Robust Control of Structures Subject to Uncertain Disturbances and Actuator Dynamics

Research Report

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Chapter 1

Introduction

Nowadays, control systems play a major role in all engineering fields, including manufacturing, electronics, communication, transportation, computers and networks, military systems and building of civil engineering structures [Murray*etal*03]. The last one was an unknown field for the control engineers until 1970's. In the last thirty years, the application of control systems to the civil engineering structures becomes a very interesting field both to the society of civil and control engineers. Developments in this field have been possible thanks to huge technological advances in areas such as sensing, computation and control devices manufacturing, among others. Several reasons to apply control on structures can be found in [SpeSai97]. Among them, the important one is the protection of civil engineering structures and human beings when strong external forces, for example, strong earthquakes, are acting on the structures. When a moderate external force like wind is acting on the structure uncomfortable acceleration and displacements may occur. Thus the need of a control system to improve the structural dynamic behavior and to provide human comfort.

The first real implementations of structural control were based on base isolation, viscoelastic dampers and tuned liquid dampers. Many years later the active control concept appeared and its first real implementation was made in the 11-story Kyobashi Seiwa building in Tokyo, Japan, to reduce the vibration of the building under strong winds and moderated seismic excitations [Sak*etal*02]. Recently, the techniques of semiactive and hybrid control were proposed for structural control and their implementations have been made successfully in Japan and USA. A meaningful reference of the practical effectiveness of a structural control system was the significant imporvement of the structural performance in a real situation as like the Kobe earthquake of January 17, 1995. It caused the collapse of a vast number of buildings together with a heavy toll of human lives. There were two buildings equipped with seismic isolation systems and a certain response control effect against the major earthquake was observed on these buildings. However, several buildings in the adjacent Osaka area, equipped with active control systems and being designed for control of wind-induced vibrations, ceased to function when the earthquake struck. This situation warns us that oncoming seismic motions cannot be predicted and has demonstrated that the best way to ensure the safety of the controlled civil engineering structures is to look for the best design strategies of control systems which contemplate in all possible actions that could occur in them.

Control of civil engineering structures is still an open field to theoretical research and practical application. In order to achieve better structural performance in the future, new methodologies should be proposed and their combination with traditionally used ones should also be studied. The objective the present research is try to find some control design strategies, which must be effective and closed to the real operation conditions. As a novel contribution to structural control strategies, the theories of Interval Modal Arithmetic, Backstepping Control and QFT (Qualitative Feedback Theory) will be studied. The steps to follow are to develop first new controllers based on the above theories and then to implement the proposed control strategies to different kind of structures. The report is organized as follows. The Chapter 2 presents the state-of-the-art on structural control systems. The chapter 3 presents the most important open problems found in field of structural control. The exploratory work made by the author, research proposal and working plan are given in the Chapter 4.

Chapter 2

Structural Control: State-of-the-art

2.1 Introduction

This chapter is devoted to present the more relevant control systems utilized in structural control. The chapter is divided into two parts: the first part highlights the more common control devices while the second part presents the most common control methodologies implemented in the structural control.

It is now established that structural control is an important issue on designing new structures and retrofitting structures for earthquakes and winds [SpeSai97]. Structural control had its roots primarily in such aerospace related problems and in flexible space structures. Then, quickly it was moved into civil engineering and infrastructure-related issues, such as building and bridge protection against extreme loads such as earthquakes and providing human comfort in the structure during noncritical times [Hou*etal*97]. Thus different structural control research fields are derived, among them: development of control strategies [SpeSoo99], development of new technologies of actuators and measurements devices [SymCon99], structural modelling, and amongst others. This implies the integration of diverse disciplines such as computer science, data processing, control theory, material science, sensing technology, stochastic processes, structural dynamics, and wind and earthquake engineering.

Researchers have developed structural control systems since approximately 100 years ago when John Milne, professor of engineering in Japan, built a small house of wood and placed it on ball bearings to demonstrate that a structure could be isolated from earthquake shaking. However, only laboratory level applications were reached out [Hou*etal*97]. In the 1960s the concept of passive control was applied to buildings and bridges such as base isolation. Concepts such as active and semiactive control are not more than 30 years old in structural control [MarMag01]. In this sense, the structural control can be considered as relatively new in the control field and several limitations both in legal and implementation aspects have been present during their development and implementation. Some researchers have been devoted to do laboratory tests in order to find the appropriate model for every part of the controlled system (actuator, plant, sensors) [Dyk*etal*96b]-[Cah*etal*98], while others look for the best control strategy [MarMag01]. These two research fields conduct to four types of structural control: *Passive control*, where structural properties as stiffness and damping are augmented, *active control*, where external energy is applied to the structure, *semiactive control* where structural properties such as stiffness and damping can be modified on-line without requiring large external or additional power than a small source to change materials properties, and finally *hybrid systems* which combine some of the above systems.

Due to the complexity and particularity of the civil engineering structures, advanced control techniques, such as optimal control, predictive control and robust control are more suitable for the structural control. Some classical control strategies, PID control, for example, can provide great utility in practical applications for conventional systems of one or two degrees-of-freedom. However, it is difficult to use them to make the vibration control of multi-degree-of-freedom systems like flexible structures, because of the complexity in formulating the control law.

2.2 Structural Control Devices

2.2.1 Introduction

Different types of structural control devices have been developed and a possible classification is done by its dissipative nature.

Passive devices: Their function is to dissipate vibratory energy by augmenting some structural parametric values (stiffness and damping) of the structure without external energy consuming.

Active devices: They deliberate energy to the structural system in the opposite sense to that deliberated by the disturbances. Their nature is that of giving energy to the system.

Semiactive devices: They make the dissipation of energy in the passive way but the magnitude of dissipated energy can be controlled by means of variations on-line of structural properties such as stiffness or damping.

Different configurations of these three types of devices will be presented in the subsequent sections.

2.2.2 Passive Control Devices

Passive energy dissipation systems encompass a range of materials and devices for enhancing damping, stiffness and strength, and they can be used for both natural hazard mitigation and rehabilitation of aging or deficient structures. These devices are characterized by their capability to enhance energy dissipation in the structural systems where they are installed. Two principles are used to dissipate vibratory energy: conversion of kinetic energy to heat and transference of energy among vibration modes. The devices that pertain to the first group are those that can operate with principles such as frictional sliding, yielding of metals, phase transformation in metals, deformation of viscoelastic solids or fluids. And those of the second group are fluid orificing and supplemental oscillators, which act as dynamic vibration absorbers [Boz$etal$98], [Cah$etal$98], [Cah$etal$00].

Since the principal motivation of the present study is to improve the structural performance by using feedback (active or semiactive) control techniques, the passive control devices will not be the major concern of this study. However, some hybrid control strategies, for example, the active or semiactive of base-isolated structures (passive systems), will be dealt with in the study.

2.2.3 Active Control Devices

Introduction

The active control systems are the opposite side of the passive systems, because they can provide additional energy to the controlled structure and opposite to that delivered by the dynamic loading. Active devices can provide better performance than passive strategies, using information of the global response and determining appropriate control forces. This device is limited to the local responses, similarly to the passive devices. An active control strategy can measure and estimate the response over the entire structure to determine appropriate control forces. As a result, active control strategies are more complex than passive strategies, requiring sensors and evaluator/controller equipments.

The merit of the active control method is that they are effective for a wide-frequency range and also for the transient vibration. However they are limited by the quantity of energy available to develop the magnitude of forces required to control the civil infrastructure. Other disadvantage of active control is that when a shift in the dynamics of the structure is occurred, its performance may be less than expected and may even result in an unstable condition, whereby unbounded energy is specified by the controller.

Active control strategies have been proposed and implemented in a number of civil structures [SpeSai97]. In 1989, the Kajima Corporation installed the first full-scale application of active control to a building [Sak*etal*02]. Two active mass drivers were installed on the roof of the 11-story Kyobashi Seiwa building in Tokyo, Japan, to reduce building vibration under strong winds and moderate seismic events. Also, there are currently nearly 40 buildings and towers implemented with active control strategies. Additionally, 15 bridge towers have been implemented with active and hybrid control devices during bridge erection. [Tan95], provided detailed lists of these full-scale applications. Table 2.1 provided by [SpeSoo99]) presents a list of the active control implementations on civil engineering structures. They are located in Japan, China, Taiwan (see figure. 2.1b) and USA (see figure 2.1a) and they were erected before 1999. Some examples of active control strategies (see figure 2.1c) include active base isolation, active bracing, tuned liquid column damping, impact absorbers, multiple connected buildings and active mass driver [Hoc03], [HolWik03], [SetMat03], [NisShi03], [Ric*etal*03], [SpeSoo99], [SooSpe02] and [NasKob03]. These are natural extensions of passive control strategies with the difference that sensors are used to measure the building responses and control computer are used to send out control signal to the actuator.

Active Tuned Mass Damper (ATMD)

The active tuned mass dampers are probably the most well-known and excellent vibration-control devices. It consists of a mass attached to a structure such that it oscillates at the same frequency of the structure but with a phase shift. A hydraulic actuator or an electric motor is used to provide a control force u to counteract or to mitigate the motion of the structure. A schematic diagram of the ATMD actuator is presented in the figure 2.2b, where m_D is the actuator mass, b_D is a damping constant, k_D stiffness constant, F_W and u are the excitation and control forces. The parameters m_B, b_B and k_B are the corresponding quantities associated with the structure. The Kyobashi Seiwa Building was the first full-scale implementation of active control technology, where the active mass damper or active mass driver system was designed and installed.

