第五章　结构主动减震控制
Chapter 5 Active structural vibration control

5. 1　结构主动减震控制概述

Introduction to active structural vibration control

5. 2　结构主动减震机理和系统组成

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active control algorithm

5. 1　结构主动减震控制概述
Introduction to active structural vibration control

5. 1. 1 结构主动减震控制的基本概念和分类
Concepts and classification of active vibration control

- 概念 concepts

结构主动控制是利用外部能源（计算机控制系统或智能材料），在结构物受激励振动过程中，**瞬时施加控制力或瞬时改变结构的动力特性，**以迅速衰减和控制结构动力响应的一种减震（振）技术。

Active structural vibration control is a control technology by applying instantaneous control force or instantly altering the dynamic properties of structures through some external energy supply to rapidly modify or control the motion of a structure

分类： Classifications

（1）按主动控制的利用程度分类：Classification by utilization of active control

① 结构（全）主动控制（Active Control）；

② 结构半主动控制（Semi Active Control）；

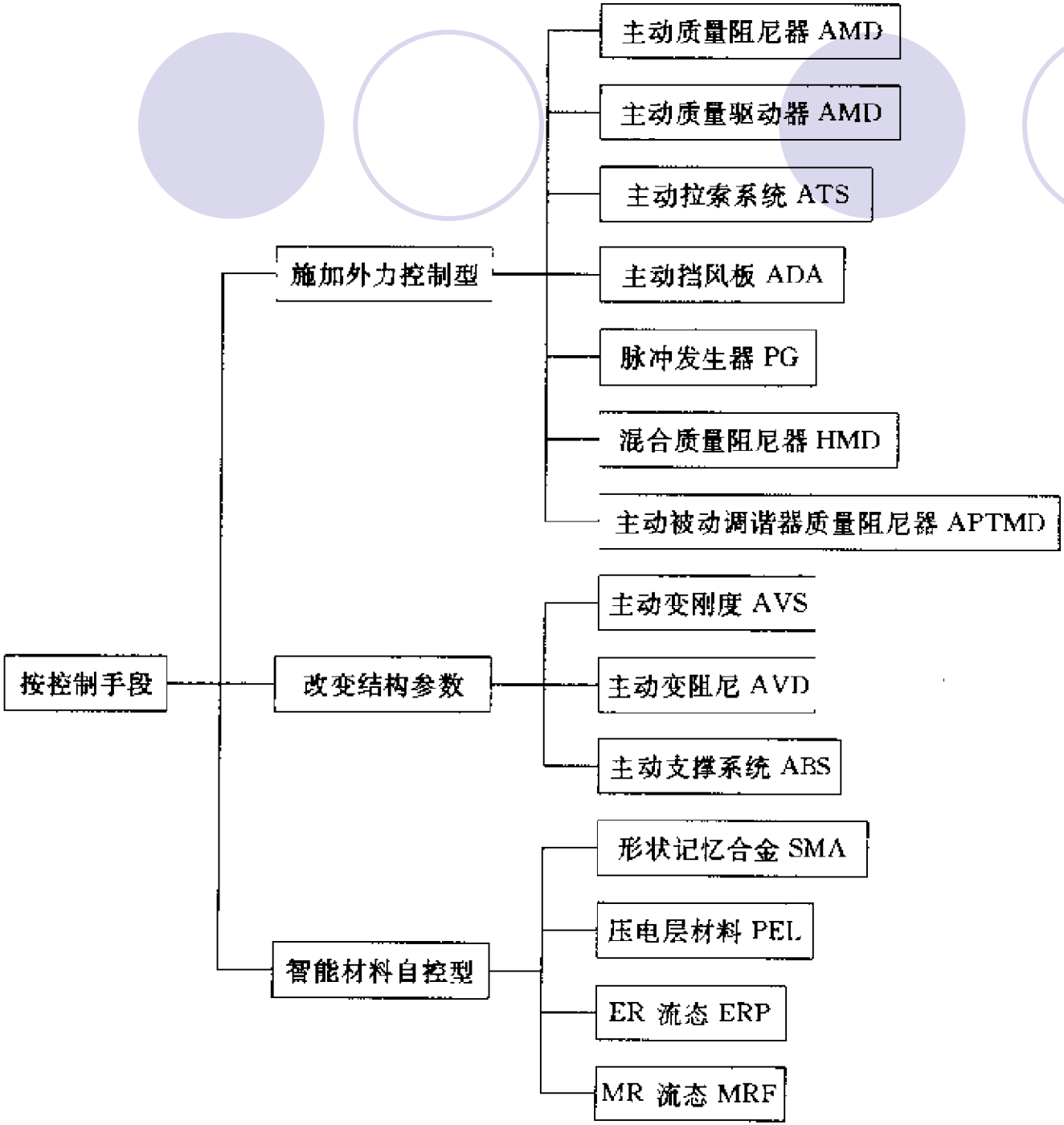
③ 结构混合控制（Hybrid Control）。

（2）按实现控制的手段分类： Classification by implementation means

① 施加外力控制型；by applying external control force

② 改变结构参数型；by altering the structural parameters

③ 智能材料自控型。By using intelligent self-control materials


按控制手段
施加外力控制型
主动质量阻尼器 AMD
主动质量驱动器 AMD
主动拉索系统 ATS
主动挡风板 ADA
脉冲发生器 PG
混合质量阻尼器 HMD
主动被动调谐器质量阻尼器 APTMD
改变结构参数
主动变刚度 AVS
主动变阻尼 AVD
主动支撑系统 ABS
智能材料自控型
形状记忆合金 SMA
压电层材料 PEL
ER 流态 ERP
MR 流态 MRF

5.1.2 优缺点和应用范围 Advantages, disadvantages and application

- 优点如下：Advantages

（1）减震控制效果好；enhanced effectiveness in motion control. The degree of effectiveness is, by and large, only limited by the capacity of the control system;

. （2）适应性广；applicability to multi-hazard mitigation situations

（3）经济性好; More economical, Save the engineering cost

