THE STATE-OF-THE-ART AND PRACTICE OF STRUCTURAL CONTROL OF CIVIL STRUCTURES FOR HAZARD MITIGATION IN MAINLAND CHINA

J. P. Ou[1,2] and H. Li[2]

[1] *Professor, Dept. of Civil and Hydraulic Engineering, Dalian University of Technology, Dalian, China*
[2] *Professor, Dept. of Civil Engineering, Harbin Institute of Technology, Harbin, USA*
Email: oujinping@dlut.edu.cn, oujinping@hit.edu.cn, lihui@hit.edu.cn

ABSTRACT :

Structural control is emerging technology for hazard mitigation in civil engineering and has been comprehensively studied over the world. This paper introduces the research and applications of passive control, active control and smart control, which include novel passive dampers, functional materials and smart dampers, active control systems, and their performance investigations; control algorithms for nonlinear structures; design methods adopted in the National Seismic Design Code for Buildings; and applications of structural control technology in buildings, bridges and offshore platform. Considering that one structure can have various failure mode and different failure modes make the structure with different reliability. The failure mode control, which makes the structure have highest reliability, is also studied.

KEYWORDS:
Control, dampers, smart control, failure mode control, civil structures

1. INTRODUCTION

Structural vibration control has been studied for three decades and a number of achievements in passive control, active control and smart control have been made in mainland of China. For passive control, some novel energy dissipation devices, including velocity and displacement dependent dampers and energy absorb dampers have been developed. The performance of the dampers has been experimentally investigated. The analytical approaches of buildings incorporated with passive dampers have been proposed and parametric studies have been carried out. The range of parameters of the dampers was proposed for the purpose of design. The proposed approaches have been adopted in the Seismic Design Code for Buildings (GB2001). Recent years, passive energy dissipation techniques have been extensively used for both new and existing structures. For smart control, functional materials, such as magnetostrictive Tefernol-D/epoxy composites (MTDC), magnetorheological (MR) fluids and functional-based smart control systems have been developed, such as MR dampers, shape memory alloy (SMA)-based dampers, PZT-based variable friction dampers and MTDC -based variable friction dampers. The electro-mechanical properties and models of the smart dampers have been experimentally studied. The semi-active control algorithms for cables and nonlinear structures were proposed. The stability and fault tolerance property of the control algorithms for nonlinear structures were derived. A nonlinear structure model by MR damper playing the role of nonlinear components was proposed. The control algorithms for nonlinear structure were verified through shaking table test. For active control, a hybrid mass damper consisting of a tuned mass damper (TMD) and an active mass damper (AMD) on the top of TMD has been designed for mitigation of wind-induced vibration of the New Guangzhou TV Tower.

This paper is a summary of the technology of structural control in mainland of China.

2. STRUCTURAL PASSIVE CONTROL

From the end of 1980s to that of 1990s, many researches focused on their interests on passive control. A number of passive energy dissipation devices were proposed, including various viscous dampers, viscoelastic dampers, metallic dampers and friction dampers. The performance of the dampers was experimentally investigated. This year, Li (2008) theoretically studied the model of metallic dampers only by material mechanics, which provides a new potential way to modeling the performance of damper through mechanics. The parametric studies of the buildings incorporated with four kinds of dampers were carried out and the reasonable range of the parameters was proposed, which is convenient for the preliminary design of passive dampers. Ou and Wu (Ou, 2004) proposed the analytical approaches for the buildings with passive dampers, including mode decomposition method and response spectrum with large damping ratio. In 1997, Shenyang Government Office Building was retrofitted using 134 Pall-type friction dampers in the first three stories, which is the first time for passive damper used for retrofit in mainland of China (Ou, 2004). In 1998, several important buildings in Beijing, which were designed and constructed in 1950s, were retrofitted using passive dampers, such as the Beijing Hotel retrofitted using viscous-spring dampers, the Beijing Railway Station retrofitted using viscous dampers, and so on. In 2001, the new version of Seismic Design Code for buildings was published and the passive energy dissipation technology and isolation technology were included in the Code (Chapter 12). After that, many buildings were designed using passive dampers. Recent years, for 2008 Beijing Olympic Game, a number of stadiums were retrofitted using passive dampers, such as the Capital Stadium retrofitted using 67 X-typed steel dampers (Ou and Li, 2008).

