DESIGN AND IMPLEMENTATION OF ACTIVE DYNAMIC VIBRATION ABSORBER FOR BROADBAND CONTROL

BY

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A dissertation submitted in fulfilment of the requirement for the degree of Master of Science in Mechatronics Engineering

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ABSTRACT

Dynamic Vibration Absorbers (DVA) are passive devices that attenuate vibration at a single resonance frequency. However, to use the DVA for the reduction of vibration in multi degrees of freedom (MDOF) systems which have more than one resonance frequency requires modification of the DVA. These modifications are accomplished by using active control strategy on the DVA. This transforms the DVA into an Active Dynamic Vibration Absorber (ADVA). Various actuator systems have been used for the transformations of DVA into ADVA. These include Proof Mass Actuators (PMA), Piezoelectric Absorbers and Smart spring Absorbers. Limitations in the ADVA design and their control strategy which always affect their performance include friction force, energy requirement and complexity of design. In this research, a less complex design of an Active Dynamic Vibration Absorber (ADVA) and its controller is proposed. The ADVA adaptively tunes to attenuate vibration of the broadband resonance frequencies of MDOF system with minimum limitations. This study includes the mathematical modeling and experimental verifications of the resonance frequencies of the three degrees of freedom (3DOF) system on which the ADVA was implemented. Based on the broadband resonance frequencies of the 3DOF system, a prototype ADVA has been developed. The ADVA uses a proportional–integral–derivative (PID) controller to change its stiffness adaptively to reduce vibration. The optimal location of the ADVA on the MDOF system was also identified. Experimental results show that the ADVA was able to reduce the vibration of the MDOF system at all the modes. Due to the properties of the ADVA spring material used in this study, vibration attenuation at the first mode was limited to 5dB. For further research, a spring material with a lower modulus of rigidity is suggested to improve the performance of the ADVA.

خلاصة البحث

إنّ ممتصات الاهتزاز الديناميكي DVA عبارة عن أجهزة سلبية لتخفيف الاهتزاز على تردد الصدى الأحادي . و لكن لاستخدام DVA للحد من الاهتزاز في أنظمة الدرجات المتعددة من الحرية (MDOF)التي لديها عدة ترددات للصدى, فإنه يتطلب تعديل DVA. يتم إنجاز هذه التعديلات باستخدام سيطرة استراتيجية فعّالة على DVA. هذا يحوّل DVA إلى ممتصات اهتزاز ديناميكي فعّالة (ADVA). و قد أُستخدمت أنظمة مشغلات ديناميكية مختلفة لهذا الغرض من التحول (DVA إلى ADVA). وتشمل هذه المحركات والدليل الشامل (PMA)، امتصاص الكهروإجهادية وامتصاص ربيع الذكية. القيود في أنظمة المشغلات الديناميكة واستراتيجية تحكمها تشمل قوة الاجهاد, احتياجات الطاقة و تعقيد التصميم. هذه تؤثر دائما على أداء ADVA. في هذا البحث يُقترح تصميم أقلُّ تعقيداً لممتصات الاهتزاز الديناميكي الفّعالة (ADVA) ولجهاز تحكمها. ADVA تتغير بتكيف لتخفف من الاهتزاز لترددات الصدى على نطاق واسع لنظام MDOF بأقل قيود. هذه الدراسة تشمل النمذجة الرياضية والتحقق التجريبي من ترددات الرنين (الصدى) من نظام درجة ثلاثة من الحرية (3DOF) الذي تم فيه تنفيذ ADVA. بناءاً على ترددات الرنين (الصدى) واسعة النطاق للنظام 3DOF، تم وضع نموذج أولي لل ADVA. ADVA تستخدم وحدة تحكم المشتقة الجزئية النسبية (PID) لتغيير صلابتها بتكيف لتخفف من الاهتزاز. كما تم تحديد الموقع الأمثل لل ADVA على نظام MDOF. وقد أظهرت النتائج أنّ ADVA كانت قادرة على الحد من اهتزاز النظام MDOF في جميع الأوضاع. بسبب القوة الميكانيكية التي تتمتع بها مواد ADVA ، فإن تخفيف الاهتزازات في الوضع الأدنى كانت محددة بـ 46%. ويُقترح استخدام مواد أفضل لتحسين أداء ADVA.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Mechatronics Engineering.

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institution.

