke so that appropriate braking can be applied to the system when needed. Very limited power is needed, because the actuator is small and the active mass driver portion of the system only goes on during excitations. The tuned mass portion is always active because it does not require electricity. If the external load of the structure is too great, the AMD will not operate because nothing can be gained control wise and would only waste electricity.[24]

A stationary vibration test was conduced upon the Ando Nishikicho Building shortly after the building's completion. It was found that the DUOX system targets the first two modes of vibration of the structure and was effective in increasing damping by 8.5% and 6.4% in these modes. Since its installation, the system has been tested by mother nature many times. On October 12, 1993 the Tokyo area experienced a 7.1 earthquake. During this loading, it was found that the control device performed with the expected efficiency. The RMS displacement of the building was reduced by 61% with the addition of the control system. Similarly, on February 21, 1994, typhoon winds triggered the control system. With the DUOX device in operation, the maximum acceleration was reduced by 70%. [25]

This system was so successful, that Kajima decided to place it within the Dowa Kasai Phoenix Tower of Osaka which was completed in 1995. The Dowa Kasai Phoenix Tower, which is twice the height of the Dowa Nishikicho Building, has also shown that the DUOX system is an effective means of control for taller structures. It is interesting to note that in this building, two DUOX devices were used in order to control a dominate torisonal mode of the tower. [26]

Kajima's Control Systems

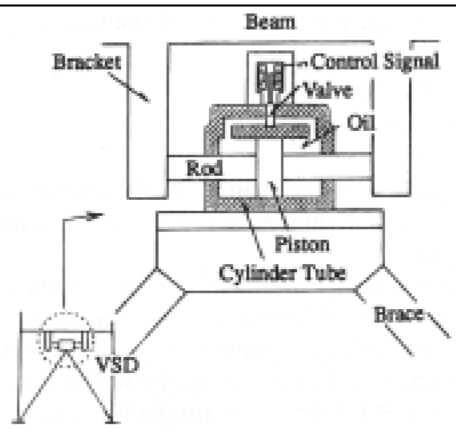
AVS - Active Variable Stiffness System & AVD - Active Variable Damping

In the late 1980's after the establishment of the Kobori Research Complex, the complex's researchers focused their efforts upon the development of a control system which could be used to protect structures from large earthquakes. As a result, the Active Variable Stiffness System (AVS) was developed. By 1990, the AVS control system was completed and installed in an actual building.

The AVS system is a unique system and is best described with the assistance of a diagram. See Figure 12. The basic building block of the system is the variable stiffness device mechanism. The mechanism contains "V" bracing to which connected at the apex of the brace is a variable stiffness device. This device can be locked engaging the brace to resist lateral loads or the lock can be opened allowing the brace to be ineffective. In this system no actuator is used and electrical mechanisms only lock and unlock the device. Therefore, this system is considered a semi-active control system. Because the lock mechanism is small and is only a valve regulating oil flow in a piston, it will not induce any vibrations into the primary system. Since no actuators are used, the lock/unlock mechanisms require very little power giving the system an immediate cost saving benefit over the active control systems. In AVS, the electrical power required is supplied by an external power source. In the event that power is lost to the structure, a back up power supply allows the AVS system to operate for an additional 30 minutes. [27]

Figure 12 - VSD Mechanism

Source: Kobori, T. et al. Seismic Response Controlled Structure with Active Variable Stiffness System. Earthquake Engineering and Structural Dynamics, Vol 22, 925-941, 1993.