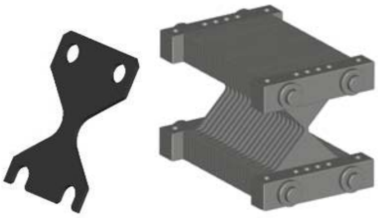


Figure 1 Configuration of damper

When the passive damper was used to retrofit the existing buildings, the ductility factor should be large because the yield displacement of the old building is so small, whereas, the ultimate displacement of the building with dampers should be large enough to meet the requirement of the Code. For X-typed steel damper, it is a challenge issue. The authors proposed a novel X-typed steel damper to overcome the fault, as shown in Figure 1.

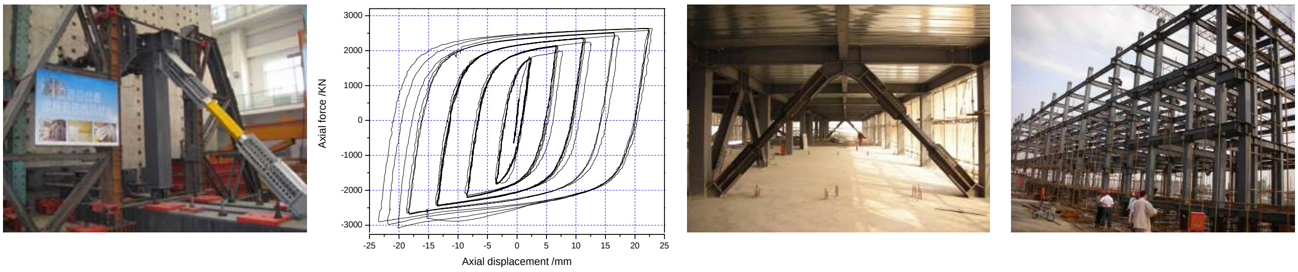


Figure 2 Scenarios of the test of frame with BRB and in the Beijing Tonghui Jiayuan Building

Buckling restrained brace (BRB) has good energy dissipation capability and is readily connected with frame. The performance of BRB with various damping force capability and the reliability of the joint were experimentally investigated at HIT. 24 BRBs have been incorporated into the Beijing Tonghui Jiayuan Building, which is a six story steel moment frame. All the information of this study is shown in Figure 2.

3 SMART DAMPING CONTROL SYSTEMS

Since the middle of 1990s, Ou and his group researched smart damping control, including MR control systems (Ou, 2004), SMA -based dampers (Mao, 2006), PZT-based variable friction dampers (Ou, 2004) and magnetostrictive Tefernol-D/epoxy composites and their dampers.

3.1 MR dampers and their applications

Ou (Ou, 2004) has systematically researched MR control systems, including the fabrication and properties of MR fluids, the design method of MR damper, the electromechnical properties and modeling of MR dampers. In 2004 and 2005, MR dampers have been implemented into cables of the Shandong Binzhou Yellow River Highway Bridge to mitigate the wind-rain-induced vibration (Liu, 2006), as shown in Figure 3. The in-situ test was carried out and the results indicate that the semi-active MR dampers can achieve further reduction of cable vibration compared with passive-on and passive-off MR dampers. Negative stiffness control and interaction between cable and MR dam pers were observed and further studied. A control algorithm with few observations only for cables was proposed based on the Galerkin’s method.