（4）对外部环境和地面运动不敏感 relative insensitivity to site conditions and ground motion.

- 仍存在的问题： Existing problems

（1）减震的有效性；the effect of vibration control is temporary

（2）控制系统工作的稳定性；the instability of control system

（3）时滞问题；time delay

5.1.2 优缺点和应用范围 Advantages, disadvantages and application

- Existing problems

（4）能量输入问题；input of energy

（5）经济性问题；economical problem

（6）系统装置的日常维护问题。The daily maintenance of system

- application

it is mainly applied in the vibration control of the following structures under wind, earthquake and environmental excitation

（1）高层、超高层建筑；high-rise and super high-rise building

（2）高耸塔架或特种结构；high-rise towers or special structures.

（3）桥梁或其他大跨度结构；bridges and other large-span structures

（4）生命线工程结构。Lifeline projects

5. 2 结构主动控制的减震机理和系统组成
The mechanism and components of structural active control system

5.2.1 Mechanism of structural active control

the mechanism and components of the system is introduced by taking the typical active control system——active mass damper (AMD) as an example.

n个自由度的线性结构，采用主动减震控制结构体系。在地震激励下的运动方程为：

The Linear structure with n DOF adopts active vibration control systems, its equation of motion is:

$$M\ddot{x} + C\dot{x} + Kx = F\ddot{x}_g + EU$$

Suppose that the open-closed loop configuration is used in which the control force U is designed to be a linear function of the measured displacement vector x, the velocity vector and the ground acceleration. The control force vector takes the form:

$$U = K_b x + C_b \dot{x} + F_b \ddot{x}_g$$

5. 2 结构主动控制的减震机理和系统组成
The mechanism and components of structural active control system

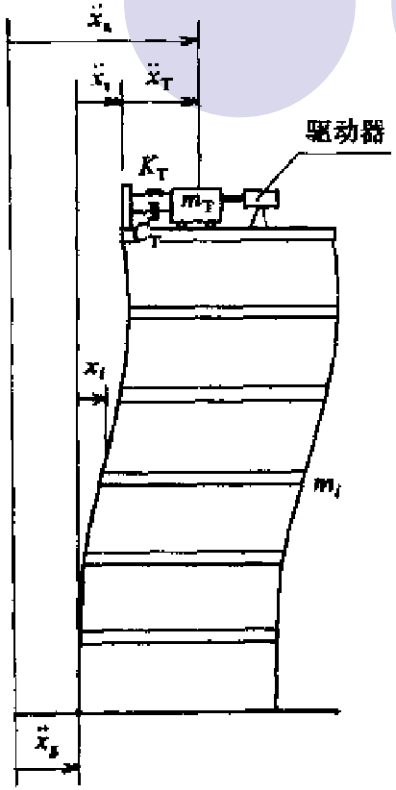
The substitution of equation of U into equation of motion yields:

