Structural Control for Civil Engineering Applications

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Overview

- Background
- Motive of Structural Control
- Distinctive Features of Structural Control
- Evolution of Structural Control
- Classification of Structural Control

Background

Civil Structures: Long-span Bridges

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Civil Structures: High-rise Buildings

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Background

Civil Structures: High-rise Buildings

Overview

Increase in construction of high-rise buildings


civil structures: high-rise buildings

Background

Seismically-excited Structures

Overview

Northridge Earthquake, 1994

Kanisko, 72 deaths, 1500 injured, 1000s homeless, > $15B cost

Northridge Earthquake, 1994

Overview

Great Hanshin Earthquake, Kobe, Japan, 1995

Kanisko, 6434 deaths, 33k injured, 300k homeless, > $150B cost

Great Hanshin Earthquake, Kobe, Japan, 1995

Overview

Sichuan Earthquake, China (2008)

Sichuan Earthquake, China (2008)

Overview

Estimated losses: 70k deaths, 370k injured, 5.0m homeless

Sichuan Earthquake, China (2008)
**Other Recent Earthquakes**

- **Chi-Chi** (Taiwan, 1999): 20,000 dead, 20,000 injured, $6B damage
- **Kocaeli** (Turkey, 1999): 20,000 dead, 20,000 injured, $6B damage
- **Nisqually** (Seattle, WA, 2001): 1 death (heart), 400 injured, $1B damage, $2B damage
- **India** (2001): 20,000 (official), 90,000 (unofficial) dead
- **Sumatra** - **Andaman** (Indonesia, 2004): 2,500 dead, 10,000 injured, 100,000 homeless

**Wind-excited Structures**

- **Tacoma Narrows Bridge**, Tacoma, Washington
- **Tokyo Wan Aqua-line**, Tokyo, Japan
- **Millennium Foot Bridge**, London, England

**Structure & Aerodynamic instability phenomenon**

Wind-induced vibration

Period of Phenomenon = Period of Structure (Resonance)

After completion of the superstructure, oscillation with an amplitude over 0.5 m was observed. To suppress it, 16 tuned mass dampers (TMD) were installed. Part of the steel deck was stiffened.

**Human-excited Structures**

**Millennium Foot Bridge**, London, England
Implementation of passive control systems for retrofitting the bridge
- fluid-viscous dampers (horizontal movement)
- tuned mass dampers (vertical movement)

Background

Human-excited Structures

Motivation of Structural Control

Increased flexibility
- the trend toward taller, longer and more flexible structures

Increased safety levels
- higher safety level demands: tall structures, nuclear power plants

Increased stringent performance requirements
- strict performance guide lines: radar tracking stations, radio telescope structures, aerospace structures

Better utilization of materials and lower cost
- economic considerations: savings in materials, weight and cost

Distinctive Features of Structural Control

Civil engineering structures are statically stable.
- the addition of purely active control force can cause destabilization.
- in contrast to aerospace structures which requires active control for stability.

Loads are highly uncertain.
- earthquake and wind loads have no definite magnitude and arrival time.
- on the other hand, mechanical loads are fairly well documented.

Performance requirements are generally coarse.

Classification of Structural Control

Passive, Active, Semi-active Control

Passive Control
- non-controllable
- no power required

Active Control
- controllable
- significant power required

Semi-active Control
- controllable
- little power required
Classification of Structural Control

Applicable range of structural control systems

<table>
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<tr>
<th>Structure</th>
<th>Energy absorbing mechanism</th>
<th>User control</th>
<th>Active control</th>
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<td>Isolated building</td>
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| J.A. Calantarients (1909): | a different isolation system to isolate the building from its foundation using layers of talc or mica. Building slides during an earthquake.

Evolution of Structural Control

Modern structural control concept
- T. Kobori (1956): proposed a basic concept of active seismic-response-controlled structure. (The earliest attempt to formulate the problem of active control for applications to civil engineering structures)
- J.T.P. Yao (1972): indicated the way to the present active control research in the field of civil engineering.