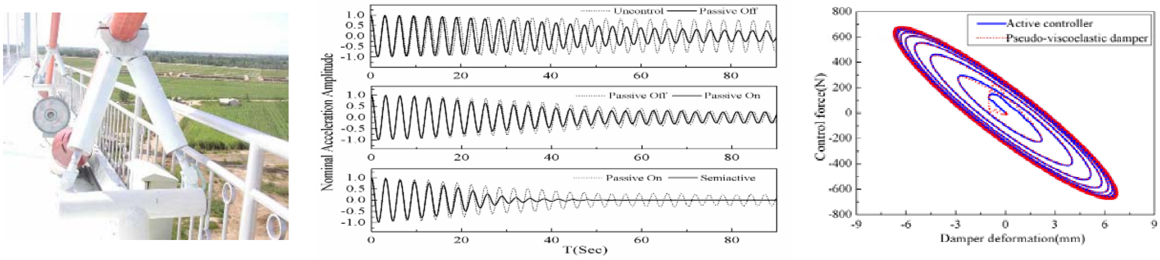


Figure 3 Applications and in-situ test of MR dampers in a cable-stayed bridge

An isolation system consisting of 8 MR dampers and rubber isolators has been installed into Offshore Platform CB32A located in the Bohai Bay to mitigate the ice-induced vibration and seismic response. It is worth mentioned that Ou (Ou, 2004) proposed an isolation system with MR damper for offshore platforms, as shown in Figure 4. The filed measurement indicates that the damping ratios of offshore platform incorporated with MR damper-based isolation between jacket legs and platform increase. The pictures of MR dampers at this offshore platform and are shown in Figure 4.

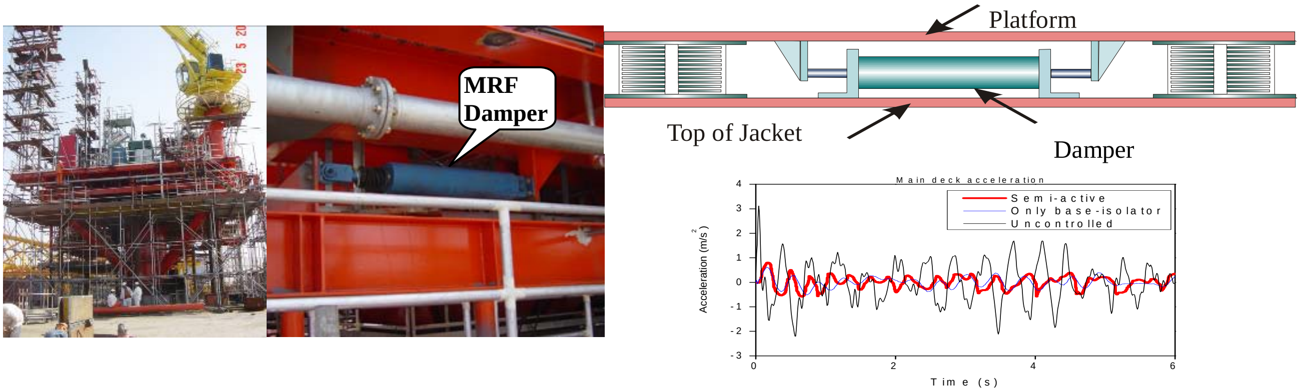


Figure 4 Applications and in-situ test of MR dampers in a cable-stayed bridge

Pounding between the adjacent superstructures has been a major cause of highway bridge damage in the past several earthquakes. Pounding reduction of highway bridges subjected to earthquake ground motions by using MR dampers were tested (Ou and Li, 2008). A series of shaking table tests on a 1:20 scaled base-isolated bridge model were performed to investigate the effects of pounding of the bridge. The test specimen on the shaking table and the results are shown in Figure 5. It can be seen from Figure 5 that the acceleration is very large when pounding occurs, while displacement is not so large. The pounding phenomenon of the bridge incorporated with semi-active MR damper disappears. Comparison of semi-active control, passive-on and passive-off indicates that semi-active control can achieve further reduction than the passive control strategies. The pounding phenomenon of the bridge with passive-off control is still observable. The comparison between experimental results and analytical results is also shown in Figure 5. It can be seen from Figure 5 that there is discrepancy between experimental results and analytical results. The models of concrete and MR damper suffering from pounding should be further studied.