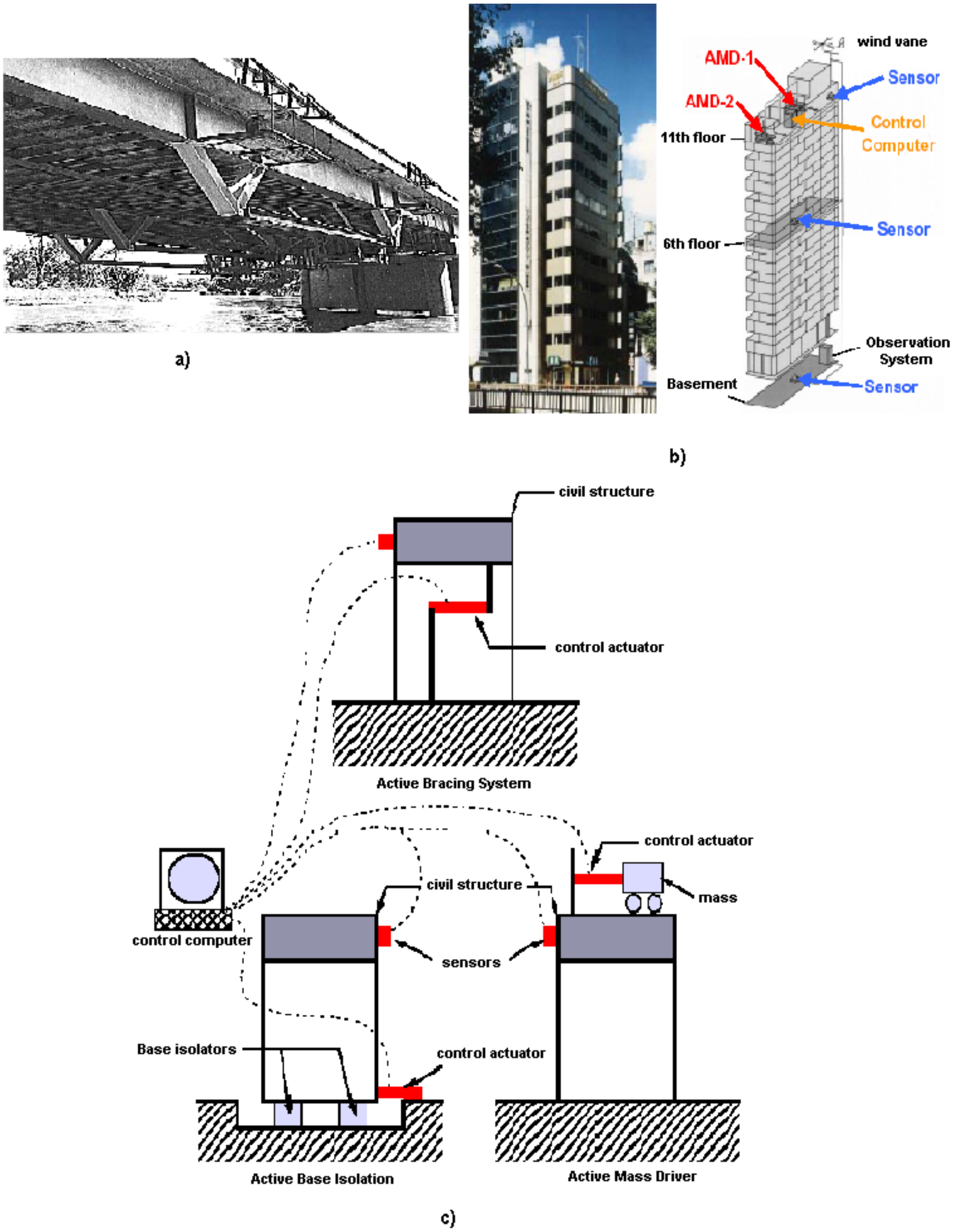


Figure 2.1: Active control systems and implementations. a). Actively controlled Kiobashi Seiwa building. b). First Full-Scale Implementation of Structural Control in the US. c). Examples of active control strategies

Table 2.1: Full Scale Implementation of Active Structural Control before year 2000

Location	Building	Year Completed	Building Use	No. of Stories	Type of Vibration Control Device*
Japan	Kyobashi Seiwa Bldg, Tokyo	1989	Office	11	AMD
	Kajima Research Lab. # 21, Tokyo	1990	Office	3	SAVS
	Shimizu Tech. Lab., Tokyo	1991	Laboratory	7	AMD
	Sendagaya INTES Bldg., Tokyo	1992	Office	11	HMD
	Elevator Tech. Lab.	1992	Laboratory	(60 m)	AGS
	Hankyu Chayamachi Bldg.,Osaka	1992	Office/Hotel	34	HMD
	Kansai Intl Airport, Osaka	1992	Control Tower	(88 m)	HMD
	Land Mark Tower, Yokohama	1993	Office/Hotel	70	HMD
	Osaka Resort City 200, Osaka	1993	Office/Hotel	50	HMD
	Long Term Credit Bank, Tokyo	1993	Office	21	HMD
	Ando Nishikicho Bldg., Tokyo	1993	Office	14	HMD
	NTT Kuredo Motomach Bldg., Hiroshima	1993	Office/Hotel	35	HMD
	Penta-Ocean Exp. Bldg., Tokyo	1994	Experimental	6	HMD
	Shinjuku Park Tower, Tokyo	1994	Office/Hotel	52	HMD
	Dowa Fire Marine Ins., Osaka	1994	Office	29	HMD
	Porte Kanazawa, Kanazawa	1994	Office/Hotel	30	AMD
	Mitsubishi Heavy Ind., Yokohama	1994	Office	34	HMD
	Hamamatsu ACT Tower, Hamamatsu	1994	Office/Hotel	(212 m)	HMD
	Riverside Sumida, Tokyo	1994	Office	33	AMD
	Hotel Ocean 45, Miyazaki	1994	Hotel	43	HMD
	RIHGA Royal Hotel, Hiroshima	1994	Hotel	35	HMD
	Hikarigaoko J City Bldg., Tokyo	1994	Office/Hotel	46	HMD
	Osaka WTC Bldg., Osaka	1995	Office	52	HMD
	Dowa Kasai Phoenix Tower, Osaka	1995	Office	28	HMD
	Rinku Gate Tower Bldg., Osaka	1995	Office/Hotel	56	HMD
	Hirobe Miyake Bldg., Tokyo	1995	Office/Residential	9	HMD
	Plaza Ichihara, Chiba	1995	Office	12	HMD
	Herbis Osaka, Osaka	1997	Hotel	38	AMD
	Nisseki Yokohama Bldg., Yokohama	1997	Office	30	HMD
	Itoyama Tower, Tokyo	1997	Office/Residential	18	HMD
	Otis Shibyama Test Tower, Chiba	1998	Laboratory	39	HMD
	Bunka Gakuen, Tokyo	1998	School	20	HMD
	Daiichi Hotel Oasis Tower, Ohita	1998	Office/Hotel	21	HMD
	Odakyu Southern Tower, Tokyo	1998	Office/Hotel	36	HMD
	Kajima Shizuoka Bldg., Shizuoka	1998	Office	5	SAHD
	Sotetsu Takashimaya Kyoto Bldg., Yokohama	1998	Hotel	27	HMD
	Century Park Tower, Tokyo	1999	Residential	54	HMD
USA	Highway I-35 Bridge, OK	1997	Highway Traffic	–	SAHD
Taiwan	TC Tower, Kaoshiung	1999	Office	85	HMD
	Shin-Jei Bldg., Taipei	1999	Office/Commerce	22	HMD
China	Nanjing Communication Tower,	1999	Communication	(310 m)	AMD

Active Tuned-Liquid-Column Dampers

An active tuned-liquid-column damper is composed of two vertical columns connected by a horizontal section in the bottom and they are partially filled with water or other fluid. Two propellers are installed inside and at the center of Tuned-liquid-column (see figure 2.2c). These two propellers are powered by a servomotor to generate the control force. The dynamic behavior of a TLCD can be characterized as a single-degree-of-freedom system. A TLCD is quite effective for any changes of water head and attack angle of the earthquake at the tuned frequency. Analytical and experimental studies have been reported by [Hoc01], [Sam*etal*98]. In hybrid systems this type of device have been used [Har*etal*94], [Tam*etal*95]. [Hoc03] studied the dynamic response of of high-rise buildings equipped with this type of devices.

Seesaw-type Active Dynamic Vibration Absorber (SADVA)

The SADVA device is a type of active devices which consists of a simple combination of actuators. It is constructed such that the frame, supporting a tuned mass damper, is vertically and rotationally driven like a seesaw by two actuators. Thus, it is possible to control the horizontal and vertical responses of a structure [Yos*etal*96]. This type of active dynamic vibration absorber has a mechanism such that the guide base of auxiliary mass is inclined and slided by double support actuators. One characteristic of this device is its short actuator stroke, since the actuators are driven just to incline the base, no to drive the mass directly, (see figure 2.2a). A mathematical model of a SADVA is presented by [Yos*etal*96]. [Yos*etal*96] implemented this type of devices on a single-story model in order to investigate its fundamental properties and on a five-stories building model in order to investigate its performance to control the structure as vertically as horizontally.

2.2.4 Semi-active control devices

Introduction

There are many definitions for semi-active control devices. The mostly accepted one is to define a semi-active control device as one that cannot inject mechanical energy into the controlled structural system but some of its properties can be dynamically varied [SpeSai97]. These devices are a promising development tool in protection of civil engineering structures. They combine the best features of both passive and active control systems and offer some adaptability, similar to active control systems, but without the requirement of large power sources for their control action. This advantage is fundamental in hazard situations like earthquake or strong winds, where the main power source of the structure may fail during such situation. Its stability in a bounded-input bounded-output sense is inherent, thus it is possible to implement high authority control strategies. This may result in performances that can surpass that of comparable active systems [Dyk*etal*97b]. Some authors have written important survey on semiactive control systems such as [[SymCon99], [MarMag01], [Hou*etal*97], [Chr01]].

The most important semiactive control devices developed until now correspond to variable-orifice fluid dampers, controllable friction devices, controllable tuned liquid dampers and controllable-fluid dampers. They will be presented in this section.

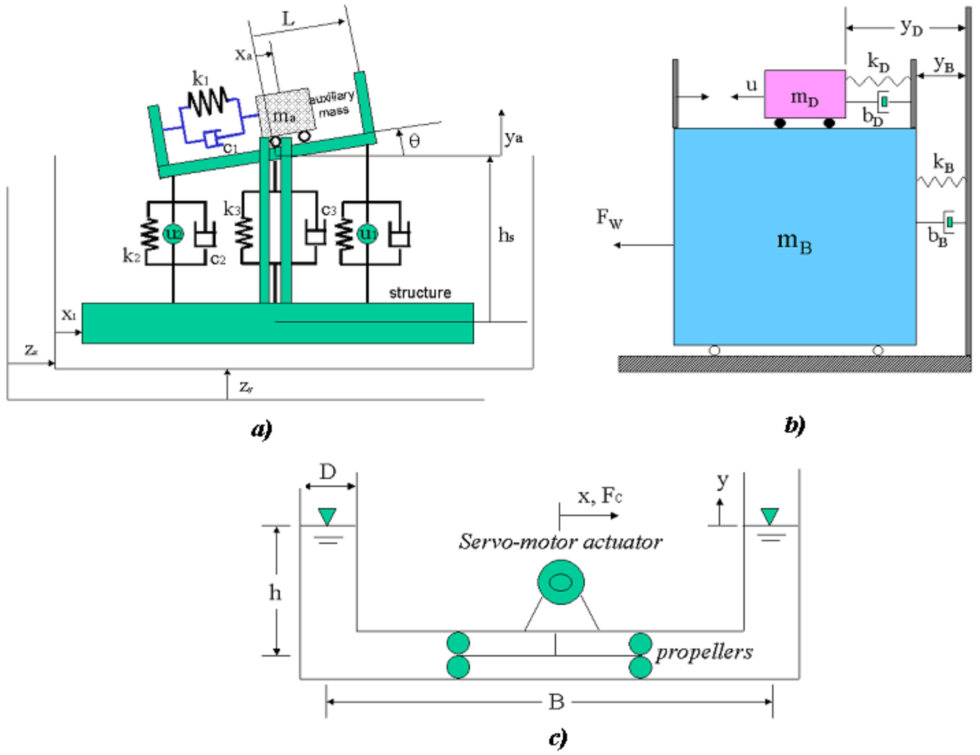


Figure 2.2: Active control devices a.) ATMD b.) SADVA c.) ATLCD

Variable-orifice fluid dampers

The variable-fluid orifice damper is a typical example of a semiactive damping device. Its operation principle consists in controlling the damping coefficient by adjusting the opening of a valve to alter the resistance to flow of a conventional hydraulic fluid damper (see fig 2.3). This action causes the regulation of a large force with a low external power, thereof its semiactive nature. Normally, this device is installed into a structure equipped with a brace or a wall, and its analytical model can be expressed as a Maxwell model, which implies physical constraint associated. One definition of semiactive fluid damper adopted by [SymCon97] is that it behaves as linear viscous dampers with adjustable damping coefficient.