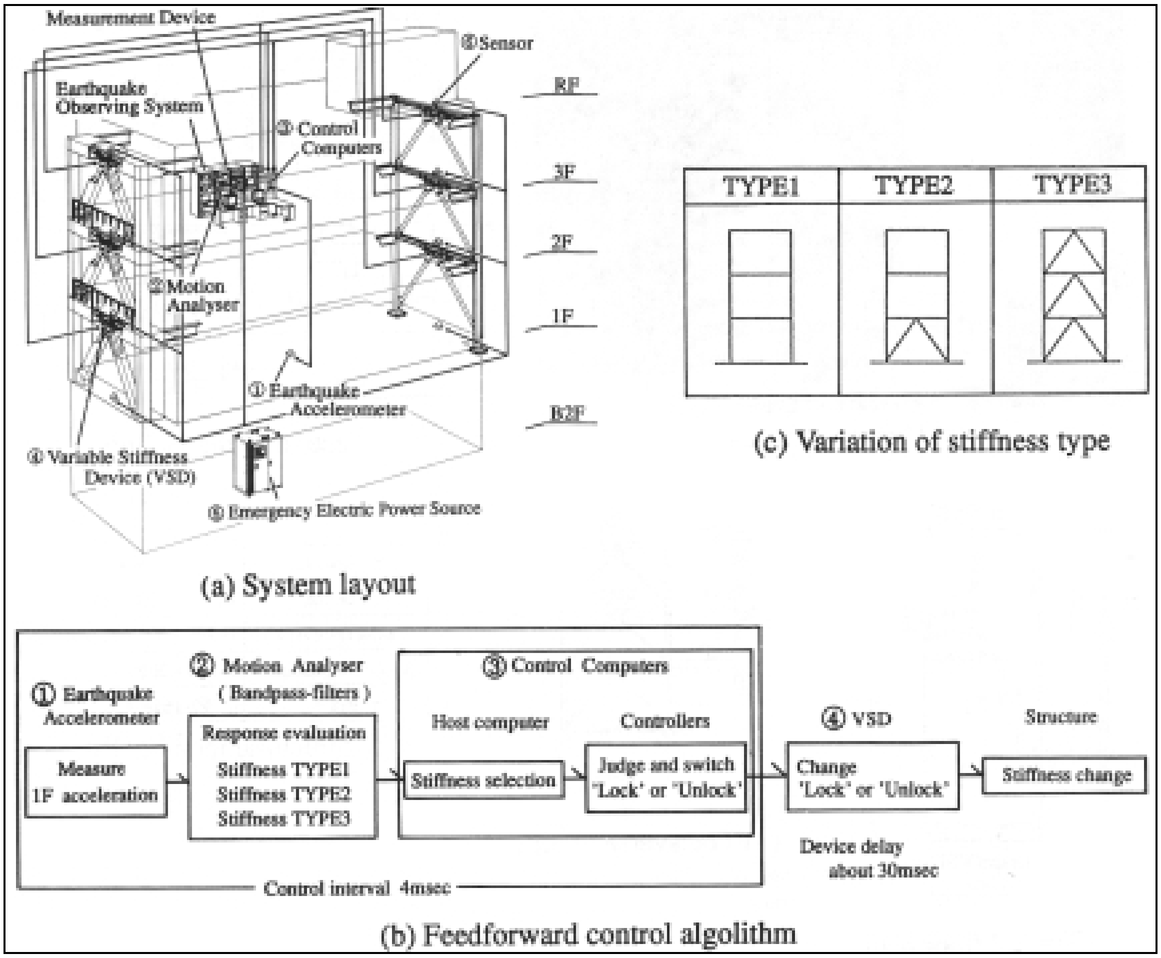
(a) Outline of VSD mechanism

Design Load	35tonf
Size	730mm × ø290mm
Weight	250kg
Stroke	±50mm
Diam. of Piston	ø180mm
Diam. of Rod	ø100mm

(b) Specification of VSD

In a typical AVS system, more than one variable stiffness device mechanism is used. Currently, AVS has been installed within the Shaking Table Laboratory Building at the Kajima Technical Research Institute, a three story steel structure. In this application, three bays on each side of the structure with "V" bracing contain the variable stiffness devices. When no ground excitations are present, all braces are locked for lateral resistance against winds. See Figure 13.