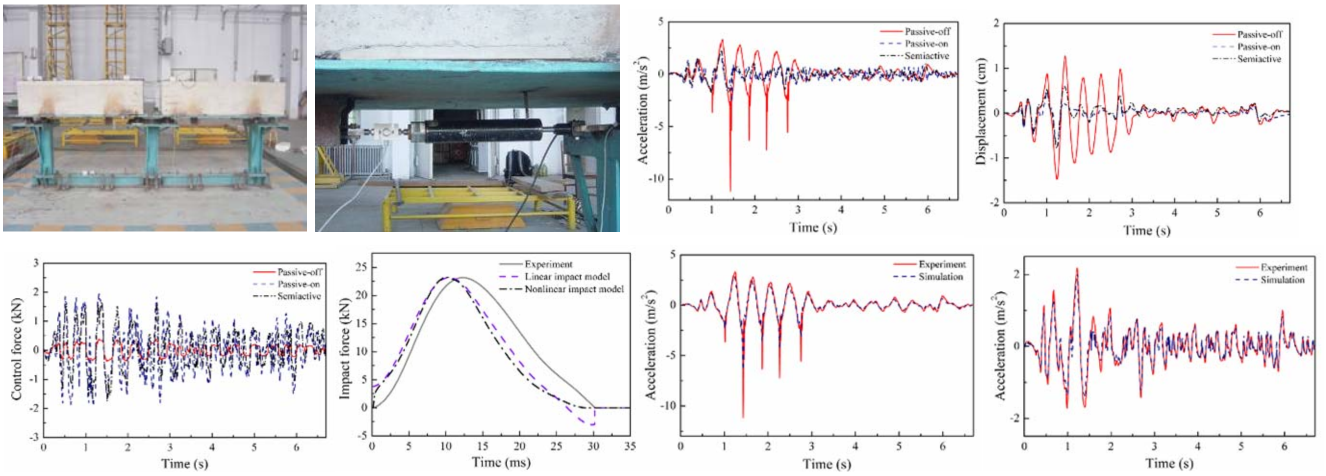


Figure 4 Control of pounding effects of bridges using MR dampers

3.2 Magnetostrictive Tefernol-D/epoxy composites and –based variable friction damper

As a giant magnetostrictive material, Terfenol-D is capable of saturation magnetostriction of 1000~1500ppm at room temperature and relatively small applied field. But its brittleness and large eddy current losses at high frequencies prevents it from applications. Recent two years, Dong et al (2008) proposed the magentostrictive composite (MTDC) materials, which are composed of Terfenol-D particles dispersed within a polymer matrix, present high advantages respect to the monolithic magnetic material, an insulating layer was formed by the matrix between the particles which increases the resistivity and reduces eddy current losses at high frequencies. Moreover, the composite form is substantially tougher and easier to manufacture than the monolithic Dong et al (2008) studied the MTDC and properties of the composites were experimentally investigated. The results indicate that the properties of MTDC are much better than that of the Tefernol-D, as shown in Figure 6. Furthermore, a variable friction damper using the MTDC as actuator was developed and used to suppress the oscillation of cables, as shown in Figure 6. It can be seen from Figure 6 that the variable friction damper can further mitigate the cable vibration than passive friction damper even with the same maximum damping force.

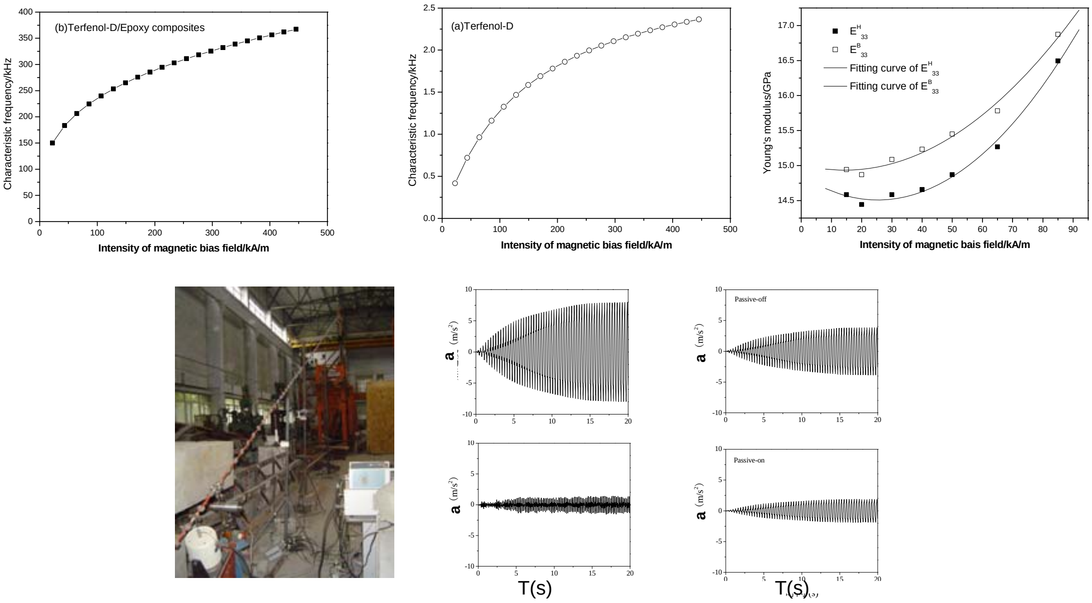


Figure 6 Cable vibration control using magnetostrictive composites-based smart damper