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&

Yassin Lagoke Ladipo

TABLE OF CONTENTS

Abstract ii
Abstract in Arabic iii
Approval Page iv
Declaration Page v
Copyright Page vi
Dedication vii
Acknowledgements viii
List of Tables xi
List of Figures xii
List of Symbols xiv
List of Abbreviations xv

CHAPTER ONE: INTRODUCTION 1
1.1 Background 1
1.2 Problem Statement and its Significance 3
1.3 Research Objectives 4
1.4 Research Scope 5
1.5 Research Methodology 5
1.6 Dissertation Outline 7

CHAPTER TWO: LITERATURE REVIEW 8
2.1 Introduction 8
2.2 Structural Vibration Control 8
2.3 Passive, Active and Hybrid Control System 10
2.3.1 Active Vibration Control Strategy 13
2.4 Dynamic Vibration Absorber Overview 18
2.4.1 Tuning of Dynamic Vibration Absorber 22
2.5 Summary 24

CHAPTER THREE: MODELING AND SIMULATION RESULTS 25
3.1 Introduction 25
3.2 Undamped Motion of Building Model 25
3.3 Damped Motion of Building Model 28
3.4 Dynamic Response of Building Model 30
3.5 Dynamic Response of Building Model with ADVA 32
3.5.1 Optimal Location of ADVA 34
3.5.2 ADVA Anti-Resonance Mode 36
3.6 Summary 37

CHAPTER FOUR: ADVA DESIGN AND CONTROL ALGORITHM 38
4.1 Introduction 38
4.2 Active Dynamic Vibration Absorber Prototype 38
4.3 Prototype Consideration 40
4.3.1 Lock Mechanism 42

4.4 Active Dynamic Vibration Absorber Configuration 45
4.5 Control Algorithm 46
4.6 Actuator Controller 47
4.6.1 Position Value Presetting for the ADVA Actuator 48
4.6.2 Velocity Value Presetting for the ADVA Actuator 49
4.7 LabVIEW State Machine 51
4.8 Summary 52

CHAPTER FIVE: EXPERIMENTAL SETUP AND DATA ACQUISITION ... 53
5.1 Introduction 53
5.2 Building Model 53
5.3 Experimental Setup 54
5.4 Excitation Force Configuration 55
5.5 Data Acquisition System 55
5.6 Summary 56

CHAPTER SIX: CONTROL STRATEGY AND EXPERIMENTAL RESULTS 57
6.1 Introduction 57
6.2 Control Flow Diagram 57
6.3 Controller Tuning 61
6.4 ADVA Performance Evaluation 62
6.4.1 Performance at First Mode 64
6.4.2 Performance at Second Mode 65
6.4.3 Performance at Third Mode 66
6.5 Summary 68

CHAPTER SEVEN: CONCLUSION AND RECOMMENDATION 69
7.1 Conclusion 69
7.2 Recommendation 70

BIBLIOGRAPHY 72

Publications 75

APPENDIX A: MATLAB code for building model resonance frequencies 76
APPENDIX B: LabVIEW state machine code for controller strategy 79
APPENDIX C: BLDC motor control strategy 83

LIST OF TABLES

Table No.		Page No.
2.1	Summary of actively controlled buildings	9
2.2	Structural protective systems	10
2.3	Performance metrics	21
3.1	Resonance frequencies of building model	31
4.1	ADVA design parameters	40
4.2	Properties of ADVA components	45
4.3	PID controller for actuator	50
5.1	Properties of building model	52
6.1	Performance of ADVA at resonance frequencies	66

LIST OF FIGURES

Figure No.		Page No.
1.1	Research methodology chart	6
2.1	Classification of vibration control method	12
2.2	Active structural control schematic diagram	14
2.3	Principle of feedback control	15
2.4	Principle of feedforward control	16
2.5	Representation of Active Dynamic Vibration Absorber	22
3.1	Schematic diagram of building model	25
3.2	Stiffness of column	26
3.3	Sketch of equivalent stiffness in each floor	27
3.4	Equivalent 3DOF system	28
3.5(a)	Frequency Response Function of the first floor	29
3.5(b)	Frequency Response Function of the second floor	29
3.5(c)	Frequency Response Function of the third floor	29
3.6(a)	Vibration displacement of first floor	35
3.6(b)	Vibration displacement of second Floor	35
3.6(c)	Vibration displacement of third Floor	35
3.7(a)	Anti-resonance mode using ADVA at first mode	36
3.7(b)	Anti-resonance mode using ADVA at second mode	36
3.7(c)	Anti-resonance mode using ADVA at third mode	36
3.8	Frequency response of third floor of building at all modes	37
4.1	Compression springs	39