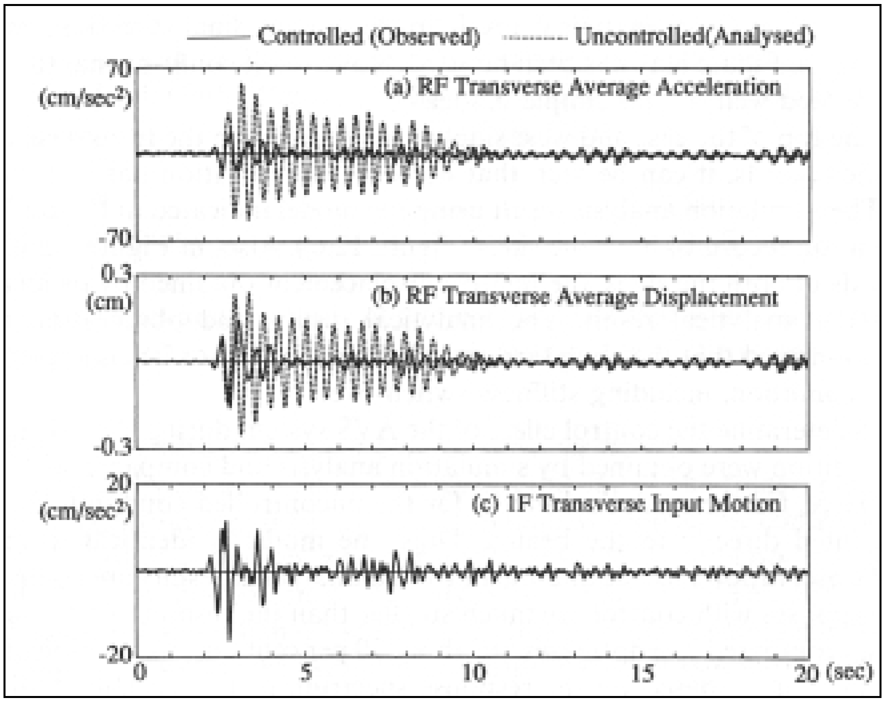
Figure 13 - Shaking Table Building at KaTRI
Source: Kobori, T. et al. Seismic Response Controlled Structure with Active Variable Stiffness System. Earthquake Engineering and Structural Dynamics, Vol 22, 925-941, 1993.



This system is only for earthquake excitations and employs a feed forward control algorithm. Basically, the stiffness of the building can take on three types. Type 1 is with all three braces disengaged, while Type 2 allows only the first floor brace as an engaged brace. The last stiffness type is Type 3 and is all three braced engaged. The natural frequencies of Type 1, Type 2, and Type 3's primary modes are 1.24 Hz, 1.70 Hz and 2.06 Hz respectively. The earthquakes ground motion is detected at the first floor by an accelerometer. This measurement is sent directly through a bandpass filter which can determine which of the three states provides stiffness that ensures minimized deflections and accelerations. This process takes 4 msec. to calculate the stiffness type desired so time lag is not of serious concern.[28]

The AVS system has been tested in simulation analyses and during actual earthquakes. In both instances, the AVS has been effective in achieving a stiffness far from the resonant region. Figure 14 shows the control effect of the system during the November 19, 1991 earthquake which struck the Tokyo area.

Figure 14 - AVS System Results During November 19, 1993 Earthquake
Source: Kobori, T. et al. Seismic Response Controlled Structure with Active Variable Stiffness System. Earthquake Engineering and Structural Dynamics, Vol 22, 925-941, 1993.



Similar to the AVS concept of a locked and unlocked braced frame is the Active Variable Damping System (AVD). The system's device is also considered a semi-active control device which is ideal for structures employing braced frames for lateral resistance. In this system, a variable damper is used instead of a lock mechanism at the top of the braced frame. Again, this system is only for earthquake excitations and uses a velocity feedback control algorithm. During an earthquake, a tall building which is protected by an AVD system can vary the damping ability of each braced frame in order to get the building's stiffness away from the resonant frequency as well as dampen energy out of the system. The beauty of this system is that it is not powered externally, but rather by batteries located in the basement of the structure. These batteries can operate for well over 7 minutes before losing power. Currently, a building is under construction which will utilize this new and promising technology.

Conclusion

The Japanese research efforts in the area of structural engineering in general are impressive. One area of on going research which has captured the imagination of many Japanese structural engineers has been active structural control. In the United States the commitment to the area of structural control has been slow in developing. This difference between the two nations is evident in the structural control systems in actual use today. In Japan well over 20 buildings employ the active control technology where as in the United States no buildings use active control. On the surface, this might imply that the United States is behind the Japanese but closer look would reveal that this is not necessarily the case. After investigating the Kajima control systems, one can not argue that they have effectively developed control systems for wind and moderate seismic loads. However, generally speaking, it has not been proven the cost effectiveness of current active control systems. For example, in the development of the AMD system for the Kyobashi Seiwa Building, Kajima subsidized the cost of the AMD system for the building's developer. Two things hinder the cost effectiveness of the systems; the first is that expensive research efforts are needed to develop and design the systems and secondly, the electricity and maintenance costs over the system's life add up. As it stands now, passive control devices such as base isolation are more cost effective in reducing structural vibrations.