4. NONLINEAR STRUCTURAL VIBRATION CONTROL

Most current research on structural control has been restricted to linear structures. However due to the inelastic deformation under intense ground motion, control of structural nonlinear vibration has received considerable attention recently. Li (2008) systematically studied the structural nonlinear vibration control using artificial intelligent technique combining with slide mode control. First, the adaptive fuzzy sliding mode (AFSM) control algorithm was proposed to control structural nonlinear vibration combining sliding mode control and adaptive fuzzy control. Since all states of structural nonlinear vibration were needed to compute the AFSM control force, based on few measured output the dynamical neural network (DNN) observer was designed to approximate the arbitrary nonlinear dynamic system, which led to the output feedback control of structural nonlinear vibration using the intelligent control algorithm as shown in Figure 7. Robust analysis was also performed. Additionally, DNN was used to identify the nonlinear structure with faults. Based on this DNN model, the corresponding fault tolerance controller was proposed to control structural nonlinear vibration. The simulation is performed on the nonlinear Benchmark structure. The results show that AFSM control is very suitable and robust for the control of structural nonlinear vibration. The DNN observer can also estimate total states. The proposed DNN fault tolerance controller is able to control structural nonlinear vibration in case of actuator faults. Based on above active control results, MR damper was used to realize semi-active control of structural nonlinear vibration.

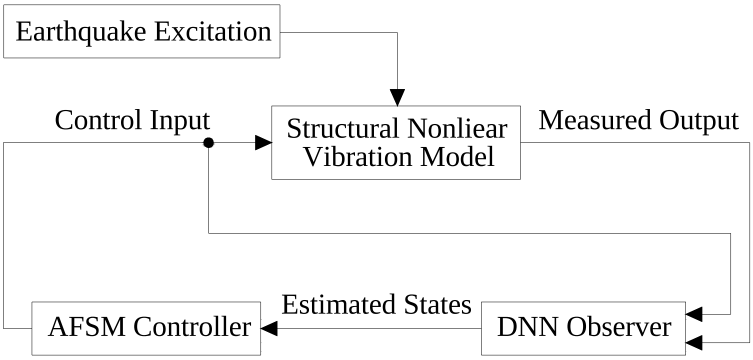


Figure 7 Control block diagram of AFSM controller using DNN observer

Finally, MR rotary brake was used to mimic the plastic hinge to establish a nonlinear vibration model, as shown in Figure 8. The hysteretic loops of different nonlinear behaviors were realized through the control of voltage input to the MR rotary brake, which were shown in Figure 9. Furthermore, linear behavior can also be realized by maximizing the voltage input to the MR rotary brake, as shown in Figure 9(e). MR damper was incorporated into the test model to implement the semi-active control. Test results indicate that the structural nonlinear vibration model can be easily recovered to initial state without any cost after nonlinear vibration tests. Through controlling the input voltage to MR rotary brake, different nonlinear behaviors can be achieved. The above intelligent algorithms were also verified to be effective for the control of structural nonlinear vibration, as shown in Figure 10 and Figure 11.