In [KurKob98] this type of devices have been developed and different control strategies have been implemented. Physical meaning is related with displacement of the controlled structure. In [Kur*etal*03] a semiactive oil damper have been developed and implemented. It has been proved that this device can dissipate energy twice more than a passive damper. A novelty in the design is that the controller is included into each device, which can take advantage against strong situations such as seismic motions or strong winds where vibrations can cause faults in the electrical power deliberation. Results of both simulation and implementation were obtained and it was demonstrated the good approximation between the model and the real device, when dynamic loading tests were conducted. The physical meaning of the

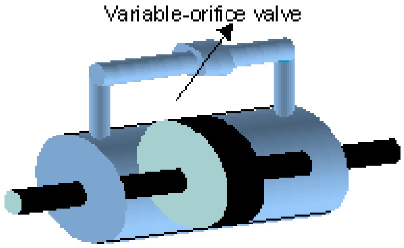


Figure 2.3: Schematic of Variable-Orifice Damper

variable damper's constraint was focused on the force-displacement relation.

Real implementations on high-rise buildings have been accomplished. The most important ones are:

∗ [Kur$etal$00] implemented this device on a 11-story building and the damping augmentation capacity was ensured.

∗Real implementation made on the Shiodome Kejima Tower in Tokyo, recently finished.

∗Full-scale experiment with variable-orifice damper implemented by [KamKob94] at the Kobori research complex. Here, devices were installed on both sides of the structure in the longitudinal direction, which resulted effective to reduce structural responses.

∗Implementation made by [Kur$etal$99] on the Kajima Shizuoka Building in Japan. Devices were installed inside the walls on both sides of the building.

∗Experiments conducted by [SacPat93] on a single-lane model bridge. The objective of this implementation was to dissipate the energy induced by vehicle traffic.

∗Full-scale experiment on a bridge on interstate highway I-35 conducted by [Pat$etal$99a]; [Pat$etal$99b]; [Kue$etal$99]. This experiment corresponds to the first full-scale implementation in USA.

Controllable fluid dampers

Another type of semiactive devices is the controllable fluid dampers. In these devices some properties of their internal fluid can be modified by means of an electrical/magnetic field, resulting a modification in the quantity of force absorbed. The principal advantage of this type of devices is that the piston is the only moving part. Consequently, it can change rapidly from a state to another (linear viscous fluid to a semi-solid in milliseconds) when exposed to an electric/magnetic field. Two types of semiactive controllable fluid dampers are found: Electrorheological (ER) and Magnetorheological (MR) damper. Their difference is the type of fluid used: Magnetorheological or Electrorheological fluid.

Electrorheological Damper: The ER damper normally consists of a hydraulic cylinder containing micron-sized dielectric particles suspended within a fluid. In presence of electric field it offers a variation of resistance to flow and consequently its dynamic behavior can be modified (see figure 2.4a-b). Because its electrical performance the action response is very fast (about 10^{-4} [seg] to 10^{-5} [seg]) [LeiRei93a], respect to other type of semi-active control devices. The Bingham visco-plastic material model is used to model ER materials under quasisteady flow and can be mechanically represented by a dash-pot in parallel with a frictional element (see figure 2.4c). Figure 2.4d presents the real and modelled behaviour of a ER damper excited to 0kV, 2kV and 5kV at a frequency of 2kHz.

Several ER dampers have been developed and adapted to civil engineering structures. The most important developments have been obtained by [Gav96a]; [Gav$etal$96b]; [Gav01]; [EhrMas94];[Mas$etal$94]; [LeiRei93a]; [LeiRei93b] among others.

Magnetorheological Damper: The MR damper has become an alternative of ER damper. Its operation principle is similar to ER damper, except that the external signal applied is a magnetic field, which becomes the inside fluid from semisolid to viscous state and it exhibits a viscoplastic behavior similar to that of an ER fluid. MR devices with a high bandwidth can be constructed and controlled with low voltage (i.e. 12-24V) and low electrical currents about 1-2 amps. Batteries can supply this level of power.

The principal advantages of MR damper respect to ER damper are:

a). MR damper is not sensitive to impurities such as are commonly encountered during manufacturing and usage while the ER damper does it.

b). MR devices can operate at temperatures from -40C to 150C and slight variations occur in the yield stress.

c). Wider choice of additives can be generally used with MR fluids to enhance performance conditions, such as stability, bearing life, etc.

d). The transition velocity of the MR devices is faster than the ER device.

A MR damper model was developed in [Dyk$etal$96b], where a simple mechanical model is used to describe its behavior. This model was demonstrated to accurately predict the behavior of a shear-mode MR damper over a wide range of inputs [Yi$etal$98]. In [Yi$etal$98] dynamics introduced by the resistance and inductance of the circuit when changes are produced in the input command, are represented by a first order time lag. They are accounted for introducing a first order filter. In [Spe$etal$97b] a model to predict the behavior of the MR damper for a time-varying command input is presented, in which above mentioned dynamics are also introduced. A representation of typical responses of this phenomenological model are shown in the figure 2.5.

Numerical examples and implementations to demonstrate the effectiveness of MR devices have been developed in ([Dyk$etal$96a], [Dyk$etal$97b]). These developments have demonstrated that MR dampers may be closed to the linear active control performance, while only a power fraction of that required by the active controller is enough. In [YosDyk02] an implementation of MR dampers on a nonlinear benchmark building is developed. The Lord Corporation designed and built a full-scale, 20-t MR damper

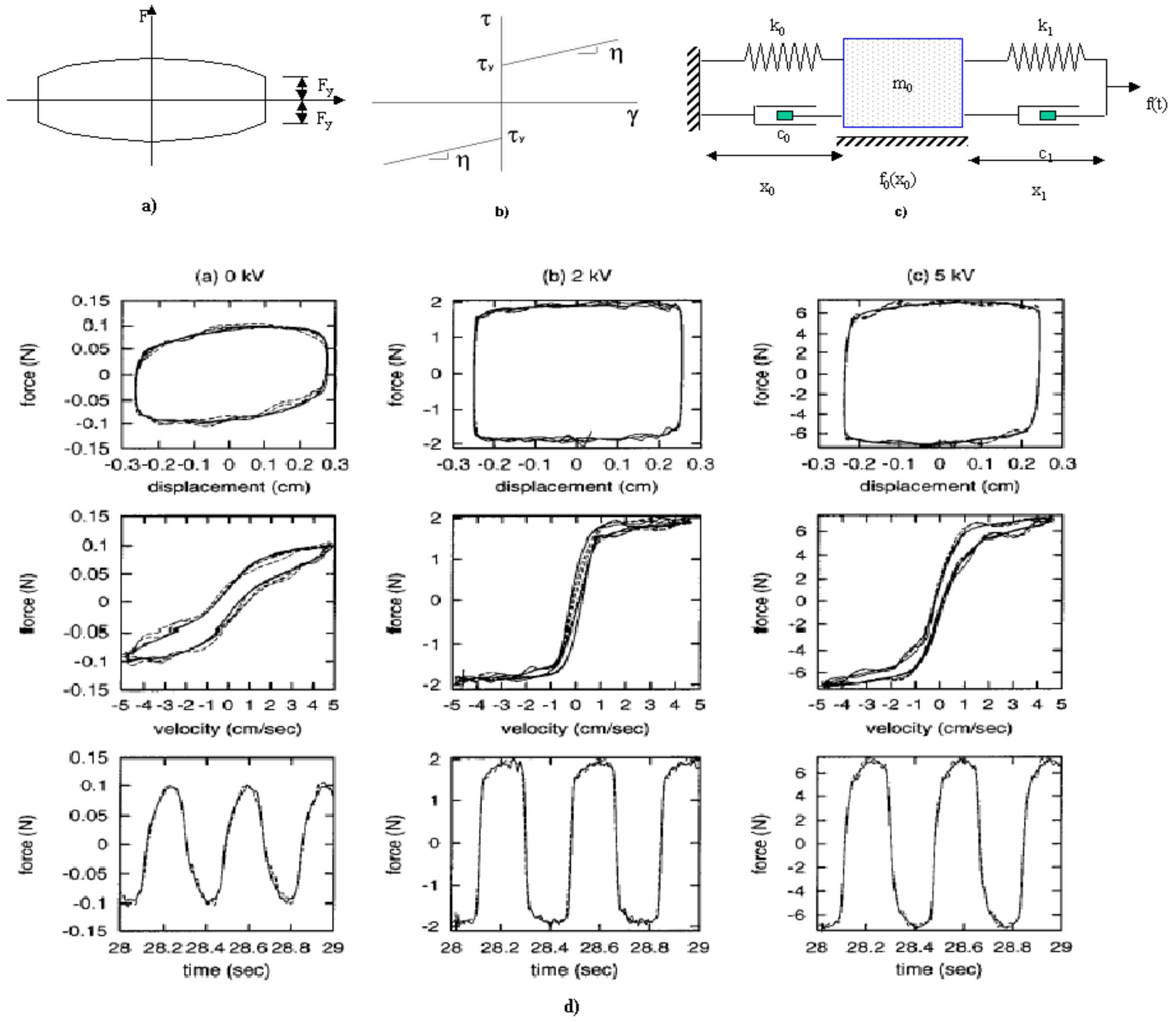


Figure 2.4: Electrorheological Damper a)ER behaviour in the strain rate plane b)ER behaviour in the force-displacement plane c) ER Mechanical analogy d) ER Hysteresis at 2.5 Hz, data (dashed lines) and model (solid lines)

with approximately 1m long and a mass about 250 kg and 5 L of MR fluid which may be the more biggest MR damper in structural control implementations. Full-scale implementations have been conducted both in design and implementation where its applicability is demonstrated ([Spe*etal*97a], [Dyk*etal*97a]).

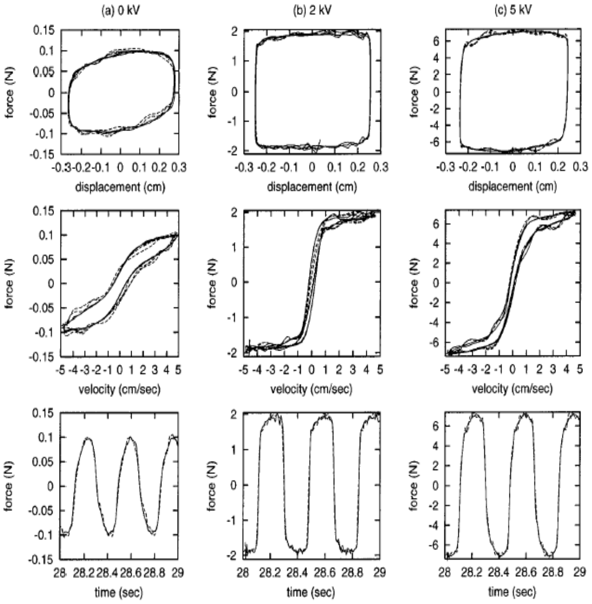


Figure 2.5: Comparison of predicted response and experimental data for step response tests on a MR damper.

Other Semiactive Control Devices

Other semiactive control devices, not frequently used or recently developed are variable-friction damper, impact damper and controllable tuned liquid dampers.

Variable-Friction Damper. Its functioning principle consists in utilizing forces generated by surface friction to dissipate vibratory energy. These forces can be varied by means of an electrical signal or a gas pressure, which varies the friction coefficient of the device. In [DowChe94] the ability of these devices to reduce the inter-story of a seismically excited structure was investigated. In [Fen*etal*93] and [Fuj*etal*94] these devices have been used in parallel with a seismic isolation system. At the University of British Columbia a friction device was developed. In this the force at the frictional interface is adjusted by allowing slippage in controlled amounts, similar to the device proposed in [AkbAkt90] and [Pan*etal*96].