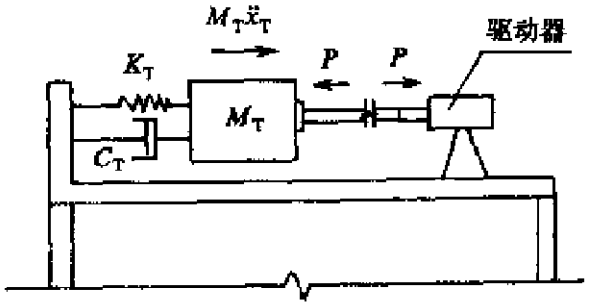
$$M\ddot{x} + (C - EC_b)\dot{x} + (K - EK_b)x = (F - F_b)\ddot{x}_g$$

- It shows that the active control is immediately appealing and exciting. On the one hand, it is capable of modifying properties of a structure in such a way as to react to external excitations in the most favorable manner. On the other hand, direct reduction of the level of excitation transmitted to the structure is also possible through active control.
- The choice of the control gain matrices depends on the control algorithm selected. A number of control strategies for structural applications have been developed,

5. 2. 2 主动控制施加控制力的减震控制

The vibration control by active control force





当AMD主动控制结构体系受到地震激励时，产生地震反应。

AMD系统的驱动器驱动质量块，使质量块产生运动，质量块的惯性力等于控制系统对结构施加的控制力，它通过弹簧、阻尼器和驱动器作用在结构上，衰减和控制结构的地震反应。

When the AMD active control system is excited by earthquake, the seismic response of structure occurs. The mass is driven by the actuator of AMD system, and the inertia force of the mass, equal to the control force, is applied on the structure by the control system through the springs, dampers and drivers, to control and modify the displacement response of the structure.

5. 2. 3 主动变刚度、变阻尼的减震体系

Active variable stiffness and Active variable damping system

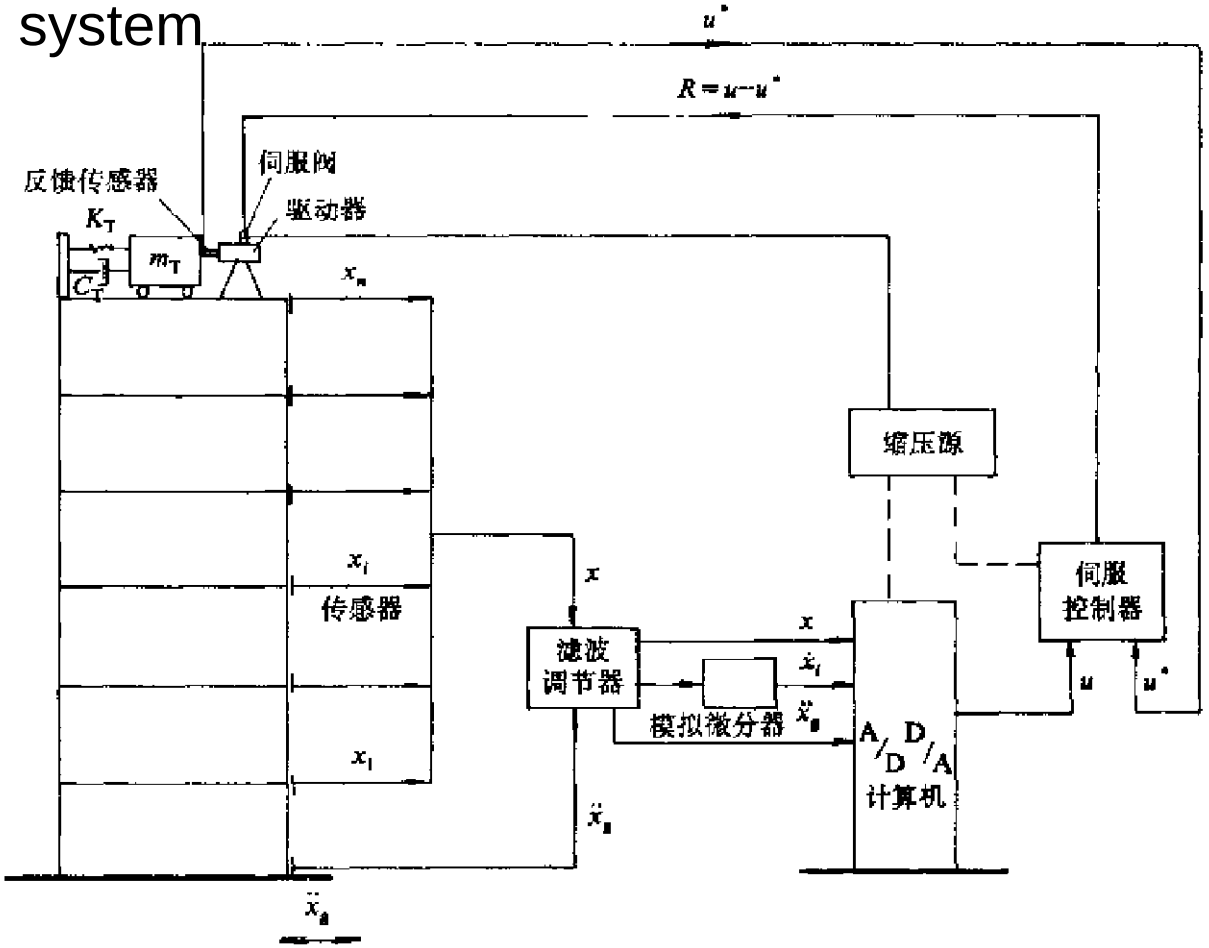
如果主动控制系统对结构的减震控制，不是通过施加控制力，而是直接对装置于楼层之间的可变液压阻尼器(Variable Hydraulic Dampers)进行控制，直接调整结构的刚度特性和阻尼特性，从而衰减和控制结构的地震反应，这种控制体系，称为主动变刚度AVS和主动变阻尼AVD控制体系。变刚或变阻尼的控制策略可采用不同的控制算法。