4.2(a)	Helical spring and clamp	43
4.2(b)	Absorber mass	43
4.2(c)	Guide rod	43
4.2(d)	BLDC motor attached to ADVA chassis	43
4.3	Active Dynamic Vibration Absorber Design	44
4.4	Block diagram of a PID controller	48
4.5	Setting target velocity and position via serial communication	49
4.6	Control strategy	52
4.7	Experimental setup showing 3DOF system and ADVA	52
5.1	Shaker frame	54
5.2	Block diagram representation of system	56
5.3	Experimental set up	58
6.1	Feedback-based tuning controls	60
6.2(a)	Time response at first resonance frequency	63
6.2(b)	FRF at first resonance frequency	63
6.3(a)	Time response at second resonance frequency	64
6.3(b)	FRF at second resonance frequency	64
6.4(a)	Time response at third resonance frequency	64
6.4(b)	FRF at third resonance frequency	64

LIST OF SYMBOLS

ω	Frequency
ζ	Modal eigenvector
τ	Damping factor
ψ	Modal shapes
δ	kronecker delta function
E	Modulus of rigidity of column material
d_a	Spring outer diameter
ω_a	Natural frequency of ADVA based on number of coils
m_a	Absorber mass
b	Spring inner diameter
EI	Flexural rigidity
α	Mass proportional constant
β	Stiffness proportional constant
λ	Lambda
ρ	Density
n_a	Number of active spring coils
G_a	Modulus of rigidity of spring material
D_a	Spring mean coil diameter (outer diameter-wire diameter)
d_a	Spring wire diameter

LIST OF ABBREVIATIONS

3DOF	3 Degrees of freedom
ACW	Anticlockwise
ADVA	Active Dynamic Vibration Absorber
AMD	Active Mass Damper
ATMA	Active Tuned Mass Absorber
ATMD	Active Tuned Mass Damper
AVA	Active Vibration Absorber
AVC	Active Vibration Control
BLDC	Brushless Direct Current
CW	Clockwise
DAQ	Data Acquisition
dB	Decibel
DVA	Dynamic Vibration Absorber
FFT	Fast Fourier Transform
FRF	Frequency Response Function
HMD	Hybrid Mass Damper
MDOF	Multi Degrees of Freedom
PMA	Proof Mass Actuator
SDOF	Single Degree of Freedom
TMD	Tuned Mass Damper
VA	Vibration Absorber

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Vibrations can be described as unwanted motion. Most of the time, it gives disturbing effect on engineering systems. It is important to be able to predict, analyze and control the motion resulting from these excitations. In structural engineering, buildings are subjected to excitation forces such as wind, earthquakes and this usually reduces or eliminates human comfort. The dynamic response of the buildings can be altered to remove such discomfort in the following ways:

1) By controlling the natural frequencies of the system and avoiding resonance under external conditions.
2) By preventing excessive response of the system, even at resonance. This is achieved by introducing a damping or energy-dissipating mechanism.
3) By reducing the transmission of the excitation force from one part of the buildings to the other using vibration isolators.
4) By reducing the response of the system with the addition of an auxiliary mass damper or vibration absorber.

These methods can be classified as passive, active or hybrid (Korenev and Reznikov, 1993). The first three methods represent passive control method while the fourth is an active control method.

In passive control, the controlling devices have no feedback capability between them. However, in active control, devices incorporate real-time recording and instrumentation, which is integrated with the input source and actuators. A combination of both the features of active and passive control is known as hybrid control.

Research into active control of vibration in structural engineering is relatively a recent area when compared to passive control (Preumont and Seto, 2008). In this area, the protection of the structure is effected by controlling the motion of the structure using an active control system. The active control system is supplied with an external energy. In practical terms, this is achieved by designing, fabricating and installing the active control system in full scale structures (Soong and Costantinou, 1994).