Semi-active Impact Dampers. The semiactive impact dampers have been mostly used in reducing vibration and noise in turbines and gear cases and recently studies have been started in the mitigation of vibrations of structures under earthquake excitations [MasYan73]. Its semi-active principle consists of allowing favorable impacts only in some frequency bands, which produces significant vibration reduction. In [PapMas96] these type of devices were studied and it was shown that significant vibration reduction can be obtained in lightly damped systems when a random excitation is applied to the system. , because without semi-active control, in some frequency bands, the device give significant vibration reduction, but in other frequency bands may not be effective. The semi-active control corrects this defect.

Semi-active Controllable Tuned Liquid Dampers. The controllable tuned liquid dampers utilize the motion of a sloshing fluid or column of fluid to mitigate the vibration of a structure. They are based on the passive tuned sloshing damper (TSD). The semi-active principle consist in varying the length of the sloshing tank to change the properties of the device [Kar94], [Yeh$etal$96] and [Lou$etal$94]. A semi-active device based on a TLCD with a variable orifice is shown by [Har$etal$94].

Semi-active Continuously Variable Stiffness Control (SAIVS) device. The SAIVS device consists of sets of spring elements and telescoping tubes. Each set consists of a spring supported on the inside by two tubes. The tubes telescope into each other and allow extension and compression of the springs freely. These tubes guide the springs and prevent the spring from buckling. The telescoping tubes develop frictional forces, which are beneficial due to the resulting energy dissipation. A DC servomotor, with a rack and pinion assembly, controls the position of the device between the fully closed and open configurations. The power required by the DC servomotor to position the device is nominal, hence its semiactive nature. This type of devices is proposed in [NagMat98a]. Tests were performed with harmonic excitation generated by a servo-hydraulic actuator, and it was demonstrated that the device can switch the stiffness continuously and smoothly. Also, tests performed on a shake table with a SDOF system, demonstrated its capacity to reduce both steady state displacement and acceleration response [NagMat98b].

2.3 Structural Control Algorithms

2.3.1 Introduction

During the last two decades, various types of structural control strategies have been applied to the control of civil engineering structures. Depending on the available information about the types of structures, mathematical models associated, measurements, actuators and disturbances, each control system can be suitable only for some, not all, types of structures. In this section, three types of most representative control algorithms and their respective applications in civil engineering structures are presented due to the limitation of space.

2.3.2 Optimal Control

Introduction

The general optimal control problem may be stated as follows: given a system subjected to external inputs, find the control which minimizes a certain measure of the performance of the system [Yos$etal$02]. Optimal control algorithms are based on the minimization of a performance index that depends on the system variables, while maintain a desired system state and minimize the control effort. According to classical performance criterion, the active control force u is found by minimizing the performance index subject to a second order system. The performance index can include a measure of operating error, a measure of control or any other characteristic which is important to the user of the control system.

There are two control design objectives: Regulator problem, which consists in stabilizing the system so that its states and/or outputs remain small, and Tracker or servomechanism problem which controls the system so certain prescribed outputs follow the desired trajectories and all states remain bounded. Two main optimal control techniques are derived, they are the Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian (LQG), Clipped Optimal Control and Bang-Bang Control. These techniques are here presented.

LQR Optimal Control Algorithm

In 1960 three major papers were published by R. Kalman and coworkers. One of they discussed the optimal control of systems, providing the design equations for the linear quadratic regulator (LQR). This technique is characterized by requiring that all the state variables are available. This algorithm is the classical one used for active and semiactive control of structures. However it is not always possible to use it for structural control due to the limited number of sensors that could be installed in the large structures. The control input takes the form $u = -\mathbf{K}x$, where $\mathbf{K}$ is a $n \times n$ feedback matrix. Then, the control design problem is to choose the m entries of the feedback matrix $\mathbf{K}$ to yield a guaranteed desired behavior of the closed-loop system. The selection of such entries is made by minimizing a linear quadratic index chosen of the form:

$$J = \frac{1}{2}x^T(t_f)S(t_f)x(t_f) + \frac{1}{2}\int_0^{t_f}(\mathbf{x}^T Q\mathbf{x} + \mathbf{u}^T\mathbf{R}\mathbf{u})dt \tag{2.1}$$

where $[0,\, t_f]$ is the time interval of interest, and the symmetric weighting matrices $S(t_f)$, Q and R are the design parameters that are selected to obtain the required performance. They must be chosen so that $x^T(t_f)S(t_f)x(t_f) \geq 0$, $\mathbf{x}^T Q\mathbf{x} \geq 0$, for all $x(t)$ and $\mathbf{u}^T\mathbf{R}\mathbf{u} > 0$ for all $u(t)$. Thus, S and Q should be positive semi-definite while R should be positive definite. The self-multiplication formulations $\mathbf{x}^T Q\mathbf{x}$, $\mathbf{u}^T\mathbf{R}\mathbf{u}$ are termed quadratic. The control $u(t)$ is weighted in the performance index to allow regulation without using excess control energy.

LQR control algorithm can be designed to achieve different structural control objectives, such as minimization of absolute acceleration response, story drift, base shear, etc. Designing the control law by means of a performance index, which normally includes the system response, makes more easy and effective the use of LQR control algorithm in any kind of structure. Several applications of LQR control have been used in semiactively controlled structures [Kur$etal$98], [SadMoh98], [Fuj$etal$94], [NerKri95], [Agr$etal$98]. [SymCon97] applied this algorithm on a small scale model with a semiactive control system where a fluid damper is used. A variation of LQR control is the Instantaneous Optimal Control, which uses a performance index as control objective similar to LQR control algorithm, but this does not need to solve the Riccatti equation.

LQG-Optimal Control Algorithm

The LQG method for structural control was examined by Yang and Yao in 1974. It is based on calculating the control gain k that minimizes the performance index with the difference that an observer (i.e Kalman filter) is included in the design equations, such as:

$$\hat{\dot{x}} = A\hat{x} + Bu + L(y - C\hat{x}); \qquad u = -K\hat{x} + y \tag{2.2}$$

Then the design problem here is to select K and L, to obtain good robustness and high performance. Several applications of this theory have been made in civil engineering structures both active and semiactive control [Yos$etal$94]; [Yos$etal$98]; [YiDyk00]; [Bak$etal$02], [Bak$etal$03].

Clipped-Control

This clipped-control consists in designing a linear optimal controller K that calculates a desired control forces vector $f = [f1, f2, f3, .., fn]$. The computation of this force is based on the measured structural responses and the measured control force vector applied to the structure. The clipped optimal control can be considered as a practical approximation of the LQR controller when it is impossible to obtain the optimal control force value from the LQR design. Thus, the control objective in clipped optimal control is to keep the available force f, that can be delivered by the device, as closed as possible to the optimal force d.

This algorithm has been used in structural control mainly in [Dyk$etal$96a]; [Dyk$etal$97a]; [Dyk$etal$97b]; [DykSpe97a]; [DykSpe97b]; [Yos$etal$02]; [JanDyk01]; [JanDyk02]; [Yi$etal$98]; [Yi$etal$00], [Dyk$etal$99]; [Dyk$etal$96b]; [Dyk98], and its efficiency has been demonstrated.

Bang-Bang Control

This strategy is useful in the case where the performance index is the pure minimum-time objective of the form $J(t_0) = \int_{t_0}^{t_f} 1dt = t_f - t_0$. Then, the solution is to apply infinite control energy over an infinitesimal time period. A Lyapunov function is established, (i.e. vibrational energy of the structure). A possible objective of the control strategy may be to reduce the rate in which energy is transmitted to the structure, thus the control can be satisfied by minimizing $\dot{V}$.

ER and MR dampers are well suited to bang-bang control applications, due to their fast response times [McCGav95]; [Dyk98]; [DykSpe97a]; [JanDyk01]; [JanDyk02]; [HatSmi97];.

2.3.3 Robust Control

Introduction

In the real world, there is always uncertainty in any mathematical model of the plant to be controlled. This is the case of the civil engineering structure model. The actual response of the plant may be different from the that of design model. Additionally, the behavior of the plant may change by aging or by variation of operating conditions. Thus, the principal objective of robust control is to develop feedback control laws that are robust against plant model uncertainties and changes in dynamic conditions. A system is robustly stable when the closed-loop is stable for any chosen plant within the specified uncertainty set and a system has robust performance if the closed-loop system satisfies performance specifications for any plant model within the specified uncertainty description.

The need of using robust control in structural control is because that the structure models contain appreciable uncertainty. This uncertainty may be expressed as bounds on the variation in frequency response or parametric variations of the plant. The mostly used robust control approaches in control of structures are H_∞ control theory, Lyapunov theory based control and Sliding Mode Control. They will be described in the present section.

H_∞ Control

Controller design problems where the H_∞ norm plays an important role were initially formulated by George Zames in the early 1980s. H_∞ control algorithm is a design method, where the transfer function from excitation (u) to controlled output (y)is designed to be lower than a prescribed small value. The goal is to find a constant state-feedback matrix F to stabilize a matrix P, which is a combination of state matrix, and to satisfy a given ∞-norm bound $||F_1(P,F)||_\infty < \gamma$ on the closed-loop response. Because H_∞ control algorithm designs the controller in frequency domain, the frequency shape function can be used easily, it makes the control of specified frequency rang possible and the spillover can be avoided. It is suitable for system subject to unmodelled dynamics or unknown disturbances.

In [Yan$etal$96] this method is used in seismically excited buildings. In [Yan$etal$03] two H_∞ controllers with peak response constraints and energy-bounded or peak-bounded excitations are proposed. These controllers are capable of directly addressing the design requirements of the structure and the controller capacity constraints in the design synthesis of the controller. A long-span cable-stayed benchmark bridge subject to earthquakes is used to illustrate the applicability of such controllers to practical problems and control performances. Others applications of this method on civil structures have been developed by [BakBoh99], [Sch$etal$94], [Jab$etal$95], [Yos$etal$94], [Yos$etal$98]; [Wan03] and [Kos$etal$96].

Control Based on Lyapunov Stability Theory

Control based on Lyapunov stability theory consists in selecting a positive definite function denominated Lyapunov function. According to Lyapunov stability theory, if the rate of change of the Lyapunov function is negative semi-definite, the closed-loop system is asymptotically stable (in the sense of Lyapunov). The objective of the law is to select control inputs, which make the derivative Lyapunov function as negative as possible. This function has been a tool used in design of feedback controllers, for stability analysis. The importance of this function is that it may contain the variables to be minimized in the system (i.e. system states, control law error, control force, etc).

Lyapunov theory based control is one of the most commonly techniques used in the control of structures. Several developments are found using this method [DykSpe97a]; [JanDyk01]; [Yi$etal$00]; [Gav01]; [Luo$etal$01]; [JanDyk02]; [DupSto95]; [HatSmi97]; [McCGav95]; [NagMat98a]; [LeiRei93a]; [Rod$etal$03a]. Some authors have applied this technique in direct approach [Lei94]-[LeiRei93a] or by combining the state variables with others parameters [Luo$etal$98].

In [Yi$etal$00], the multiple semi-active control devices are applied to a six-story test structure, where the variable in the Lyapunov function corresponds to states of the model (displacements and velocities relatives to the ground). Higher performance levels were obtained with respect to the passive system.

In [ReiLei98] a control input function is assumed to be continuous in state variables and linear in control action, but additionally admissible uncertainty is considered. Then, a practical stability, the ultimate boundedness, of the system is demonstrated.

In [McCGav95] a Lyapunov function is used to represent the total vibratory energy in the structure (kinetic plus potential energy). This approach is a decentralized bang-bang control because this law requires only measurements of the absolute velocities of the place (i.e. floor) where control devices are installed.