Both the Japanese and the Americans have recognized these facts. In the United States for example, control research is funded only by public money via organizations like the National Science Foundation (NSF). For this reason, organizations such as NSF will provide support for control research they feel will work and will be used in the future. The current trend in NSF funding shows that semi-active control research is most promising for the future. Kajima has also recognized this with the current development of the AVD system. Semi-active control systems use less electricity than the active control systems. They also will be more reliable and perhaps less maintenance will be required over their life span. Semi-active control will be a cost effective technology which will be seen in future structures.

Future research efforts will need to focus on some pressing issues facing control designers today. First, active control systems are unable to control the first peak response of the structure. Generally, this impulsive peak is the most severe of the earthquake record and could do the most damage. The area of non-linear control is another area of needed research. Better sensor technology should be developed to make sensors easier to install and cheaper to purchase. To complement the sensors should be faster computers which can handle more sophisticated control algorithms.

In closing, Kajima's success in active control research should be applauded. They have taken the world lead in this technology and have been extremely open and supportive of joint US-Kajima research ventures. Hopefully, such a relationship can be maintained and control systems which are cost effective can be developed for the good of society all over the world.

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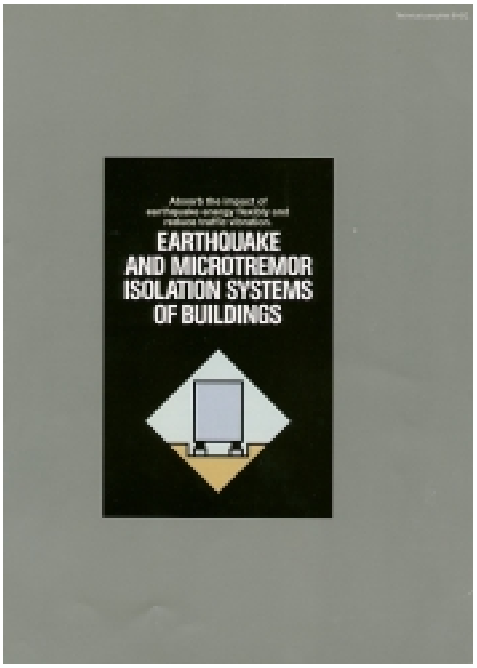
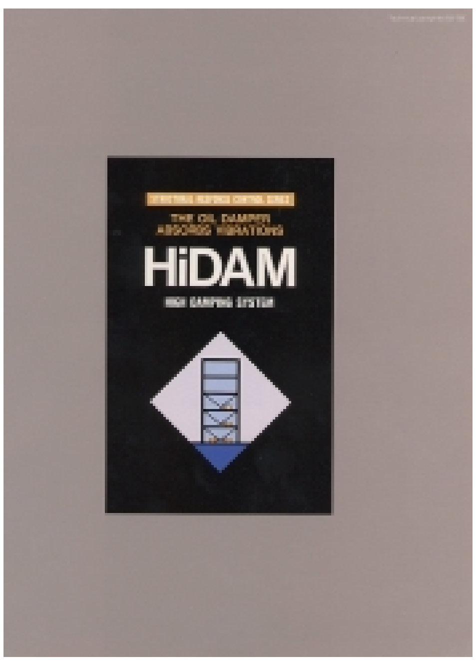
Appendix A:

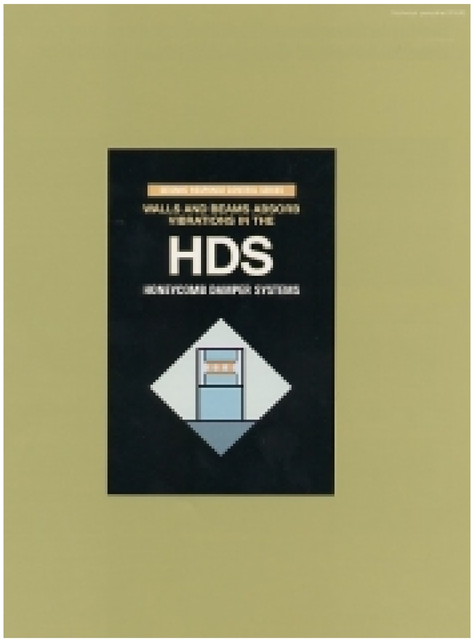
Kajima's Passive Control Technology Brochures