Evolution of Structural Control

Introduction
- Metallic Yield Dampers
- Friction Dampers
- Viscoelastic Dampers
- Viscous Fluid Dampers
- Tuned Mass Dampers
- Tuned Liquid Dampers
- Base Isolation Systems

Passive Control

It is usually relatively inexpensive.
- It consumes no external energy (energy may not be available during a major earthquake).
- It is inherently stable.
- It works even during a major earthquake.
- Introduction

Energy Dissipation Mechanisms
- Conversion of kinetic energy to heat:
  - frictional sliding
  - yielding of metals
  - phase transformation in metals
  - deformation of viscoelastic solids or fluids
  - fluid orificing
- Transferring of energy among vibrating modes:
  - supplemental oscillators, which act as dynamic vibration absorbers.

Energy Dissipation Performance

Metallic Yield Dampers

- Inelastic deformation of metallic substances.
- The idea of utilizing added metallic energy dissipators within a structure to absorb a large portion of the seismic energy: the conceptual and experimental work of Kelly et al. (1972) and Skinner et al. (1975).
- Several of the devices considered: torsional beams, flexural beams, and U-strip energy dissipators.
Metallic Yield Dampers

- A triangular plate damper or triangular added damping and stiffness devices (TADAS)

Metallic Yield Dampers

- Low-yield strength steel
- 42-story high-rise RC condominium

Friction Dampers

- Friction:
  - an excellent mechanism for energy dissipation
  - used for many years in automotive brakes to dissipate kinetic energy
  - It is important to minimize stick-slip phenomena to avoid introducing high-frequency excitation.
  - Compatible materials to maintain a consistent coefficient of friction over the intended life of device
  - Not to slip during wind storms or moderate earthquakes.
  - under severe loading conditions, the devices slip at a predetermined optimum load before yielding occurs in primary structural members.

Friction Dampers

- Pall-Friction Damper

Friction Dampers

- Rotational Friction Damper
This new friction damper device is based on rotational friction and designed to:
- be stable in performance over many cycles
- be compact
- be easy to manufacture
- be fast and simple to install (no need for a qualified staff)
- be requiring little or no maintenance
- be inexpensive

Viscoelastic Dampers
- Metallic and frictional devices: seismic application
- The VE dampers: applications in both wind and seismic protection
- VE solid materials can be used to dissipate energy at all deformation levels
- Characteristics of VE materials
  1) rate dependent behavior (viscous)
  2) elastic behavior (elastic)
  3) store and dissipate energy at all deformation levels

VE dampers dissipate energy through shear deformation of the VE layers.

Viscoelastic Dampers
- World Trade Center in New York (1969)
  - 10,000 Visco-elastic dampers in each tower
  - Lively distributed from 10th to the 110th floor
  - Damping: 2.5%-3%

Viscoelastic Dampers
  - 260 viscoelastic dampers to reduce wind-induced vibration

Viscoelastic Dampers
- The Two Union Square Building in Seattle (1988)
  - 16 large dampers were installed parallel to four columns in one floor
  - to reduce wind-induced vibration
**Viscoelastic Dampers**

- **Wall Type**: B, C Building
- **Brace Type**: M, Department Store

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**Viscous Fluid Dampers**

- **The action of solids (inelastic deformation)**: metallic, friction and viscoelastic dampers
- **The action of fluids**: viscous fluid dampers (e.g., the automotive shock absorber)
- Viscous fluid dampers, widely used in aerospace and military applications, have recently adapted for structural applications.
- For low damping force rate, a simplified force-velocity relationship:
  \[ F = C_0 V \]
  where \( C_0 \) is independent of the frequency but dependent on ambient temperature.
- Most viscous fluid dampers in current applications:
  \[ F = C_0 V^n \]
  where \( 0.3 \leq n \leq 0.75 \)
  - obtained by special design of the orifices
  - advantages: the force tends to flatten out at higher velocities