Sliding Mode Control

The sliding model control was introduced by Utkin in 1977 to the Western world. Sliding mode control is characterized by discontinuous control, which restricts the state of a system to a sliding surface by switching the control structure on both sides of a stable hyperplane in the state-space. The method requires to design first a sliding surface that is defined by $\sigma = \mathbf{Sx} = 0$ and represents the closed-loop control performance. Then, the control gain is calculated to make the state trajectory to reach the sliding surface and to maintain in it afterwards until sliding to the origin. This technique can achieve excellent robustness of the control system. In the sliding mode the system satisfies $\sigma = 0$ and $\dot{\sigma} = 0$. In order to find the control law, a Lyapunov function is defined as $V = \frac{1}{2}\sigma^2$. Then, time derivative is given by $\dot{V} = \sigma\dot{\sigma} = \sigma S\dot{x} = \sigma S(\mathbf{Ax}+\mathbf{Bu})$ whose negativeness is achieved by using some discontinuous control law which uses only the information on the bounds of uncertainty.

[Luo$etal$98]-[LuoRod00]-[Luo$etal$02] use this control method on different structures, such as buildings and bridges. In [KenTet03], this technique is used to control a seismic excited tall building in which the dynamic interaction between the structural components is taken into account (see figure 2.6) and springs are installed between them to produce appropriate control forces by utilizing the variable stiffness.

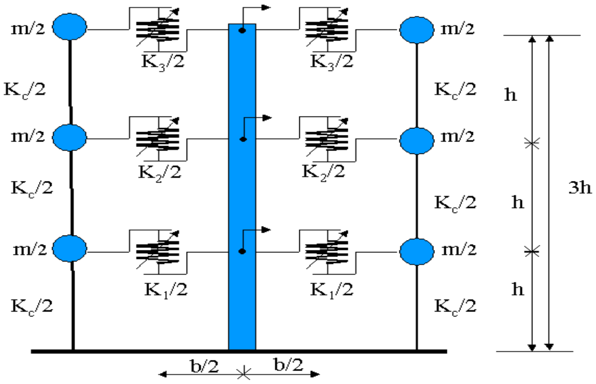


Figure 2.6: Tall Building Model with Varying Springs

2.3.4 Predictive Control

Introduction

The methodology of predictive control was introduced in 1974 in a doctoral thesis by J.M Martin S. and the original basic principle was a US patent in 1976. This principle can be defined as: Based on a model of the process, predictive control is the one that makes the predicted process dynamic output equal to a desired dynamic output conveniently predefined. The predictive control strategy may be generalized and implemented through a predictive model and a driver block, as shown in figure 2.7. The predictive control generates, from the previous input and output process variables, the control signal that makes the predicted process output equal to the desired output. In fact, predictive control results in a simple computational scheme with parameters having clear physical meaning and handling of time delays related to the actuators in the control system is easy. Predictive control has been shown to be an effective strategy for structural control [MarRod96], [Luo$etal$98]

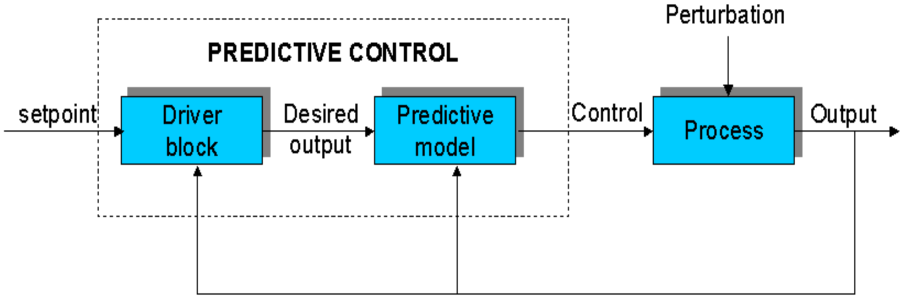


Figure 2.7: Basic block diagram for predictive control system (PCS)

Model Based Predictive Control

A model based predictive control consists in generating, from the previous input and output process variables, the control signal that makes the predicted process output equal to the desired output. The performance of this technique depends significantly on the prediction made by the model. The basic strategy of predictive control implies the direct application of the control action in a single-step prediction, thus the predictive control must be formulated in discrete time. At each sampling instant k, the desired output for the next instant $k+1$ is calculated, which is denoted by $y_d(k+1|k)$. The basic predictive control strategy can be summarized by the condition $\hat{y}(k+1|k) = y_d(k+1|k)$, whit $\hat{y}(k+1|k)$ the output predicted at instant k for the next instant $k+1$ and the control $u(k)$ to be applied at instant k must ensure the above condition. An essential feature of the model based predictive control is that the prediction for instant $k+1$, necessary to establish the control action $u(k+1)$, is made based on the information of the outputs $y(\cdot)$ and the inputs $u(\cdot)$ known at the instant k and at preceding instants. However, such prediction may differ from the real output, which will be measured at instant $k+1$, thus the real measurement at $k+1$ is used as the initial condition instead of the output that was predicted for this instant, which is essential for the effectiveness of the predictive control.

At the NatHaz Modelling Laboratory at the University of Notre Dame researchers are studying the design and development of the Model Predictive Control. It has been effectively shown to be feasible for structural control applications in [Mei$etal$98].

In [Rod$etal$87] a predictive control in civil engineering was employed. In [Lop$etal$94] the predictive control in modal space and tried to control the first few mode shapes individually to reduce the overall structural response was used. In [WanLiu94] The Rodellars predictive control method in hybrid control system was used, which isolated the structure by frictional interface with the sliding base actively controlled by hydraulic actuators.

Adaptive Predictive Control

An adaptive predictive control system, consists in the combination of a predictive control system and an adaptive system, such as is shown in the figure 2.8 [MarRod96]. In an adaptive system, the predictive model gives an estimation of the process output at instant $k+1$ using the model parameters estimated at instant k, the control signals and the process outputs already applied or measured at previous instants. The predictive model calculates the control action $u(k)$ in order to make the predicted output at instant $k+d$ equal to the driving desired output at the same instant. The objectives that one would expect to obtain from an adaptive predictive control system can be summarized by [MarRod96]. After a certain time for adaptation, the process output should follow a driving desired trajectory (DDT) with a tracking error that is always bounded in the real case or is zero at the limit in the ideal case and the (DDT) should be physically realizable and bounded.

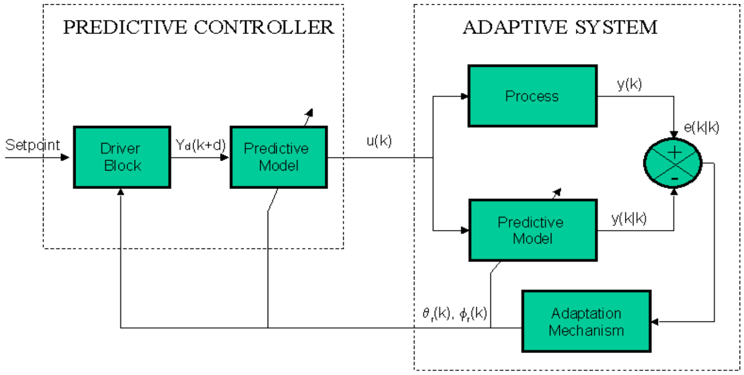


Figure 2.8: Overall block diagram of an adaptive predictive control system

Chapter 3

Open Problems in Structural Control

3.1 Introduction

In structural control, the principal goal is to be able to develop control integrated methodologies which include modelling, control design, measurements techniques and control equipment design. However, several limitations have been found, specially those of implementation and design. Such problems have been considered in last years by several researchers, and some problems have been solved, but some others do not. The principal open problems that exist in structural control are: uncertainty, nonlinearity, actuator dynamics, measurement limitations and coupling.

3.2 Uncertainty in Civil Engineering Structures

Most of control system designs on civil engineering structures are based on a structure model. Generally, such models include considerable uncertainty, which is present by several reasons, among others: unconsidered parametric nonlinearities, parameters variation by excitation or aging (structured uncertainties), neglected dynamics (unstructured uncertainties) or may result from non-deterministic features of the structure.

3.2.1 Parametric Uncertainty

The civil engineering structures are one of the systems that contain more error source because of parametric uncertainties. Majority of authors assume that the structure can be modelled as a linear time invariant system (LTI), where LTI model implicitly assumes that the structural properties are constant and exactly known. However, time varying parametric uncertainties are inherently associated with structure and they must be considered in control design.

Materials properties in structures, such as stiffness or damping, cannot be estimated exactly and strong assumptions must be done. For example, concrete contains different phases during its drying, thus different values of stiffness and damping are present. Only after having got dried a stable value of its properties may be obtained. However, in that state there does not exist a measurement equipment being able to estimate such properties. Then, only theoretical approximations may be made, through coefficients established such as young modulus combined with empirical knowledge of experts.

Other sources of uncertainties are generated during modelling, under some strong assumptions. A standard model for structures is the Finite Element Model. To obtain such model, it is necessary to concentrate parameters in a finite number of nodes. It implies that parametric values of nodes are approximated values and uncertainties are present.

During last years, the problem of control on uncertain systems has gained the attention of an increasing number of researchers [Luo$etal$03a], [Luo$etal$02], [Yan$etal$03], [Wan03], [GatRom03]. Some authors represent the nonlinear element behavior by mean of uncertainty and it can be integrated into control design (named robust, because it can tolerate uncertainties) [Hsu$etal$95].

3.2.2 Unmodelled Dynamics

Another aspect to take into account in structural control is that a whole model cannot contain all necessary information of the physical system. Such is the case when the structural dynamics has not been completely modelled. This produces a source of uncertainty in the model and in some cases the computation of the states of the structure may be completely different from the actual value. For example, to model a bridge the n-first frequencies are used to establish the model, however the other frequencies may give important information about the behaviour of the structure when an external force, such as an earthquake, is acting. Implementing a control law with this type of models, in which there exist neglected dynamics, may produce undesired control actions or at least control performance weakening. Thus, an open problem is to take considerations with respect to this type of models, when a control law is designed.

3.2.3 Uncertain Disturbances

All physical systems have natural frequencies that depend directly on their components and configuration, this is the case of civil engineering structures. When an uncertain external force is applied at the same frequency as the natural frequencies (or resonant frequencies), the magnitude of the state variables may grow indefinitely. In very flexible structures, such as cable-stayed bridges, an excitation force at these frequencies can result in destructive behavior. For example, for a cable-stayed bridge (see figure 3.1), 10 natural frequencies are considered in the evaluation model and they are those provided in table 3.1. The structure excited at such frequencies acquires modes shape such as shown in figure 3.2. Figure 3.3 shows two representative transfer functions of the model [Dyk$etal$00]. The big problem of this type of disturbances is its uncertain and unpredictable nature, which makes that at the moment of implementing a control law it is more complex to ensure robustness and good performance.