In active control, an auxiliary mass is used to reduce the amplitude of vibration on the structure. It is attached by means of springs or damping devices to the vibrating structures. Depending on the application in active state, the auxiliary mass system can be classified as either an Active Mass Damper (AMD) or Dynamic Vibration Absorber (DVA) also known as Dynamic Absorber. In DVA, the auxiliary mass system can be tuned to alter the vibration response of the main system. The excitation force on the primary system usually has a constant frequency or a constant multiple of frequency.

If it is impossible to incorporate damping into a structure that vibrates, the damping characteristics of an auxiliary system to be attached to it can be altered. This provides the necessary damping for the main system. When used in this manner, the auxiliary mass system can be taken to be one form of a Damper. The names Damped Absorber (DA) or AMD is given to this type of system (Saleh and Ahsan, 2006).

In controlling the actuators, the active control forces are generated depending on the utilization of measured data obtained from sensors and the control algorithm being used. The control algorithm can be classified as closed-loop control, open-loop control or closed-open-loop control. In closed-loop control, the control forces are generated based on feedback responses from the structure to be controlled. In open loop, the active control forces are obtained from measured external excitations alone. Closed-open-loop control involves both external loads and structural response quantities (Chey, 2007).

In this research, an auxiliary system, which serves as an Active Dynamic Vibration Absorber (ADVA) was used as a device to control the dynamic response of a prototype 3DOF system. The ADVA was used for the three resonance modes of the 3DOF system. It will attenuate vibration within the broadband modes of the resonance frequencies. The results of the active vibration control of the broadband resonance frequencies of the prototype-building model used as the 3DOF system will be presented. In addition, the performance of the ADVA will be discussed.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

The response of structures to dynamic forces such as earthquakes and wind loads is of importance to structural engineers. Although there have been many improvement in this area, the use of active control in the reduction of structural vibration effects is a relatively new field compared to passive control (Preumont and Seto, 2008). A number of serious challenges also exist. These include, increasing the reliability on active control system, eliminating reliance on external power supply, reduction of implementation cost and gaining acceptance over non-traditional passive control method.

Despite the advancements made in the use of DVA in structural vibration control, its location on the vibrating system is important. Being a discrete device, a DVA has fixed parameters and its behaviors cannot be changed during operation. This makes it effective only at one resonance frequency. It thus becomes useless when placed at other modal nodes or lines (Peng, Ng and Hu, 2005). Obviously, the use of an ADVA results in reduced vibration across a broadband range but complexity of design and lower reliabilty becomes a reality. The engineering concept of tuning a DVA also known as Tuned Mass Damper thereby making it active appears simple, but a practical implication usually makes it difficult.

Thus, a major challenge is presented in the design and implementation of Active Dynamic Vibration Absorber for broadband control.

1.3 RESEARCH OBJECTIVES

The main objectives of this research are:

a) To model and develop the dynamic response of a three degrees of freedom (3DOF) system both theoretical and experimentally.
b) To identify the optimal location of the Active Dynamic Vibration Absorber on the developed three degrees of freedom system.
c) To develop an Active Dynamic Vibration Absorber.
d) To develop a control algorithm for the Active Dynamic Vibration Absorber.
e) To evaluate the performance of the developed Active Dynamic Vibration Absorber and its control algorithm.

1.4 RESEARCH SCOPE

The focus of this research is to design an ADVA for use in vibration control of a prototype 3DOF system. The ADVA will be used to attenuate vibration within the broadband, which include the resonance frequencies of the 3DOF system. PID controller was used in the implementation of the ADVA control algorithm.

1.5 RESEARCH METHODOLOGY

The methodology to conduct this research include;

1) Literature Review:

   Existing research on the use of ADVA in controlling structural vibrations will be reviewed.

2) Modeling of the 3DOF system:

   The dynamic response of the 3DOF system in the frequency domain will be examined. The resonance frequencies of the 3DOF system will be obtained from the dynamic response. These resonance frequencies will be used in the design of the ADVA.

3) Experimental verification of the 3DOF system modeling results:

   The 3DOF system will be tested experimentally. The resonance frequencies obtained from this will be compared with the resonance frequencies obtained from the simulation results of the modeled 3DOF system. This will ensure that more reliable resonance frequencies of the 3DOF system are known.

4) Simulation studies of ADVA control algorithm:

   The performance of the ADVA will be evaluated using simulation results. An optimal location of the ADVA will also be determined from the simulation results.