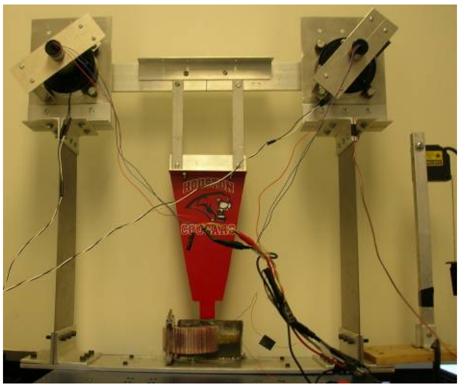
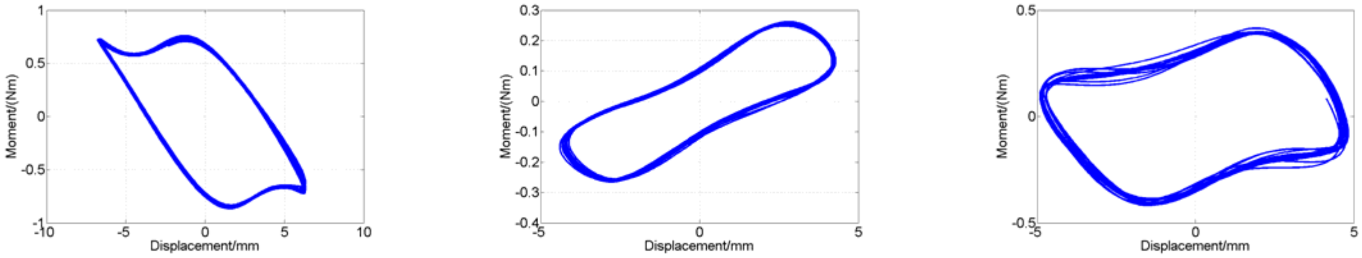
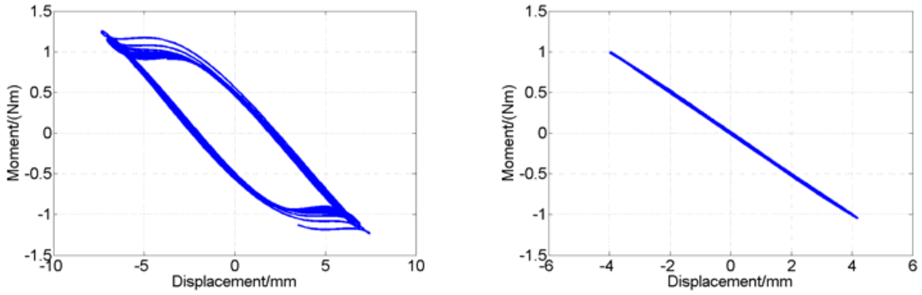


Figure 8 Structural nonlinear vibration model with MR damper

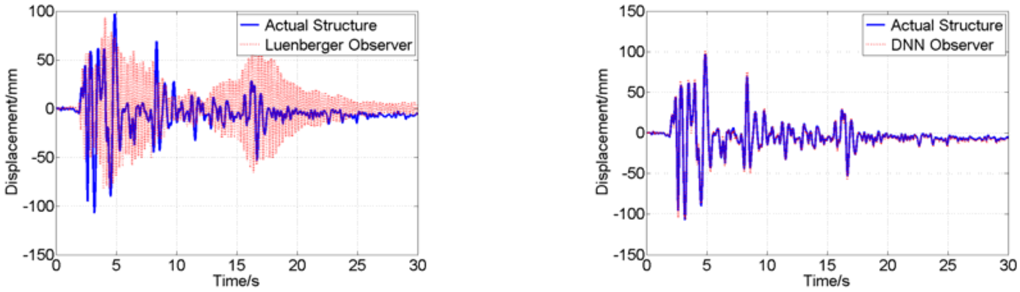


a) Case 1 b) Case 2 c) Case 3



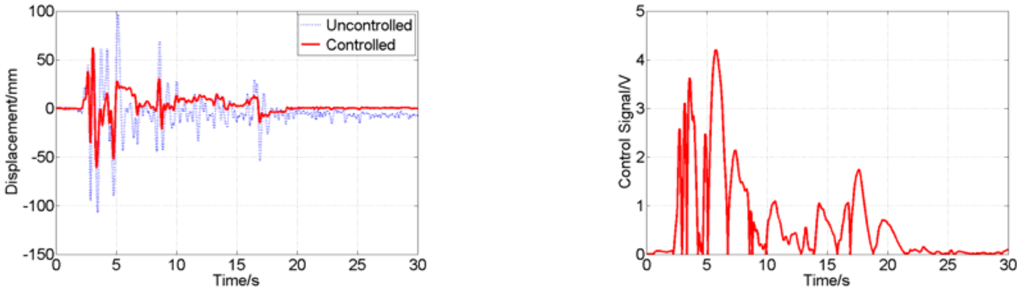
d) Case 4 e) Case 5

Figure 9 Different nonlinear behaviors of structural nonlinear vibration model



a) Luenberger Observer b) DNN Observer

Figure 10 Experimental results of observers of structural nonlinear vibration model