A possible model, which includes important uncertainties in a model of a structure is the one presented in [ReiLei98] and shown in the figure 3.4. The transfer function of the nominal structure is given by $(sI - A)^{-1}$. The blocks B and E represent the control effect matrix and the earthquake participation matrix, respectively. Variable y is the measurement vector. z_2, is the displacement vector and u the actuator displacement. w_{21} represents the input earthquake excitation and w_{22} is the sensor noise. The effects of actuator dynamics and time delay are represented by the multiplicative uncertainty Δ_i . The cladding stiffness and damping properties are treated as an uncertainty in the structural stiffness and

Table 3.1: Natural Frequencies of the Cable-Stayed Benchmark FEM model

Mode No.	**Frequency (Hz)**	**Mode No.**	**Frequency (Hz)**	**Mode No.**	**Frequency (Hz)**
1	0.2899	**5**	0.5812	**8**	0.6970
2	0.3699	**6**	0.6490	**9**	0.7102
3	0.4683	**7**	0.6687	**10**	0.7203
4	0.5158				

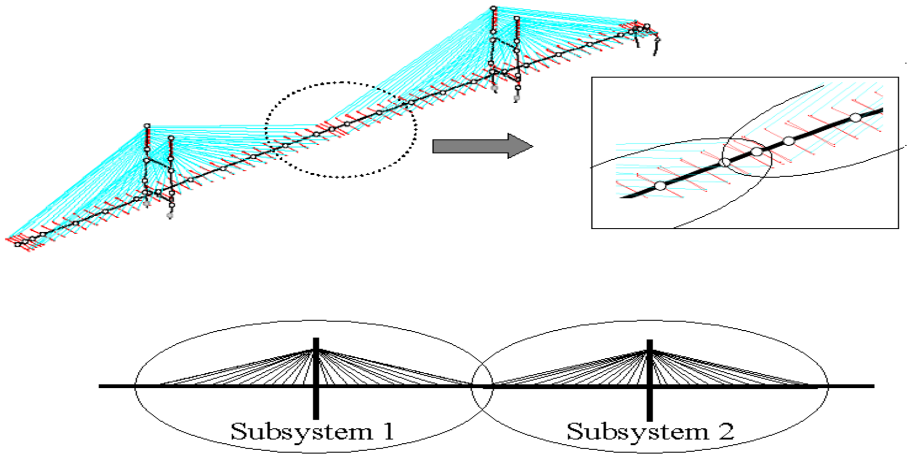


Figure 3.1: Cape Girardeu Cable-Stayed Bridge

damping, and are represented by the transfer function matrix $\Delta k(s)$.. The corresponding outputs to these uncertainty blocks are denoted as z_{11}, z_{12} and w_{11}, w_{12}

3.3 Nonlinearity

Variations in structural parameters, such as stiffness variations, are common in the structure. These variations result from the hysteretic nonlinearities introduced by the passive damping elements and degradation in stiffness caused by external forces such as earthquakes and strong winds. In controlled systems, hysteresis can cause a number of undesirable effects, including the loss of stability, limit cycles and steady-state error, among others. Hysteresis is a common phenomenon for a broad spectrum of physical systems. Two problems are present here that are to find a correct model and to design a control system with such model which normally result to be very complex and difficult to treat.

3.4 Coupling

There is a class of civil engineering structures where the excitation is induced by the coupling with another dynamic system during a period of time or permanently. Normally, the exciter structure dynamics may be considered unknown but bounded, and its online measurements are not available. This type of systems

First Mode Shape (Vertical, .2899Hz)

Second Mode Shape (Vertical, .3699 Hz)

Third Mode Shape (Torsion, .4683 Hz)

Fourth Mode Shape (Torsion, .5158 Hz)

Fifth Mode Shape (Vertical, .5812 Hz)

Sixth Mode Shape (Lateral+Torsional, .6490 Hz)

Figure 3.2: Representative Mode Shapes of the Bridge Evaluation Model

may be modelled by means of two or more coupled subsystems in which one subsystem includes the measurable dynamics, and the others the unknown but bounded dynamics. A possible methodology to follow in the decomposition of the system is that used by [BakRod95], in which the structural dynamics is described by various subsystems and some bounded coupling functions were found. Thus, the open problem here is that the designed control law by only including the known state variables and parameters should ensure the global boundedness of the controlled system.

3.5 Actuator Dynamics

The following dynamic features in a control device for civil engineering structures are present: time delay, friction force, saturation and hysteresis. These characteristics are a serious problem in control of structures because some unpredictable events occurred in very short time period, such as earthquake, require fast and effective control actions. The effectiveness of the actuator is affected directly by these dynamic conditions. Then a good control design must consider such dynamics to obtain a control law that calculate the real value of the control force that can be delivered by the actuator.

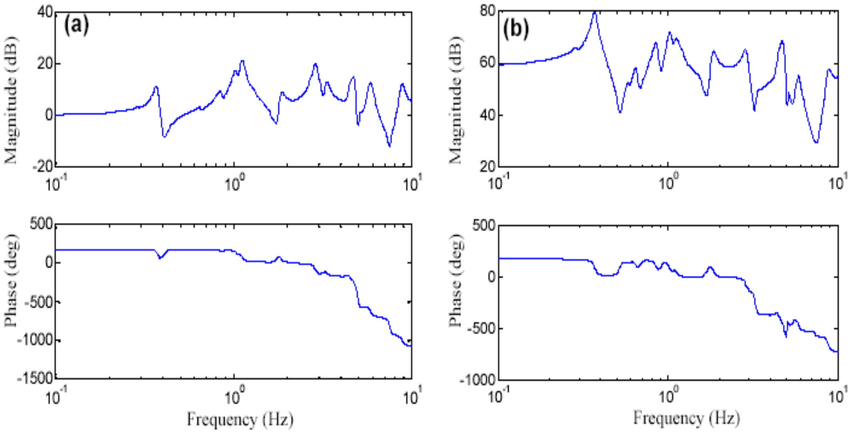


Figure 3.3: Representative Transfer Functions of the Bridge Evaluation Model

3.5.1 Actuator Time Delay

Time delay in actuators is a serious problem for a control system in achieving its effectiveness. The time delay is mainly caused by electrical and mechanical parts and it is observed in the response of the device, when changes in the input command are introduced. In situations like strong winds and large earthquakes the duration is very short and the control action must be very fast. Thus a consideration that must be taken into account in control design is the actuator time delay.

3.5.2 Actuator Saturation

Active actuators have force or torque limitation that can be generated in themselves, which is known as saturated input. In the control systems the saturation condition reduces the performance of the control system, because the saturation is not considered. Many researchers have studied this problem in order to overcome this situation [Agr*etal*97], [San*etal*99]. [NisShi03] introduces gain scheduling of a controller by formulating the input of saturation as a hyperbolic tangent function. Then, a linear system varying according to the input that the controller needs is obtained. However, more control designs must be designed in order to overcome this problem. The figure 3.5 shows this saturation condition.

3.5.3 Actuator Friction

Friction forces are present in the actuator because there exist moving mechanical components. This additional force deteriorates actuator effectiveness and must be considered in control design.

3.5.4 Actuator Hysteresis

Hysteresis is a big limitation in the good performance of the actuator. Two difficulties are present: one is to describe correctly the phenomenon by some dynamic model and the other is to obtain a control law

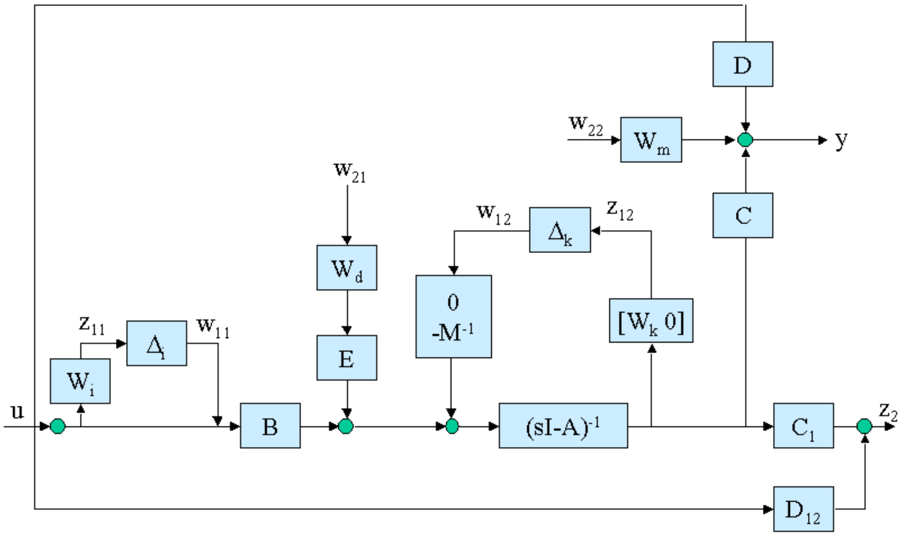


Figure 3.4: Block Diagram description of a generalized building model

based a complex system by including the above dynamic model. Some general models, which accurately represent the hysteretic phenomena, have been developed. The most known models are Hysterons, Bouc-Wen model, Chua-Stromsmoe model and Preisach model, [Sai$etal$97], which are presented in the figure 3.6. However the mathematical formulation of the models are very complex and few control implementations have been obtained.

3.6 Measurements Limitations

When a real time feedback control is used but the state variable measured does not take the real value, the effectiveness of control strategy may be reduced and the guarantees of stability may also be failed in practice. Thus, control design and modelling are dependent on mutually. The design of civil structures by including feedback control concepts must be accompanied by a commitment of advanced analytical theories to predict a more accurate system behaviour. Depending on the accuracy of the measurement devices there is always uncertainty concerning the measured variables, thus this condition must be considered at the moment of using the measurements as feedback variables [ReiLei98]. The assumed maximum difference between actual value y and measured value $\tilde{y}$ may be expressed by $\Delta_y := (\Delta x_1, \ldots), \Delta x_n$, such that $||\Delta_y||_M = 1$ and $||.||_M$ is some norm which relates the tolerances and scales measurement for the different variables. Another limitation in civil engineering structures is that only a few of sensors are installed in the structure because of space limitations or implementation problems. Thus the on-line knowledge of all state variables is not possible.

Also, it should take into account the fact that when a structure is excited, by seismic movements for example, the measurement of state variables far away from the place where the control device is installed is not always credible. Then, the control strategy should be focused on only using the on-line

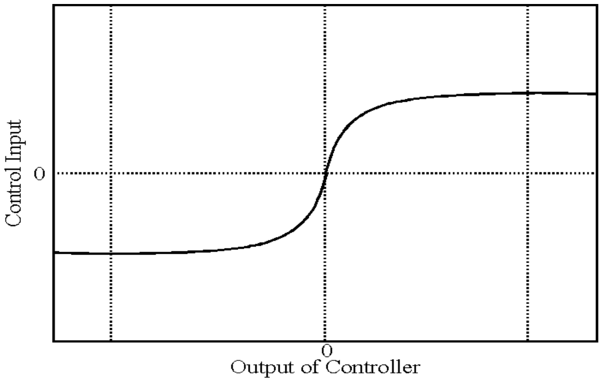


Figure 3.5: Control Input Saturation

measurements at the nodes closer to the installed control device or using estimated variables. On other hand, a supervised structural control system is an interesting subject to be studied, in which the control decisions should be made depending on the monitored state of the structural health. An initial theoretical development has been proposed in [Veh$etal$02a], [Veh$etal$02b] and [Veh$etal$02c].

3.7 Conclusions

It is difficult to develop a control strategy which can include all the aspects that affect the control system performance. The principal problem is that there is not any existing control theory that takes into account all the aspects related to structural control. However, it seems possible to find some new strategies for structural control design including every one of these aspects and to obtain some reasonable theoretical and implementable solutions.