The active control system controls the vibration of the structure by directly controlling the interlayer Variable hydraulic dampers rather than applying control force. The dampers can adjust the structural stiffness and damping, so that the earthquake response of the structure can be damped and controlled. This type of control system is named as active variable stiffness(AVS) and active variable damping (AVD) control system. The different algorithm can be used in control strategies of variable stiffness or damping.

5. 2. 4 主动控制系统的组成和工作流程

The components and work process of the active control system

以典型的AMD说明系统组成和工作流程。Taking the typical AMD as an example to explain the elements components and work process of the control system



working process of the AMD control system:

(1) **Data collection**: online measuring the ground and structure vibration response under seismic excitation by sensors.

(2) **Data processing and transmission**: The measured vibration response signal is filtered, amplified, regulated, and treated by analog differential, and is transferred to the A/D converter of a computer system

(3) **A/D conversion**: Convert a analog voltage signal into a digital voltage signal.

(4) **Control calculation**: the digital voltage can be transferred to displacement and velocity of structure by computer. Then the control force U can be calculated by the selected control algorithm.

(5) **D/A conversion**: Converts the digital voltage signal of control force (U) to analog voltage signal and feed to the servo controller.

working process of the AMD control system:

(6) **伺服控制**：伺服控制器与驱动器的反馈传感器相联，伺服传感器把计算机传来的控制力（U）的指令信号与反馈传感器驱动力(u^*)信号进行比较（负反馈），其差值传至电液伺服阀，伺服阀控制高压油从液压源输送至伺服驱动器的油缸，油缸的活塞随信号偏差而移动， 一直至信号等于零为止。这样，驱动器就按指令信号向结构施加设定的控制力，从而衰减和控制结构的振动反应。重复(1)~(5)，使结构的振动反应减至最小值。

Servo control: the servo controller is connected with the feedback sensors of the actuator. And the controller compares the command signal of the control force (U) from the computer to the signal of the driving force from the feedback sensors (u*) (negative feedback). Their difference is transmitted to the electro-hydraulic servo, which control high-pressure oil piping to the cylinder of the servo actuator. The piston of the cylinder moves with the deviation of the signal until it tends to zero. In this way, the actuator applies control force to the structures according to the command to damp and control the vibration response of the structures. Repeats the step (1) to (5) until response of the structure reduces to minimum.