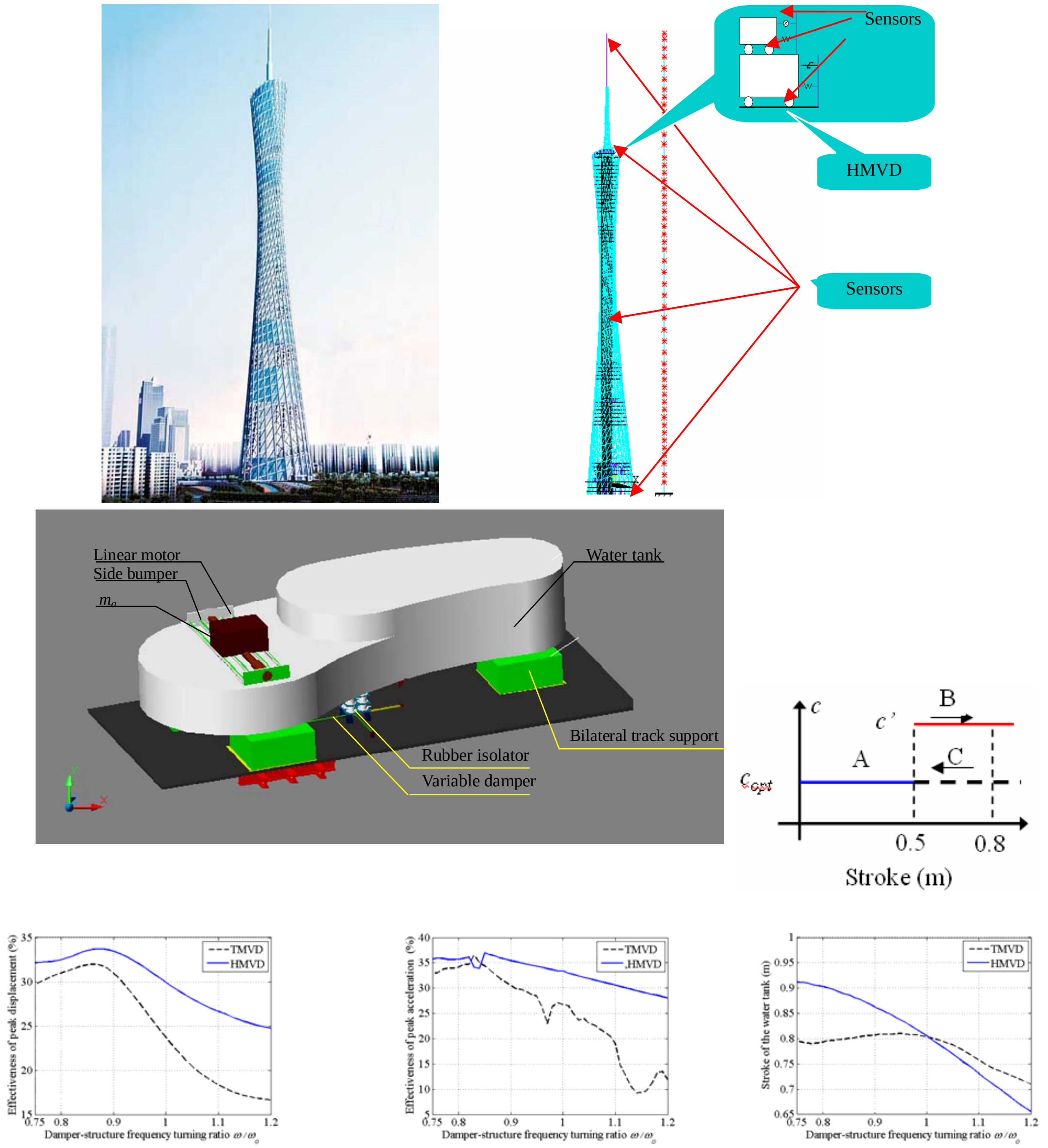


a) Control Effect b) Control Signal

Figure 11 Experimental results of controller of structural nonlinear vibration model