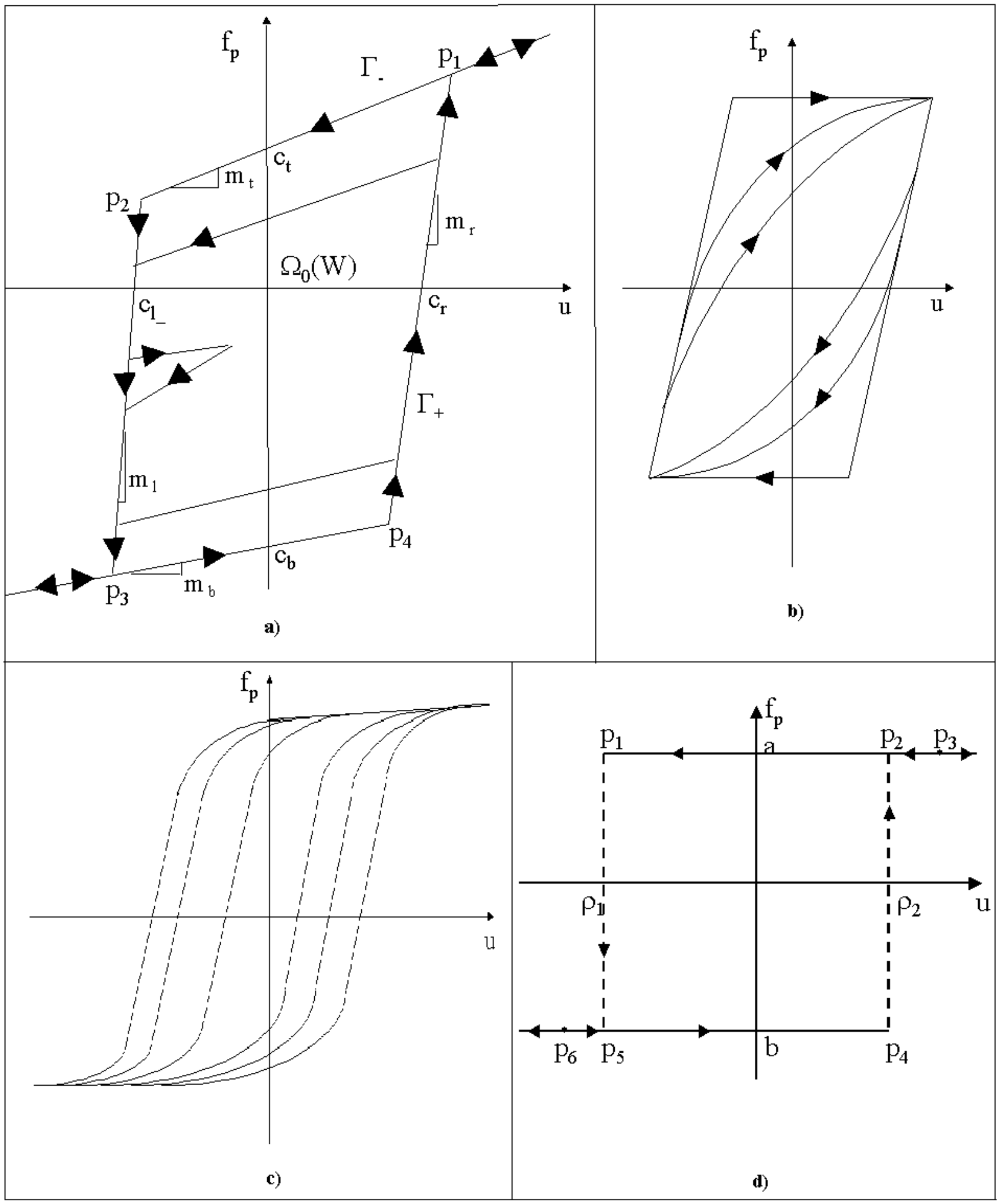


Figure 3.6: Hysteresis charts of a) Hysteron Model, b) Bouc-Wen model, c) Chua-Stromsmoe model, d) Preisach model

Chapter 4

Exploratory Work

This chapter is divided into three parts: First part presents the initial work developed to solve some open problems in structural control, second part presents the work proposal to solve some other open problems and finally part 3 presents the work plan to follow during the research stage in order to obtain the doctoral thesis.

4.1 Previous Work

Some research has been made in order solve some of the open problems presented in the previous chapter. The obtained results have been contributed to the publication in different important international conference. In the following part, the main results of the previous research are summarized in five papers.

4.1.1 Paper 1

Authors	Ningsu Luo, **Rodolfo Villamizar**, Josep Vehí and José Rodellar
Title	Active Control of Structures with Uncertain Coupled Subsystems and Actuator Dynamics using the Lyapunov Function
Congress	2004 American Control Conference
Place and date	Boston, USA, June 30-July 2, 2004.

Abstract

This paper deals with the problem of stabilizing a class of structures subject to an uncertain excitation due to the temporary coupling of the main system with another uncertain dynamical subsystem. A sliding mode control scheme is proposed to attenuate the structural vibration. In the control design, the actuator dynamics is taken into account. The control scheme is implemented by using only feedback information of the main system. The effectiveness of the control scheme is shown for a bridge platform with crossing vehicle.

submitted for review.

4.1.2 Paper 2

Authors	Ningsu Luo, José Rodellar and **Rodolfo Villamizar**
Title	Robust control law for a friction-based semiactive controller of a two-span bridge
Congress	SPIE's 10th Annual International Symposium on Smart Structures and Materials
Place and date	San Diego, USA, March 2-6, 2003.

Abstract

This paper addresses the problem of formulating a control law for the semiactive control of an experimental section of a two-span bridge, which is equipped with controllable friction devices at the joints between the columns and the deck. A finite element model is available to represent the essential dynamical features of the bridge and the semiactive devices (Uwe Dorka 2002, personal communication). Based on this model, a Lyapunov-based robust semiactive control law is derived to ensure stability and robustness properties in the presence of uncertainties. The main sources of such uncertainties come from the actuator dynamics and the lack of knowledge of the excitation, which is due to seismic loads at the column supports. After the formulation of the control law, extensive numerical tests are performed to validate the theoretical results by means of the finite element model such that an implementable control algorithm is finally proposed.

4.1.3 Paper 3

Authors	**Rodolfo Villamizar**, Ningsú Luo, Josep Vehí and José Rodellar
Title	Semiactive control of base isolated structures with actuator dynamics
Congress	European Control Conference
Place and date	Cambridge, United Kingdom, September 1-4, 2003.

Abstract

In this paper, a new semiactive control approach is presented to stabilize a base isolated structure subjected to parametric uncertainties and unknown disturbances. In the controller design, the actuator dynamics (time delay and frictional effects) are taken into account. The ultimate boundedness is achieved in the closed-loop system. Numerical simulation is done for a 10 story base isolated building, with two semiactive controllers being put on the base and the first floor, to illustrate the effectiveness of the proposed semiactive control scheme.

4.1.4 Paper 4

Authors	Ningsu Luo, **Rodolfo Villamizar**, Josep Vehí, José Rodellar, Víctor Mañosa
Title	Sliding mode control of structures with uncertain coupled subsystems and actuator dynamics
Congress	European Control Conference, Cambridge
Place and date	Cambridge, United Kingdom, September 1-4, 2003.

Abstract

This paper deals with the problem of stabilizing a class of structures subject to an uncertain excitation due to the temporary coupling of the main system with another uncertain dynamical subsystem. A sliding mode control scheme is proposed to attenuate the structural vibration. In the control design, the actuator dynamics is taken into account. The control scheme is implemented by using only feedback information of the main system. The effectiveness of the control scheme is shown for a bridge platform with crossing vehicle.

4.1.5 Paper 5

Authors	**Rodolfo Villamizar**, Ningsu Luo, Josep Vehí, José Rodellar
Title	Authors: Semiactive sliding mode control of uncertain base isolated structures with actuator dynamics
Congress	Workshop on Smart Materials and Structures - SMART'03
Place and date	Jadwisin, Poland, September 2-5, 2003.

Abstract

This paper deals with the problem of designing a semiactive sliding mode controller to attenuate the vibration of a base isolated structure subject to parametric uncertainties and unknown disturbances. By considering that the whole base isolated structure is composed of the main structure subsystem and the base subsystem (together with the isolator) through the dynamic coupling between them, the control objective is to achieve the asymptotic decoupling of the two subsystems by using semiactive control. In order to use a few sensors and actuators for the controller implementation, semiactive control devices are only put at the base and the first floor to adjust on-line the parameters of stiffness and damping. In the controller design, the actuator dynamics, such as the effects of time delay and frictional force, are also taken into account. In this way, the obtained behavior of the controlled structure is expected to be closed to the real one. The controller design is made based on the principle of sliding mode control and the theory of Lyapunov stability. A numerical example is given to illustrate the effectiveness of the proposed semiactive control approach for a 10 story base isolated building with frictional base isolator.

4.1.6 Conclusions

Control strategies for civil engineering structures have been developed where actuator dynamics have been considered. Numerical simulations have been made and the effectiveness of such strategies has been demonstrated. Next step consists in including the actuator hysteresis in the control design.

4.2 Research Proposal

In this section, control strategies and their respective development proposal are presented. Three principal themes on structural control are proposed as investigation themes for doctoral thesis. They are: robust control of structures with parametric uncertainty, controller design with actuator dynamics, and control design in frequency domain.

4.2.1 Robust Control of Structures with Parametric Uncertainty

The design of robust controller for uncertain structures will be based on control theories such as H_∞, sliding mode control and Lyapunov theory. The novelty in the control design is that the structural parameters such as stiffness, damping and mass, will be considered uncertain and they will be mathematically represented by mean of interval values. The designed control system takes into account the variation matrix added into the system and the control algorithm (i.e., H_α, SMC, Lyapunov Theory) chooses the control signal value by using a design equation with interval values. The motion equation is solved by means of interval mathematical tools. The uncertain parameters may be described by a mathematical model with parametric intervals composed by the known nominal value together with the corresponding known positive or negative deviation ($[X - \Delta X, X + \Delta X]$).

The interval method to be used is the modal interval arithmetic. Several theoretical developments and applications have been obtained [Sai$etal$02]; [SIGSai01]; [Veh$etal$00a]; [Veh$etal$00b]. Computation and interpretation of interval equations can be easily obtained from the modal interval arithmetic, which can serve as a useful tool to find the robust control law. One part of this research will be dedicated to implement the modal interval arithmetic as a tool to find the robust controller of an uncertain system. The novelty of this proposal is the inclusion of a new and efficient interval arithmetic to solve an interval equation design, which contains the parametric uncertainties of the structure.

4.2.2 Control design with actuator dynamics

Some developments in order to solve the actuator dynamics problem have been started. They correspond to the papers above listed. The dynamics considered in the initial development correspond to time delay and friction force. Next step of the research consists in including hysteresis actuator in the equation design. Also, it will try to combine backstepping control theory with other robust control techniques such as sliding mode control, Lyapunov theory or H_∞.

The technique of backstepping control is applicable both to systems whose uncertainties are expressible through a linear parametric dependence and to systems in the perturbed-chain-of-integrators form. This technique consists in the step-by-step construction of a transformed system with state $z_i = x_i - \alpha_{i-1}$, $i = 1, \ldots, n$, where α_i is the so-called *virtual control signal* at the design step i. It is computed at step $i+1$ to drive $z = [z_1, \ldots, z_n]^T$ to the equilibrium state $[0, \ldots, 0]^T$, which can be verified through a standard analysis (i.e. Lyapunov analysis). The Lyapunov functions computed at each step are used to determine the most suitable α_i. The last *stabilizing* signal (α_n) is the true control $u(t)$, which is applied directly to the original system. Some authors have utilized these strategies to solve specific problems [SirLla93], [Bar$etal$97] and [Med99].