EARTHQUAKE
AND MICROTREMOR
ISOLATION SYSTEMS
OF BUILDINGS


KIFS

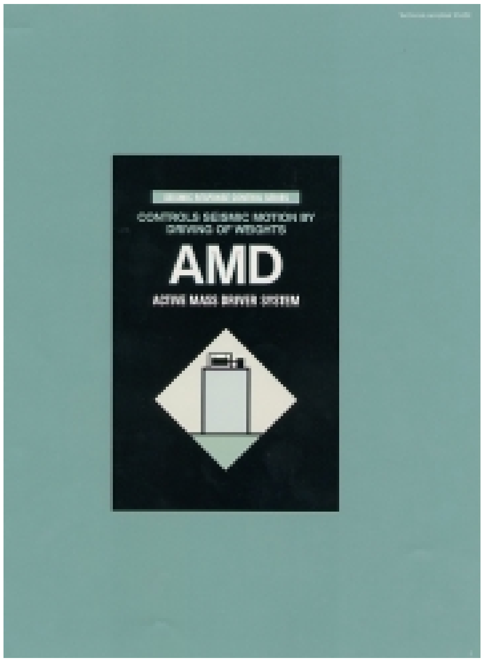

HiDAM


JDS

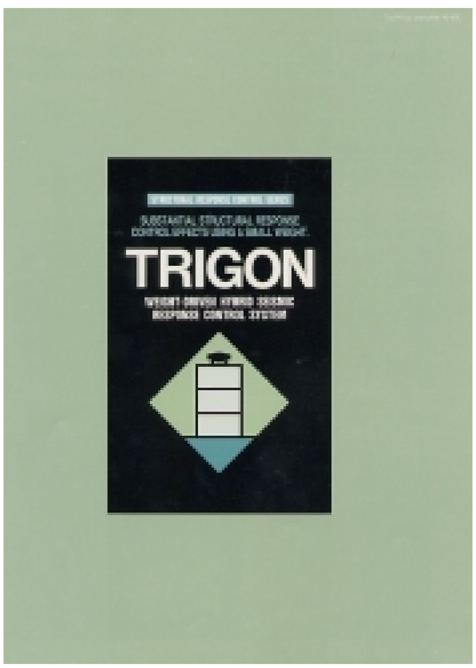

WALLS AND BEAMS ABSORB VIBRATIONS IN THE
HDS
HONEYCOMB DAMPER SYSTEMS

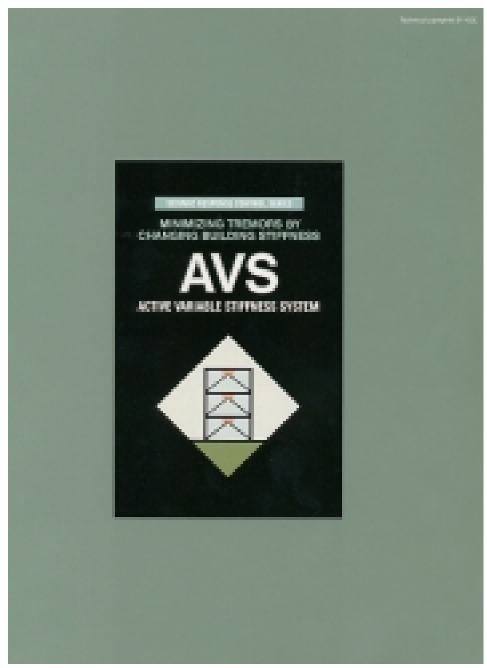
Appendix B:

Kajima's Active Control Systems Brochures


CONTROLS SEISMIC MOTION BY
DRIVING OF WEIGHTS
AMD
ACTIVE MASS DRIVER SYSTEM


THE CONTROL EFFECT IS ENHANCED
BY THE INCORPORATION OF A WEIGHT.
DUOX


SUBSTANTIAL STRUCTURAL RESPONSE
CONTROL EFFECTS USING A SMALL WEIGHT.
TRIGON
WEIGHT-DRIVEN HYBRID SEISMIC
RESPONSE CONTROL SYSTEM

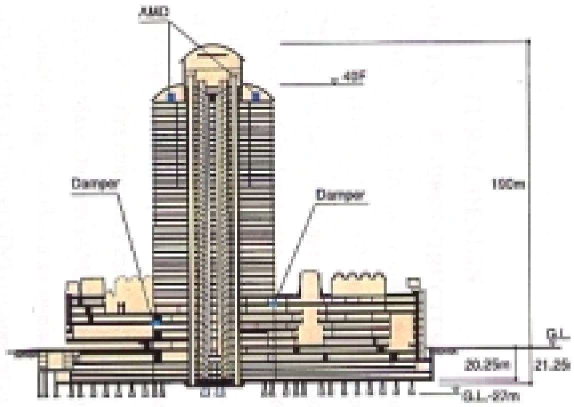

MINIMIZING TREMORS BY
CHANGING BUILDING STIFFNESS
AVS
ACTIVE VARIABLE STIFFNESS SYSTEM

Appendix C:

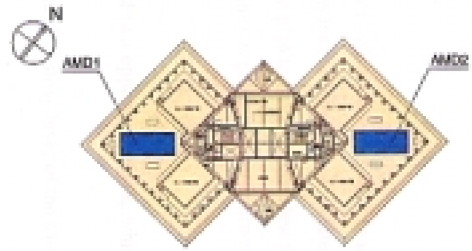
Various Japanese AMD Control System Brochures

AMD System in HERBIS OSAKA

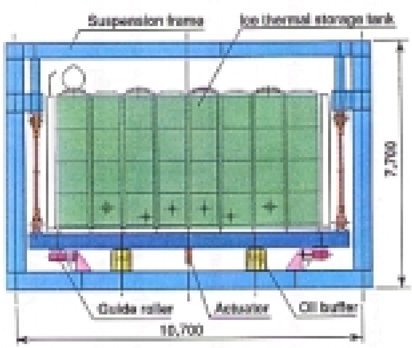
HERBIS OSAKA



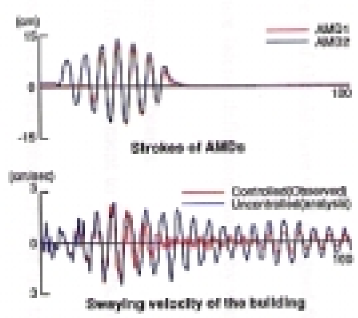
Section of the building



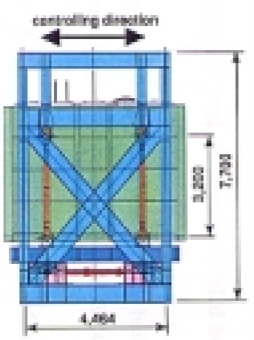
Layout plan of AMDs



Front view of AMD



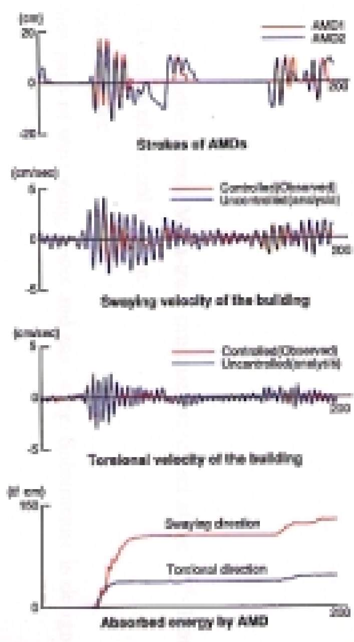
Observed records under earthquake
(June 25,1997)