5.3 主动控制算法
active control algorithm

Brief introduction to active control algorithm

主动控制算法是主动控制的基础。它的目标是，使主动控制系统在满足其状态方程和各种约束条件下，**选择合适的增益矩阵，寻找最优的控制参数，**使系统达到较优的性能指标，实现对结构的最优控制。

The active control algorithm is the fundamental element of active control. Its target is: making the active control system reaches favorable performance and optimal control of the structure by choosing appropriate gain matrix and the best control parameters before meeting the equation of state and various constraints,

Main algorithms:

（1）经典线性最优控制 Classical linear optimal control （Yang，1975）；

（2）瞬时最优控制 Instantaneous optimal control （Yang，1992）；

（3）改进瞬时最优控制 Improved instantaneous optimal control（阎维明、周福霖、谭平，1996）；

（4）模态控制 Modal Control（Martin and Soong，1976）；

（5）脉冲控制 Impulse control （Udwadia，1981）；

5.3 主动控制算法
active control algorithm

主动控制算法简介 Brief introduction of active control algorithm

（6）预测控制 Predictive control（Rodellar，1987）；

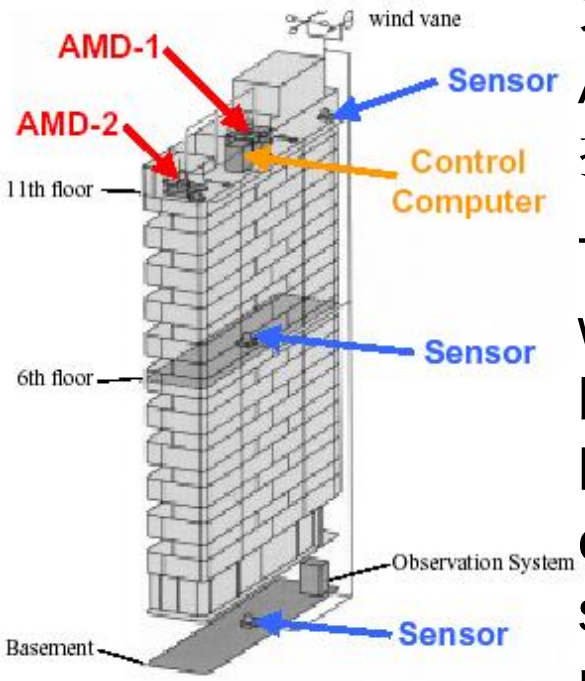
（7）自适应控制 Adaptive control（Safk，1989）；

（8）模糊控制 Fuzzy control（Yao，1989）；

（9）H∞（无限大）优化控制 H (infinity) robust control （Safonov，1991；刘栋栋，1995）；

（10）神经网络 Neural networks

5.4 Engineering applications

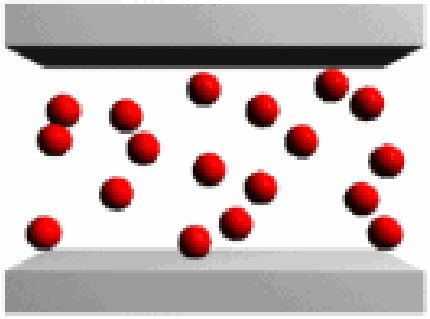


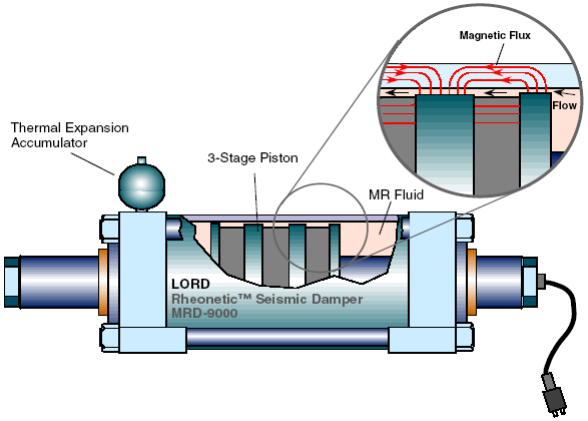
京桥Sewa大厦

Seiwa Kyobashi Building

世界上第一个使用AMD的建筑，建筑宽4m，高33m，高宽比8.25，无法满足传统的抗风抗震设计要求。屋顶设置了2个AMD系统，AMD-1控制结构主振动，AMD-2控制扭转振动。

The first building with AMD in the world, 4m width and 33m height. because of the ratio 8.25 of height to width, the building couldn't meet the conventional seismic and wind resistant requirement. Two AMD systems were installed on the roof. AMD-1 controls the main vibration of structure, and AMD-2 controls the torsion vibration.