5. HYBRID CONTROL SYSTEM OF THE NEW GUANGZHOU TV TOWER

The Guangzhou New TV Tower (GNTVT) currently being construction in Guangzhou, China, is a supertall tube-in-tube structure with a height of 610 m. It comprises a reinforced concrete inner tube and a steel outer tube with concrete-filled-tube (CFT) columns. There are 37 floors connecting the inner tube and the outer tube that serve for offices, entertainment, catering, tour, and mainly, emission of television signals. The outer tube consists of 24 CFT columns, uniformly spaced in an oval while inclined in the vertical direction. The oval decreases from 50m×80m at the ground to the minimum of 20.65m×27.5m at the height of 280m, and then increases to 41m×55m at the top of the tube (454m). The inner tube is in oval shape as well with a constant dimension of 14m×17m in plan, while its centroid differs from the centroid of the outer tube. This hyperbolic shape makes the structure vital and attractive in aesthetics while complex in mechanics. The picture of the New Guangzhou TV Tower is shown in Figure 12.



(a) Control effectiveness of peak displacement

(b) Control effectiveness of RMS displacement

(c) Stroke of the water tank

Figure 12 The hybrid AMD on the New Guangzhou TV Tower

A hybrid active mass damper (AMD) system was designed for this tower by the team of Guangzhou University and the Division of Shenzhen Graduate, Harbin Institute of Technology. The hybrid AMD system consisted of two tuned mass dampers (TMDs) with a mass of 500t each and two AMDs with a mass of 50t each. For limitation of stroke, a variable damping system was attached to the TMD, i.e. optimal damping ratio was employed for the TMD when the structure subjects to small wind loads, while large damping ratio rather than optimal damping ratio was used when the tower suffers from a strong wind for the limitation of stroke of TMD. Thus, the control effectiveness of TMD will decrease when the tower is attacked by a strong wind. To solve this problem, an AMD system with a mass of 50t and an actuator of force capability of 6t is designed to be installed on the top of the mass of TMD. Simulation results are shown in Figure 12. The results show that the hybrid AMD system can effectively reduce the wind-induced vibration of the tower even the damping ratio of TMD larger than the optimal damping ratio. The robust of the control system was also investigated by decreasing by or increasing by stiffness matrix of 15%. The results indicate that the AMD can improve the robust performance of the TMD, including uncertainties of structure and TMD.

6. FAILURE MODE CONTROL

Different failure modes make one structure have different reliability. For example, the frame is normally designed to make beam first damaged, then columns, last joints. For this topic, searching failure modes is the first consideration. Following two criteria are employed to searching for failure modes, i.e. $|K|=0$ and $\Delta \leq [\Delta]$. The failure modes can be readily found using these two criteria. An reinforced concrete frame was employed as the numerical study and preliminary results have been obtained.

7. CONCLUSIONS

Structural control is an effective technology to improve seismic and wind resistance of structures. Passive control is conveniently incorporated into structures with low cost and high reliability. After the 5.12 Wenchuan Earthquake, this technology will be more extensively used in important structures. Generally, smart damping control can achieve further reduction than passive control. In the future, the integrated semi-active control systems should be developed, which make this technology be simply, low cost and easily maintenance in practical structures. Due to readily replacement, structural control techniques can be used to control failure mode in the future. The failure mode control can also be realized by using optimal arrangement of components.

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REFERENCES

Liu M (2006). Vibration control of stay cables using magnetorheological fluid dampers and superelastic shape memory alloy dampers, PhD Thesis, Harbin Institute of Technology

Li J. L. (2008) Damping force models and applications of metal dampers used in structural passive energy dissipation, PhD Thesis, Harbin Institute of Technology (in Chinese)

Li L. Y. (2008). Study of structural nonlinear vibration control. PhD Thesis, Harbin Institute of Technology (in Chinese)

Mao C. X. (2006). Integrated systems of structural seismic damage monitoring and control, PhD Thesis, Harbin Institute of Technology (in Chinese)

Ou J. P. (2004). Advances of structural control and monitoring of civil infrastructures in the mainland of China. Proceedings of 4th Workshop on Structural Control and Monitoring, New York,, USA （Keynote lecture）

Ou J. P. and Li H (2008), Smart Materials, Devices and Structural Systems, Report of China Panel, IASCM, Proceedings of the 5th Workshop on Structural Control and Monitoring, Dalian, China