Side view of AMD

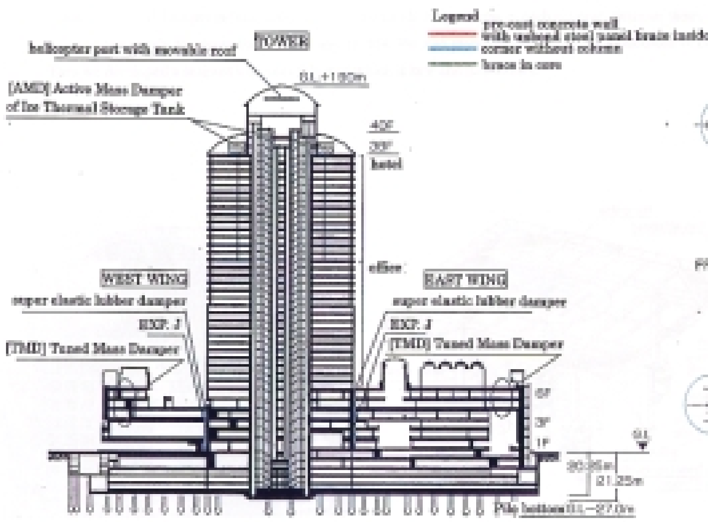
Specification of AMD

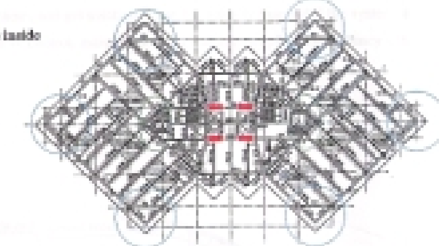
Mass element	Ice thermal storage tank	Weight	[illegible]
		Effective weight ratio to the building	0.7%/unit
Restoring element	Restoring force by suspended pendulum	Length of suspension	3.2m
		Natural period	3.6s
Damping element	Friction	Friction force	Neglected
Active element	Hydraulic actuator	Control force	[illegible]
		Braking force	[illegible]
		Control stroke	30cm
		Maximum stroke	50cm
System for excessive input		Brake by actuator	Stroke>30cm
		Oil buffer	Stroke>35cm



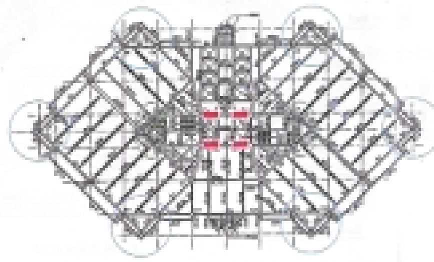
Observed records during typhoon
(Typhoon No.9709; July 26,1997)

TAKENAKA





FRAMING PLAN OF HOTEL FLOOR(TOWER UPPER FLOOR)

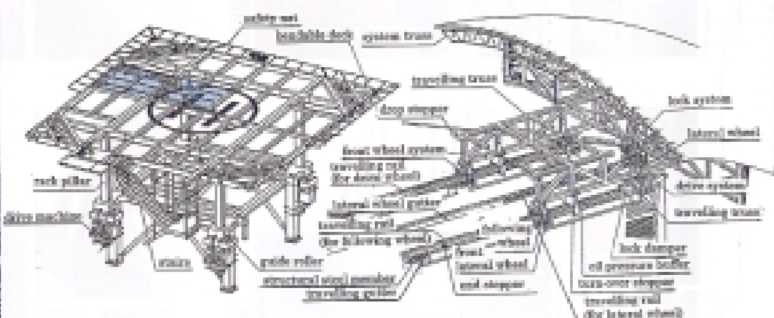


FRAMING PLAN OF OFFICE FLOOR(TOWER LOWER FLOOR)

HELIPORT

To realize the design concept "make a city which can be the world most beautiful picture", design of its roof and skyline of the city was examined. Because it must have emergency heliport on the roof by the law, we applied movable roofs above the heliport.

We disassembled the system into elements to picked up all the problems in each element, examine them, and get solution. Then we actually assembled the system to examine tentatively to ensure the solution and modify. We also made manual to give them methods of control, maintenance and training people for emergency use. Thus we developed a heliport with movable roof which is safe and functionary.



HELIPORT DECK

MOVABLE ROOF

STRUCTURAL DESIGN

OUTLINE OF SUPERSTRUCTURE

①HERBIS OSAKA has double tubular structure, which consists of a braced core and perimeter frames. Mega-truss structure, which set at the 23^{rd}-floor machine room and the 38^{th} and 39^{th} floor machine room for the hotel, provides lateral stiffness by effect of flexural reaction.

②The tower has no columns at the corner on the plan to have a good view from its corner windows.

③Because of its large plan area, expansion joints separate its superstructure into three parts of west wing, tower and east wing. Substructure is designed as one structure.

STRUCTURAL METHOD APPLIED

①Movable roof on top of the building achieved two opposite designs, which are "the roof should have well designed form as perspective" and "the roof has heliport on it for fire emergency use."

②Active Mass Damper (AMD) is applied on the 38^{th} story level of the tower to reduce lateral deflection caused by wind. Ice Thermal Storage Tank, which is for air conditioning, is used as a sway-mass.

③Tuned Mass Damper (TMD) is applied to control vertical vibrations of floor on long-spanned beams.

④Pre-cast concrete plates, which have unbond steel panel brace inside, are applied from 5^{th} basement to 39^{th} floors. It enables the building to keep its stiffness and strength, to have better sound insulating and to have effective use of interior space.

⑤Concrete, which provides strength of $800kg/cm^2$ and $600kg/cm^2$ is applied to Concrete Filled Tube (CFT) of the tower. By the concrete strength, small column section area against axial force was achieved.

⑥By using SPC combined beams from the 2^{nd} floor to the 32^{nd} floor, stiffness of steel beams is risen. It cut the 10~25% cost off.