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**Seismic Design with Fluid Dampers as Part of a Base Isolation System**

- **Seismic Design Example**: the new San Bernardino County Medical Center at Colton, California (1994)
  - nearly 200 pieces of a 320,000 lb. output Fluid Viscous Damper.
  - All buildings are base isolated on large rubber bearings, with dampers mounted in parallel with the bearings.
**Viscous Fluid Dampers**

- Seismic Damper Installation at the New Pacific Northwest Baseball Park

  - The dampers are used for seismic protection of the roof during earthquakes.
  - 3600 kN eight dampers with stroke of ±381mm

**Viscous Fluid Dampers**

Seismic Rehabilitation of an Historic Structure

This is an historic structure, and the owner wished to minimize changes to the building’s appearance.

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**Tuned Mass Dampers (TMD)**

- The objective of incorporating a TMD into a structure:
  to reduce energy dissipation demand on the primary structural members under the action of external forces.

- The mechanism of a TMD: *transferring* some of the structural vibrational energy to the TMD which consists of an auxiliary mass-spring-dashpot system anchored or attached to the main structure.

- The modern concept of TMDs for structural applications (Prahm 1909)

**Tuned Mass Dampers (TMD)**

Classical Undamped Tuned Mass Damper (TMD) (or Dynamic Vibration Absorber (DVA))

- An undamped main mass-spring system under a sinusoidal force $F_0 \sin \omega t$

  \[
  - \text{the forcing frequency } (\omega) = \text{the natural frequency of the main mass } (\omega_n = \sqrt{k/m})\\
  - \text{the response is infinite (i.e., resonance)}\\
  - \text{it can cause severe problems for vibrating systems.}
  \]

**Tuned Mass Dampers (TMD)**

- When an absorbing mass-spring system (i.e., TMD) is attached to the main mass and the resonance of the TMD is tuned to match that of the main mass (i.e., $\omega_{\text{TMD}} = \omega_n$)
  - $\Rightarrow$ the motion of the main mass is reduced to zero at its resonance frequency.
  - $\Rightarrow$ the energy of the main mass is apparently "absorbed" by the TMD.

**Tuned Mass Dampers (TMD)**

- The 2-DOF system has two natural frequencies, corresponding to the two natural modes of vibration for the system.

  - The lower frequency mode, both masses move in the same direction, in-phase with each other.
  - In the higher frequency mode, the masses move in opposite directions, 180° out of phase with each other.
Displacement vs. Frequency plots:

- The plots below show the displacements as a function of normalized frequency (driving frequency divided by natural frequency of main mass).
- The blue dashed curve: the displacement response of the undamped main mass alone.
- The blue curve: the displacement of the main mass after undamped TMD has been attached. (An additional 20% of the main mass is tuned to the resonant frequency of the main mass.)
- The red curve: the displacement of the absorber mass.
- Notes:
  1. The main mass has zero displacement at the original problem frequency.
  2. There are now two new resonant frequencies.
  3. The displacement of the TMD mass is infinite at the same two resonant frequencies.
  4. The response at the target frequency is finite (approximately 4.8).

Notes:

1. The main mass has zero displacement at the original problem frequency.
2. There are now two new resonant frequencies.
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4. The response at the target frequency is finite (approximately 4.8).
Tuned Mass Dampers (TMD)

Building TMD in Taipei 101
- 660 ton. (0.24% of building mass)
  - TMD and its support occupy five upper floors.
  - Visible from a mezzanine level.
  - $3.5-million turnkey contract.
  - Includes Dampers and 60m tall pinnacle.
  - Additional $800k for the damper ball.
  - Made of 12.5 cm thick steel plate.
  - Peak acceleration of the top was reduced from 7 mili-g to 5 mili-g.
  - The damper will not have any role during earthquakes.

Pinnacle TMDs
- Two 4.5 ton dampers
  - Flat steel masses tuned by springs are able to move horizontally in any direction.
  - To reduce cumulative fatigue damage due to wind-induced motion.