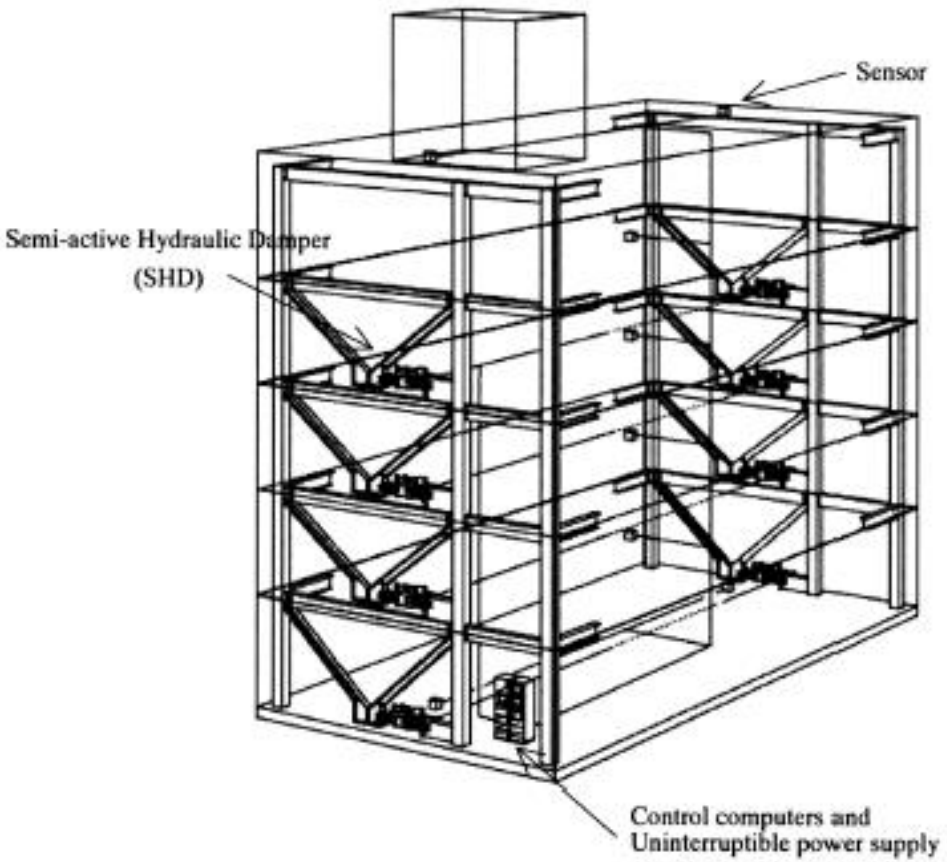


美国**Lord**公司开发的最大阻尼力为**200kN**的磁流变液阻尼器

Magnetorheological fluid damper with a maximum damping force of 200kN developed by American Lord Company

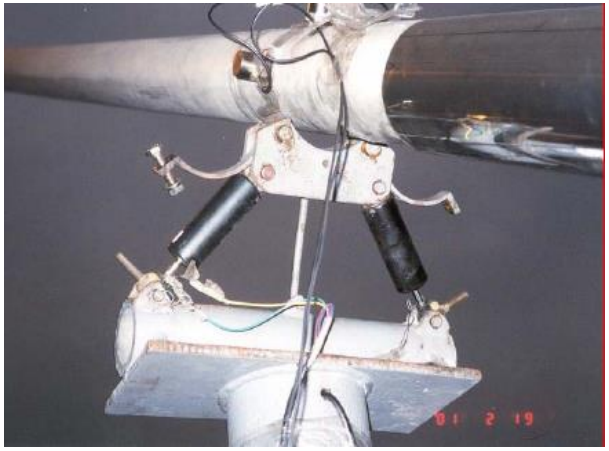
日本Sanwa Tekki公司开发的用于日本东京博物馆的300kN磁流变液阻尼器

The 300kN Magnetorheological fluid damper developed by Japanese Sanwa Tekki Company is used in Tokyo Museum



日本的鹿岛静冈大厦（Kajima Shizuoka Building）(SHD)

日本Sanwa Tekki公司开发的用于隔震居住建筑的400kN磁流变液阻尼器
The 400kN Magnetorheological fluid damper developed by Japanese Sanwa Tekki Company in the seismic isolation of Residential buildings



磁流变液阻尼器应用于洞庭湖大桥的斜拉索的风雨振动
Magnetorheological fluid damper used in Dongtinghu Bridge to control the rain-wind induced vibration vibration of the stayed cables

Details of Magnetorheological fluid damper in Dongtinghu Bridge