5) Implementation of ADVA on the 3DOF system:

   The designed ADVA and its control strategy will be implemented on the 3DOF system in real time. The attenuation of the vibration on the building model will be evaluated. These results will be used to justify the use of an ADVA in the attenuation of vibration in a broadband.

Figure 1.1 shows the flow chart of the research methodology.

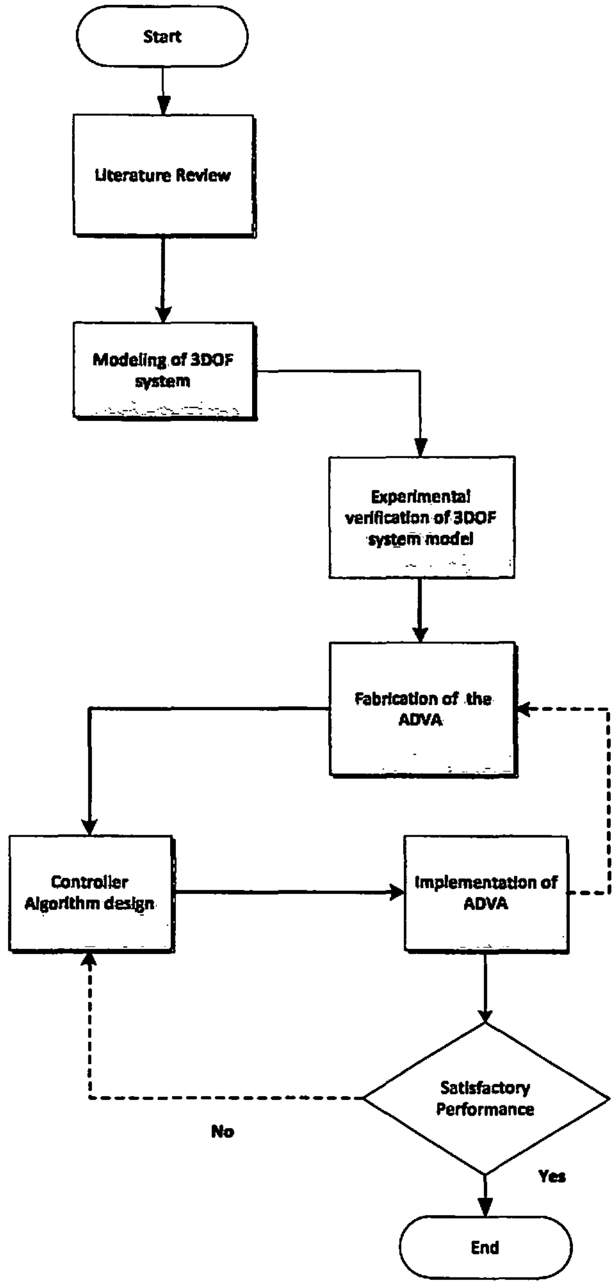

Figure 1.1: Research methodology chart

1.6 DISSERTATION OUTLINE

The dissertation consists of seven chapters. The summary of the content of each chapter is presented as follows:

Chapter One discusses the various ways of controlling vibration, the identified problem in existing methods, the objectives of this work, the methods involve in this research, scope and the arrangement of the dissertation.

Chapter Two discusses prior works in this field in the form of literature review. Also the theory of the ADVA and the 3DOF system involved in this work are described. The control theory generally used with the different actuator system is also given.

Chapter Three discusses the 3DOF system, its parametric configuration, and dynamic response with and without an ADVA. The optimal location of the ADVA on the 3DOF system for optimum performance is also determined.

Chapter Four discusses the different prototype considered in the design of an ADVA. It also describes the design of the selected prototype ADVA and its configuration. The use of LabVIEW software in the instrumentation control of the ADVA is also discussed.

Chapter Five describes the experimental set up for this research. The various components that give the desired specification of both the 3DOF system and the ADVA are presented.

Chapter Six discusses the performance of the ADVA and the control strategy at the different resonance frequencies of the 3DOF system.

Chapter Seven presents the conclusion and recommendation from this research.

CHAPTER TWO

BACKGROUND AND LITERATURE REVIEW

2.1 INTRODUCTION

This chapter discusses methods of attenuating vibration in structures that are in existence in literature. The merits and demerits of various control systems based on the controller devices are also discussed. The classification of the control algorithm based on the generated active control force is also shown. Finally, the uniqueness and simplicity of using Active Dynamic Vibration Absorber is reviewed.