Tuned Mass Dampers (TMD)

Park Tower Hotel & Residences
- Chicago, Illinois, United States
- 70 story multi-use building
  - 48 stories of condos over 18 story hotel
  - 824 ft. tall tower
  - 5 story parking garage
  - Building was designed with a tuned mass damper to control lateral accelerations.

Modified structure
- Initial structural properties:
  - T = 7.26 sec
  - Drift = 13" = h/700
  - Acceleration = 35 mg
- Final structural properties without damper:
  - T = 5.18 sec
  - Drift = 9.7 in. = h/940
  - Acceleration = 20.7 mg
- With addition of damper:
  - Acceleration = 15 mg
Liquids are used to provide all of the necessary characteristic of the secondary system. The liquid not only supplies the required secondary mass, but also the damping through viscous action primarily in the boundary layers. Gravity provides the necessary restoring mechanism.

**Tuned Liquid Dampers (TLD)**
- In TMD, typically a solid concrete or metal block acts as the secondary mass.
- Liquids are used to provide all of the necessary characteristic of the secondary system.
- The liquid not only supplies the required secondary mass, but also the damping through viscous action primarily in the boundary layers.
- Gravity provides the necessary restoring mechanism.

**Tuned Liquid Column Damper in Random House**
- Two TLCDs at the roof level (290 tons and 430 tons)
- Large U-shaped tanks at right angles.
- Moving water mass is 550 tons (0.33% of building weight) in each tank.
- Cost effective. Cheaper than a pendulum TMD.

**Base Isolation System**
- One of the most widely implemented and accepted control strategies.
- Decouple the structures and/or its components from potentially damaging earthquake-induced ground or support motions.
- Allow large deformations of control devices to achieve these goals.
Base Isolation System

- During an earthquake, a fixed-base building can sway from side to side.
- When a base isolation system is used, the sideways movement occurs mainly in the bearings, and the building hardly distorts at all.

Base Isolation System

- Basic requirements of base isolation
  1. Flexibility
  2. Energy dissipation capacity
  3. Sufficient stiffness under small load

Seismic behavior of base isolated structures

1. Flexibility
2. Energy dissipation capacity
3. Sufficient stiffness under small load

Base Isolation System

Conventional bridges with earthquake resistant design
Horizontal force is concentrated on a rigid pier.

.load dispersing bridge (Base Isolated)
RB and LRB are used to disperse the horizontal force induced on each pier.

Seismic isolation bridge
LRB is used to increase the vibration period and damp the vibration.

Square Base Isolators made of Multilayer Natural Rubber with an internal Lead Plug
**Base Isolation System**

**Function**

- **Multi-layer rubber isolator Function**
  - Load supporting / Rotation Absorbing function
  - Rubber reinforced with steel plates provides stable support for structures
  - Multilayer construction provides better vertical rigidity than single layer rubber pads for supporting a building.

**Function of lead plug (damper)**

- **Vibration damping function**
  - It absorbs large vibration of the structure
  - As the layers of rubber are distorted, the lead plug is plastically deformed, which absorbs the earthquake energy and quickly damps the vibration.

- **Trigger function**
  - Reduces vibration from sources other than earthquake
  - Vibration generated by strong winds are avoided as the relative rigidity of the lead plug restricts the flexibility of the isolation system until the plug is subjected to a certain level of force.

**Passive Control Base Isolation System**

- **USC Hospital** (First base-isolated hospital in U.S., in retrofit)
- **LA City Hall** (in retrofit)
- **New LA Cathedral** (under construction)

**Base Isolated Condominiums**

- **Lead Rubber Bearings (LRB) in Bridges**
- **Base Isolators in Bridges**
### Base Isolation System

**Example: LNG Tank**

- **Passive Control**
- **Base Isolation System**

**Example: Tohoku Univ.**

- Acceleration resp. of left bld.
- Acceleration resp. of right bld.