OUTLINE OF SUBSTRUCTURE AND FOUNDATION

①To avoid underground train which runs under the 2^{nd} basement (GL-8.5~10.0m) of the west wing, SRC truss beams, which has 8.5m height and 70m and 30m span, are applied above the underground train culvert.

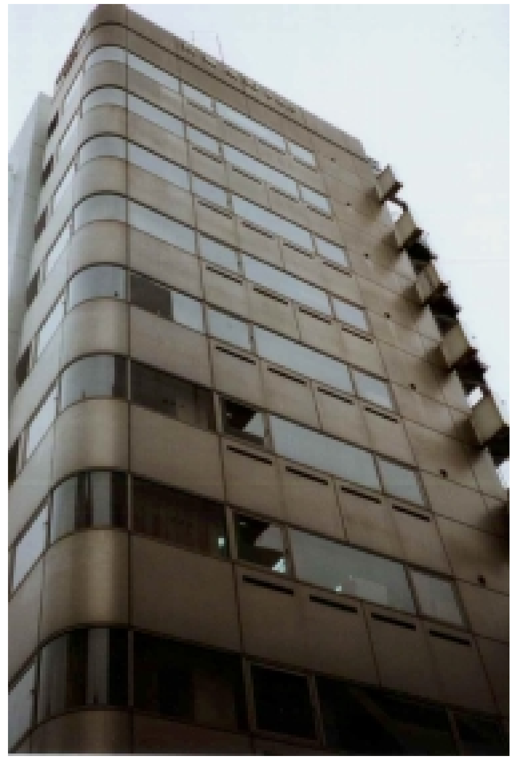
②Against floating pressure, flat-slabs with 800mm thickness are used for the 3^{rd} basement and 4^{th} basement. On the 5th floor level, concrete was filled between footing beams.

③On the south and the east side of the building perimeter, underground continuous wall, which works as both shoring, exterior wall, and pile itself, is built (The bottom of piles are on GL -47.0m, pile strength is $250t/m^2$). Cast-in-place concrete piles and continuous wall pile are used at general portion, (bottom of piles GL-27.0m pile strength is $250t/m^2$).

(Toshiyuki TANAKA, Takeshi KATAYAMA / TAKENAKA Co. Ltd.)

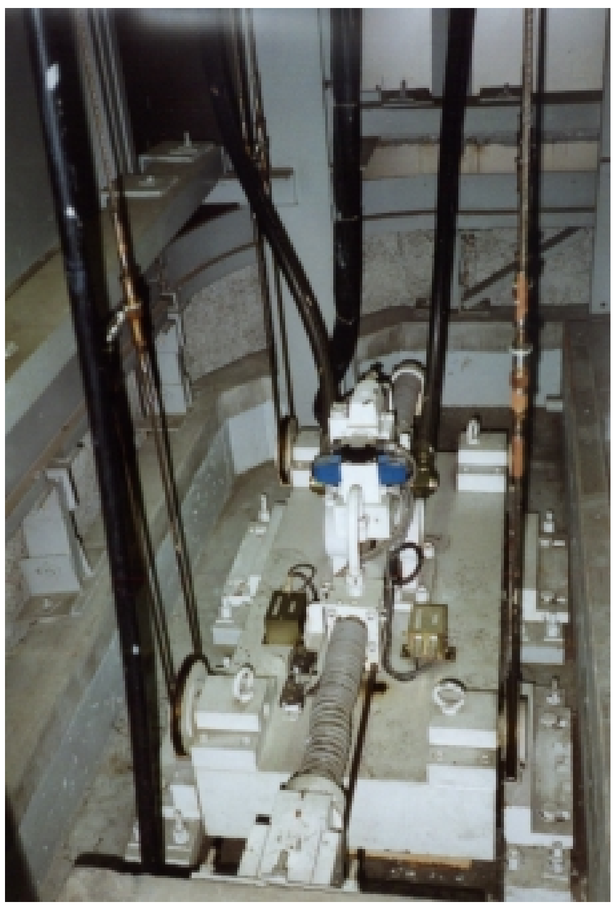
Appendix D:

Photographs of Japanese Control Systems



<u>Kyobashi Seiwa Building (1989) – Active Mass Driver (AMD) Control System</u>

Kyobashi Seiwa Building – Main AMD Masses (4.2 metric tons)



Kyobashi Seiwa Building – Secondary Mass (1.2 metric tons)