2.2 STRUCTURAL VIBRATION CONTROL

Due to recent advances made in structural design and analysis, taller buildings and structures are being constructed. In fact, it has been predicted that the next generation of buildings could be one order of magnitude taller than what we presently have as tall buildings (Yang J.N. and Soong, 1988). Tall buildings are vulnerable to adverse environment loads such as earthquakes, high wind and extreme waves.

Various methods have been used in controlling vibration in engineering. For structural applications certain things must be taken into consideration.

1) Civil engineering structures are massive and heavy, thus necessitating large control forces and devices for controlling vibrations in them.
2) The major sources causing structural vibrations are external dynamic loads.
3) These structures are presumably self-stationary and stable without these external dynamic loads.

Table 2.1
Summary of buildings with active vibration control (Spencer and Sain, 1997)

Full–Scale Structure	Location	Year Completed	Scale of Building	Control System Employed	AMD/HMD Number	Mass (tons)	Actuation Mechanism
Kyobashi Seiwa	Tokyo, Japan	1989	33m, 400tons, 11stories	AMD	2	5	Hydraulic
Kajima Research Institute, KATRI No. 21 Building	Tokyo, Japan	1990	12m, 400tons, 3stories	Active variable stiffness system (6 devices)	-	-	Hydraulic
Sendegaya INTES	Tokyo, Japan	1992	58m, 3280tons, 11stories	AMD	2	72	Hydraulic
Applause Tower	Osaka, Japan	1992	161m, 13943tons, 34stories	HMD	1	480	Hydraulic
Kansai Int. Airport Control Tower	Osaka, Japan	1992	86m, 2570tons, 7stories	HMD	2	10	Servo motor
Osaka Resort City 2000	Osaka, Japan	1992	200m,56980tons, 50stories	HMD	2	200	Servo motor
Yokohama landmark Tower	Yokohama Kanagawi, Japan	1993	296m, 260610 tons, 70stories	HMD	2	340	Servo motor
Long Term Credit Bank	Tokyo, Japan	1993	129m, 40000tons, 21stories	HMD	1	195	Hydraulic
Ando Mishikicho	Tokyo, Japan	1993	54m, 2600tons, 14stories.	HMD (DUOX)	1	22	Servo motor
Hotel , Nikko Kanazawa	Kanazawa, Ishikawa Japan	1994	131m, 2700tons, 29stories	HMD	2	100	Hydraulic
Hiroshima Riehga Royal Hotel	Hiroshima Japan	1994	150m, 8300tons, 355stories	HMD	1	80	Servo motor
Shinjuku Park Tower	Tokyo, Japan	1994	227m, 130000tons, 52stories	HMD	3	330	Servo motor
MHI Yokohama Building	Yokohama Japan	1994	152m, 61800tons, 34stories	HMD	1	60	Servo motor
Hamamatsu ACT Tower	Hamamatsu, Japan	1994	212m, 107500tons, 46stories	HMD	2	180	Servo motor
Riverside Sumida	Tokyo,Japan	1994	134m, 52000tons, 33 stories	AMD	2	30	Servo motor
Hikarigaoka J-city	Tokyo, Japan	1994	110m, 29300tons, 26stories	HMD	2	44	Servomotor
Miyazaki Phoenix Hotel Ocean 45	Miyazaki, Japan	1994	154m, 83650tons, 43 stories	HMD	2	240	Servo motor
Osaka WTC Building	Osaka, Japan	1994	252m, 80000tons, 52stories	HMD	2	100	Servo motor
Dowa Kasai Phoenix Tower	Osaka Japan	1995	145m, 26000tons, 28stories	HMD (DUOX)	2	84	Servo motor
Rinku Gate Tower North Building	Osaka, Japan	1995	255m, 7500tons, 56stories	HMD	2	160	Servo motor
Hirobe Miyake Building	Tokyo, Japan	1995	31m, 273tons, 9stories	HMD	1	2.1	Servo motor
Plaza Ichihara	Chiba, Japan	1995	61m, 5760tons, 12 stories	HMD	2	14	Servo motor
TC Tower	Kao Hsung, Taiwan	1996	85 stories	HMD	2	350	Servo motor
Nanjing Tower	Nanjing China	1997/98	310m	AMD	1	60	Hydraulic