### ACTIVE CONTROL

- **Introduction**
- **Actuators**
- **Control Algorithms**
- **Full-scale Applications**

### Introduction

**Active Control Systems**

- Initial concept paper: J.T.P. Yao (1972)
- An external source powers control actuator(s) that apply forces to the structure in a prescribed manner.
- Control forces can be used to both add and dissipate energy in the structure.
- In an active feedback system, the signals sent to the control actuators are a function of the response of the system measured with physical sensors (optical, mechanical, electrical, chemical, and so on).
Advantages (attractive features):
- enhanced effectiveness in motion control
- relative insensitivity to site conditions and ground motions
- applicability to multi-hazard situations
- greater ability to select control objectives

Disadvantages (issues to be solved):
- Capital cost and maintenance
- reliance on external power
- system reliability and stability
- gaining acceptance by the profession

Active structural control is not popular for seismic hazard mitigation because
- Energy consumption during seismic events, when power blackout is highly likely to occur
- Stability concern: what if the control system becomes unstable?

Active structural control is still very useful for reducing wind-induced vibrations in bridges and buildings
- Active mass damper (AMD)
- Hybrid mass damper (HMD)

Active Mass Driver (AMD) Experiment: Acceleration Feedback Control Strategies

Arrangement of AMD

Control Algorithms
- Optimal Control
- Stochastic Control
- Adaptive Control
- Intelligent Control
  - Neural network-based control (i.e., neuro-controller)
  - Fuzzy logic-based control (i.e., fuzzy controller)
- Sliding Mode Control
- Robust Control

Kyobashi Seiwa Building (1989)
103

KYOBASHI SEIWA BUILDING (1989)

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YOKOHAMA LANDMARK TOWER (1993): AMD

105

SHINJUKU PARK TOWER (1994):

AMD for Wind Vibration Control of Building in Use (2007)

HYBRID CONTROL

- Introduction
- Hybrid Mass Damper (HMD)
- (Semi-)Active Base Isolation
- Full-scale Applications

HYBRID CONTROL
Introduction

Hybrid Control Systems
(passive devices + (semi-)active system)

- Excitation
- Structure
- Response

Feedforward Link

Control Actuators
Feedback Link

Sensors
Computer
Sensors

Hybrid Control Systems

- The combined use of active and passive control systems
- For example,
  - a structure equipped with distributed viscoelastic damping supplemented with an active mass damper on or near the top of the structure
  - A base isolated structure with actuators actively controlled to enhance performance
  - The hybrid mass damper (HMD) is a combination of a TMD and an active control actuator, which is the most common control device employed in full-scale civil engineering applications.

Hybrid Mass Damper (HMD)

- The most common control device in full-scale structure
- HMD = TMD + active control actuator
- Advantages
  - compact
  - efficient
  - practically implementable
- DUOX HMD
  - high control efficiency with a small actuator force

Hybrid Control Systems

Full-scale Applications

HMD for Air-traffic Control Tower (Incheon Int’l Airport)

- Active tuned mass damper
  - Two dampers on the 90th floor.
  - Sensors are used to measure the building sway with a computer to control
- Shape
  - The Hole in the building reduces vortex-shedding induced force.

Hybrid Control Systems

Full-scale Applications

Shanghai World Financial Center: HMD
Hybrid (or Smart) Base Isolation

Experimental Setup

- Mass of the base: 10.5 kg
- Mass of the structure: 57.5 kg
- Total mass: 68 kg
- Max force of the MR damper (at current of 0.5 A): 45 N (6.6% of the total mass)

Structural Acceleration

Response to Strong Earthquake

Max: 0.2g (0.44g for full scale)

28% reduction (Peak)
29% reduction (RMS)

Response to Moderate Earthquake

Max: 0.07g (0.15g for full scale)

37% reduction (Peak)
49% reduction (RMS)

SEMI-ACTIVE CONTROL

- Introduction
- MR Fluids and Dampers
- MR Damper-based Control Systems
- Control of Cable Vibration
- Limitation of Semi-active Control
**Introduction**