The actuator hysteresis phenomenon can be modelled by means of a second state equation. This equation may include an uncertain actuator force, which depends of some state variables. The whole system is constructed step by step in a transformed system where the control command is found, thus the dependence problem is solved. By knowledge of bibliography, this methodology has been only proposed for Bouc-Wen hysteresis model by [Ikh$etal$03a], [Ikh$etal$03b], [Ikh$etal$03c]. The novelty in this proposal is the inclusion of backstepping technique in structural control to solve actuator hysteresis problem, where different hysteretic models will be studied, and a control law will be derived.

4.2.3 Mode-Shape Control in Structures

The objective of developing this control is to design an efficient control system which can prevent the structure of resonance in frequency modes when a uncertain disturbance, for example an earthquake, is present. The control law will be designed in frequency domain and such design will be based on the

Qualitative Feedback Theory (QFT).

QFT theory was proposed by Horowitz in 1973. It is developed in the frequency domain utilizing the Nichols Chart (NC) and based on the idea of designing a control law which considers the cost of the control implementation. Desired time-domain responses are translated into frequency domain tolerances, which lead to bounds on the loop transmission function [Hor73]. The advantage of this theory is that system nonlinearities and uncertainties can be included [BryHal95].

The novelty of this proposal is the application of a control theory which has not been applied to structural control until now but seems a promising technique in making the control design in frequency domain to prevent resonance problems in structures.

4.2.4 Implementation Models

Three models of civil engineering structures have been used in the initial developments in order to obtain numerical simulations. The same models will be used to verify the effectiveness of all control strategies proposed before and to be developed in the future.

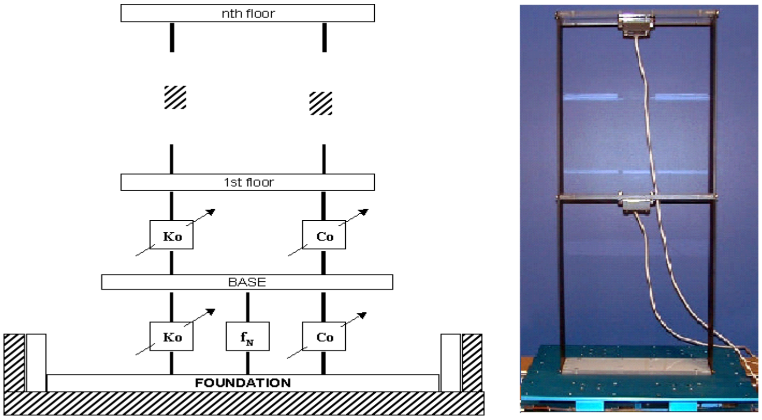
Structural Model 1

The first structure considered corresponds to a 10-story base isolated building shown in the figure 4.1a, with two semiactive controllers being put on the base and on the first floor. Its dynamic behaviour can be described by means of a model composed of two coupled subsystems, namely the main structure (S_r) and the base isolation (S_c)

$$\begin{aligned}
S_r: \quad & \boldsymbol{M}\ddot{\boldsymbol{q}}_r + \boldsymbol{C}\dot{\boldsymbol{q}}_r + \boldsymbol{K}\boldsymbol{q}_r = [c_1, 0, ..., 0]^T \dot{q}_c + [k_1, 0, ..., 0]^T q_c \\
S_c: \quad & m_0\ddot{q}_c + (c_0 + c_1)\dot{q}_c + (k_0 + k_1)q_c - c_1\dot{q}_{r1} - k_1 q_{r1} + f(q_c, \dot{q}_c, d, \dot{d}) = 0 \\
& f(q_c, \dot{q}_c, d, \dot{d}) = -c_0\dot{d} - k_0 d + f_N(q_c, \dot{q}_c, d, \dot{d}) \\
& f_N(q_c, \dot{q}_c, d, \dot{d}) = -sgn(\dot{q}_c - \dot{d})[\mu_{max} - \Delta\mu e^{-\nu|\dot{q}_c - \dot{d}|}]G\,. \qquad (4.1)
\end{aligned}$$

$\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K} \in R^{n\times n}$ represent mass, damping and stiffness matrices respectively. The base isolation is described as a single degree of freedom with horizontal displacement $q_c \in I\!R$. It is assumed to exhibit a linear behavior characterized by mass, damping and stiffness m_0, c_0 and k_0, respectively, plus a nonlinear behavior represented by a force f_N supplied by a frictional isolator, with G being the force normal to the friction surface, μ the friction coefficient, ν a constant, μ_{max} the coefficient for high sliding velocity and $\Delta\mu$ the difference between μ_{max} and the friction coefficient for low sliding velocity. The term $-c_0\dot{d} - k_0 d$ is a dynamic excitation force acting on the base due to the horizontal seismic ground motion represented by inertial displacement $d(t)$ and velocity $\dot{d}(t)$ at each time instant t. $\boldsymbol{q}_r = [\,q_{r1}\,,\, q_{r2}\,,\, \cdots\,,\, q_{rn}\,]^T \in R^n$ represents the horizontal displacements of each floor with respect to an inertial frame.

An analytical model of this structure implemented in SIMULINK software is available to do numerical simulations. Additionally, an scaled-model of a building similar to this model has been acquired by our research group to implement the control strategies proposed. Active mass damper and magnetorheological dampers are include as control devices. A photography of this equipment is shown in figure 4.1b.



a)

b)

Figure 4.1: 10 story building a). base isolated model b). scaled-model

Structural Model 2

The second structure studied corresponds to a two-span bridge, shown in Figure 4.2. At two of the three joints between the columns there are controllable friction devices (CFDs) applied in parallel to elastomeric bearings. The actuator can also be manipulated by a feedback control algorithm. In this case, the CFD scheme operates as a semiactive control system with no external energy supply required to control the dynamic behavior of the structure. This behaviour is described by the next equation:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{F}\,, \tag{4.2}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K} \in \mathbb{R}^{10\times 10}$ are the positive definite mass, damping and stiffness matrices, respectively, $\boldsymbol{x} = [x_1\,, x_2\,, \cdots\,, x_{10}\,]^T \in \mathbb{R}^n$ represents the transversal displacements of each node and the vector $\boldsymbol{F} \in \mathbb{R}^n$ describes the external excitation force, such as a seismic action.

An analytical model of this structure implemented in SIMULINK software is availaible to do numerical simulations. Additionally, a laboratory model of this structure will be builded. This equipment will be installed in the Joint Research Center in ISPRA, Italy. Laboratory tests with semiactive control will be able to be obtained and such probes will be supported by the European Commission.

Structural Model 3

This model corresponds to an elastically suspended bridge with vehicles crossing as shown in Figure 4.3. The bridge section consists of a rigid platform with elastic mounts on the left-hand and right-hand sides. Vibration of the bridge is produced when a truck crosses it with velocity $v(t)$ within a time interval $[t_0, t_f]$. The active control is implemented by two actuators located between the ground and the bridge at the left and the right ends respectively. The state equation of the system is described by:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}_c\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, t), \\ \dot{\boldsymbol{y}} &= \boldsymbol{A}_r\boldsymbol{y} + \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, t) \end{aligned} \tag{4.3}$$

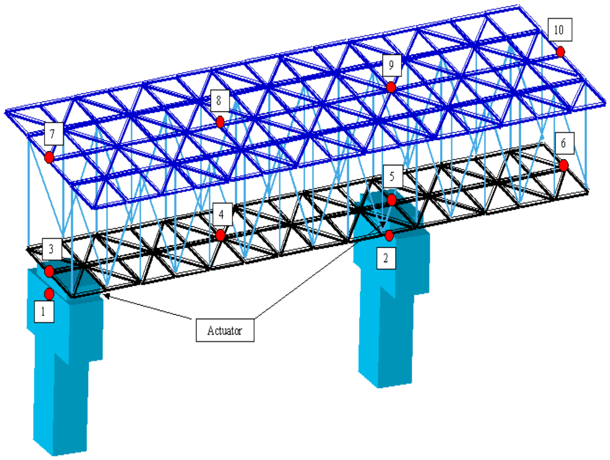


Figure 4.2: Two-span bridge with two CFDs

where the parameters of the matrices $\boldsymbol{A}_c$, $\boldsymbol{B}$ and $\boldsymbol{A}_r$ are known. The functions $\boldsymbol{g}$ and $\boldsymbol{f}$ include the uncertain coupling effects related to the truck. It is verified that the function $\boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y}, \cdot)$ is continuous for all t except a set $\{0, t_f\}$ and there exist known non-negative scalars α_c^c, α_c^r, δ_c, such that, for all $\boldsymbol{x}, \boldsymbol{y}$ and t, one has

$$\boldsymbol{g}_c = \boldsymbol{B}_c\, \boldsymbol{e}, \qquad \text{and} \qquad \|\boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y}, t)\| \le \alpha_c^c \|\boldsymbol{x}\| + \alpha_c^r \|\boldsymbol{y}\| + \delta_c \tag{4.4}$$

An analytical model of this structure implemented in SIMULINK software is available to do numerical simulations.

4.3 Work Plan

The work plan proposed to develop the doctoral thesis is distributed into two parts: The first part consists in the theoretical development and experimental verification and the second part corresponds to the writing of thesis and formal aspects for its public presentation. These two parts take approximately 20 months and they are explained below.

4.3.1 Development Stage

This stage is the main part of the thesis. Its duration is about fifteen (15) months and it contains both theoretical and experimental studies. Theoretical studies consist of developing the control strategies proposed before. The experimental studies consist of verifying such strategies on the structural models presented previously. Next steps will be followed to accomplish such objectives.

∗ Preparation of paper 5 listed in the previous work section and making its presentation in September 2003. Two (2) weeks.
∗ Complementary study of the backstepping theory. Two (2) weeks.
∗ Development of a control law using the backstepping theory by including actuator hysteresis. Three

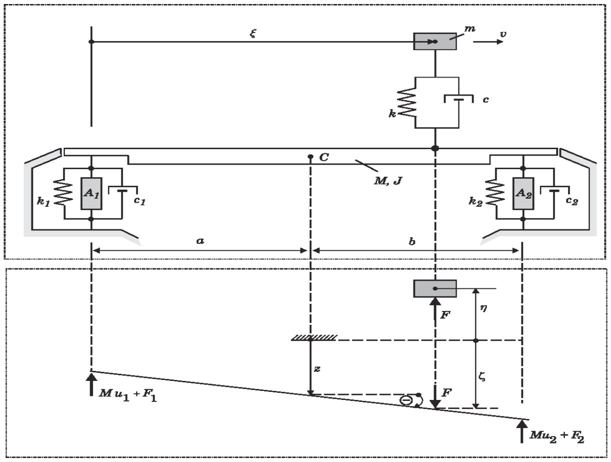


Figure 4.3: Actively controlled bridge platform with crossing vehicle

(3) months.

∗ Stay 1. Implementation of the developed control scheme using the backstepping theory. University of Pavia, Italy. Two (2) weeks.

∗ Writing a paper about the results obtained during this stage. Two (2) weeks.

∗ Development of a robust control design of uncertain structures by using modal interval arithmetic. Three (3) months.

∗ Development of a control strategy for structures with uncertain disturbances by using QFT theory. Three (3) months.

∗ Implementation of control laws found in the above stages on the structure with scaled-model. One (1) month.

∗ Stay 2. Implementation of control laws found in the above stages on other scaled-models existed in University of Washington, USA. Writing of two papers about the control laws above found. Three (3) months.

4.3.2 Writing of doctoral thesis

This stage takes about five (5) months and it consists of writing the principal results obtained during the research stage. Also, it includes the steps needed to present the doctoral thesis

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