**Semi-active Control Systems**

- Excitation
- Structure
- Response

PED

Control Actuators

Sensors

Computer

Sensors

**Introduction**

**Semi-active Control Devices**

- combine the best features of both passive and active control
- don’t require large power sources: can operate on battery power, which is critical during seismic events when the main power source to structure may fail
- performance is better than passive devices and have potential to achieve similar performance with fully active devices

**Definition**

- cannot inject mechanical energy into the controlled structure, but has properties that can be controlled to optimally reduce the responses of the system
- have no potential to destabilize the structural system (Bounded Input-Bounded Output stability)

**Introduction**

**Semi-active Control Systems**

- Smart Base Isolation
- Smart Damping?

- Control Computer

**Introduction**

**Smart Damping?**

- MR-damper
- Sensor

**Introduction**

**Smart Damping?**

- MR-damper
- Sensor

**Introduction**

**Smart Damping?**

- Low Flow Resistance
- KAJIMA
Kajima Shizuoka Building: Observations from the May 7, 1999 M4.9 Earthquake

**MR Fluids and Dampers**

**MR Fluids**
- What are they?
  - Micron-sized, polarizable, iron particles in oil
- What do they do?
  - Newtonian in the absence of applied field
  - Develop yield strength when field applied
  - Provide reliable means for a low-power, rapid response interface between electronic controls and mechanical devices

**MR Dampers**
- Magnetorheological (MR) dampers are semi-active control devices that use MR fluids to produce controllable dampers.
- Attractive features:
  - High dissipative force at low velocity.
  - Continual optimization.
  - High dynamic range
  - Inherent stability and failure-safety.
  - Mechanical simplicity.
  - Fast response-time.
  - Small device size.
  - Large temperature range.

**MR Fluid Linear Damper**
- Used in semi-active suspension system
- Used in highway vehicle seats

**MR Damper-based Control System**

Responses due to 120% El Centro Earthquake

Rheonetic SD-1000 MR Damper
- Height: 158 cm
- Mass: 304 kg

(B.F. Spencer, Jr., UIUC)
Two 30-ton, MR fluid dampers built by Sanwa Tekki using Lord MR fluid are installed between 3rd and 5th floors.

Existing solutions:
- Cable restrainers which tie together cables
- Altered surface roughness on cables
- Augment damping through discrete viscous dampers attached transverse to cable

Damping ratios of 1st in-plane mode under vibration amplitude 0.04~0.07 m/s²
It requires a feedback control system including sensors, a controller and an external power source.

It is difficult to install and maintain the conventional smart system, especially in the cases of large-scale structures such as long-span bridges.

**Semi-active Control**

**Example:** MR Damper with Electromagnetic Induction (EMI) Device (H.-J. Jung): one possible approach

**Preliminary Performance Test using Large-scale Shaking Table**

**Limitation of Semi-active Control**

**Maintenance and Implementation Issues**
- It requires a feedback control system including sensors, a controller and an external power source.
- It is difficult to install and maintain the conventional smart system, especially in the cases of large-scale structures such as long-span bridges.

**Limbition of Semi-active Control**

**How to Solve the Problems**

(Conflict Direction of Structural Control)

- Functionally upgraded passive (or smart passive) devices
  - **Approach 1**: passive devices having adaptability
    - Can mimic the function of semi-active devices.
    - Adaptive Negative Stiffness System (Nagarajaiah, Rice U.)
    - MR damper with Electromagnetic Induction Device (Jung, KAIST)
  - **Approach 2**: simpler semi-active control devices
    - Wireless sensor network
    - Decentralized control
    - Energy harvesting

**SUMMARY**

- Structural control technologies has been developed to to mitigate vibration of civil engineering structures such as bridges and buildings.
- Structural control can improve serviceability as well as safety of structures.
- Semi-active control is promising for civil engineering applications. However, limitation in implementation and maintenance should be resolved. ➔ Smart passive control

**REFERENCES**