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Structural Health Monitoring and Intelligent Vibration Control of Cable-Supported Bridges: Research and Application

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Abstract

Advances in structural health monitoring and intelligent vibration control technologies can have a great impact on the performance enhancement of civil engineering structures. In Hong Kong, a sophisticated long-term monitoring system has been devised by the HKSAR Highways Department to monitor structural performance and health conditions of three cable-supported bridges and monitoring systems for two new long-span bridges are also being developed. Implementation of these on-structure monitoring systems motivates associated technological and methodological investigations which are outlined in this paper. Newly emerging auto-adaptive and intelligent materials offer enormous potential for developing smart damping devices for vibration control of civil structures. Successful application of smart magneto-rheological (MR) dampers has recently been realized in the cable-stayed Dongting Lake Bridge for mitigating rain-wind-induced cable vibration. Experience and lessons learned from this engineering practice are summarized in this paper.

Keywords: *cable-supported bridge, structural health monitoring, intelligent vibration control, instrumentation system, smart damper*

1. Introduction

The next stage of development of structural engineering technologies will lead to a new generation of structures, which may be referred to as third-generation structures (Teng *et al.*, 2003), based on the classification of ancient non-engineered structures as the first generation and modern structures as the second generation. The third-generation structures are expected to be intelligent in the sense that they are able to continuously monitor their own state of health and activate control devices when necessary to minimize the effects of extreme loadings (e.g., earthquakes, strong winds, fires and land slides) to ensure desirable structural performance. The technological basis for the third-generation structures is formed by integrating different advanced and innovative technologies including material, sensor, control, information, communication and measurement technologies. In the transition period to full realization of the third-generation structures, the associated technological developments, for example, advances in intelligent structural health monitoring and vibration control technologies, can have a great impact on the performance enhancement of existing structures.

Solid progress is currently being made around the world on a number of fronts for the development of the technological basis for the third-generation structures. The third-generation structures shall be equipped with an integrated monitoring system that will be able to detect structural deterioration and damage and provide early warning of structural failure. In Hong Kong, a sophisticated long-term monitoring system, called *Wind And Structural Health Monitoring System* (WASHMS), has been devised by the HKSAR Highways Department to monitor the structural performance and evaluate the health and safety conditions of three long-span cable-supported bridges – the suspension Tsing Ma Bridge and the cable-stayed Kap Shui Mun Bridge and Ting Kau Bridge. This integrated on-line monitoring system with more than 800 sensors permanently installed on the bridges is deemed to be the most heavily instrumented bridge project in the world. Also, on-structure monitoring

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systems for other two new long-span bridges in Hong Kong – the cable-stayed Stonecutters Bridge and Shenzhen Western Corridor are also being developed. From the point of view of structural health monitoring, raw data are rarely of direct benefit. Its true value is predicated on the ability to extract information and knowledge useful for decision support or exploration on structural health status. Implementation of these monitoring systems also highlights the necessity for developing practical damage assessment methodologies suitable for large-scale bridge structures. Research activities towards this direction are presented in the next section.

An idealized monitoring system envisaged for the third-generation structures should integrate both sensing and actuating elements which are able to activate control devices to protect the structure from extreme loadings of natural and man-made hazards. In this way, the monitoring system provides not only the state of health of the structure but also information for the control system to make decisions with regard to its activation under extreme loadings. Advanced research in materials science has resulted in discoveries of innovative intelligent materials with unusual properties. These intelligent materials offer potential for developing smart control devices for civil engineering structures to reduce excessive structural vibration, increase human comfort, and prevent catastrophic structural failure due to strong winds and earthquakes. For example, making use of controllable yield strength of magneto-rheological (MR) fluids, smart MR devices can be devised as semi-active dampers/actuators for civil engineering applications. A collaborative research among The Hong Kong Polytechnic University, Central South University (China) and University of Illinois at Urbana-Champaign (USA) has resulted in implementation of 312 semi-active MR dampers to the cable-stayed Dongting Lake Bridge for rain-wind-induced cable vibration control. This is the world's first practical application of the MR-based smart damping technology in bridge structures. Before and after the full implementation, a series of in-situ vibration tests and measurements have been carried out to understand actual dynamic performance of the cables using MR dampers, to determine preferred damper setup, and to validate control effectiveness of this unprecedented damping technique. Experience and lessons learned from this pioneering engineering application are presented in the third section.

2. Structural Health Monitoring of Cable-Supported Bridges

2.1. Background

In Hong Kong, the development of a new international airport and port extension motivated the construction of a new transportation network. This network comprises three major cable-supported bridges, namely, the suspension Tsing Ma Bridge with 1377 m main span, the cable-stayed Kap Shui Mun Bridge with 430 m main span, and the cable-stayed Ting Kau Bridge consisting of two main spans of 475 m and 448 m respectively. The bridges were designed to serve 120 years and to satisfy stringent criteria resulting from Hong Kong's typhoon wind climate. After completing construction in 1997, the three bridges were instrumented with the on-structure monitoring system WASHMS (Lau *et al.,* 1999; Wong *et al.*, 2000). In addition, monitoring systems for other two new long-span bridges in Hong Kong - the cable-stayed Stonecutters Bridge and Shenzhen Western Corridor are also under development (Wong, 2003).

The WASHMS is composed of five subsystems, i.e., sensory system, data acquisition system, data processing and analysis system, computer system, and cabling network system. The sensory system consists of over 800 sensors permanently installed on the bridges, including strain gauges, displacement transducers, accelerometers, level sensors, temperature sensors, anemometers, weigh-in-motion sensors, and recently deployed global positioning systems (Wong *et al.,* 2001). The objectives of devising this monitoring system are: (i) to monitor the structural health (safety) conditions of the three bridges; (ii) to provide information for facilitating the planning of inspection and maintenance activities; and (iii) to verify design assumptions and parameters for future construction of cable-supported bridges.

2.2. Data Management System

Because the WASHMS involves a large number of sensors and accomplishes continuous 24-hour monitoring per day (the raw data are acquired at a rate of 140.0 MB per hour for the three bridges), the data management is a challenging task. The large volume and high dimensionality of acquired data from the WASHMS makes manual probing almost impossible. Since the geographic information system (GIS) technology provides an efficient computerized database management system for capture, storage, retrieval, analysis, and display of temporal-spatial data, it has been adopted as a platform for developing a visualized monitoring and management system in The Hong Kong Polytechnic University (Ko *et al.*, 2001). Fig. 1 shows the user interface of this system. When applying GIS to bridge health monitoring, it can provide a complete picture of the bridge information including structural property knowledge, loading/response measurement data, and environment

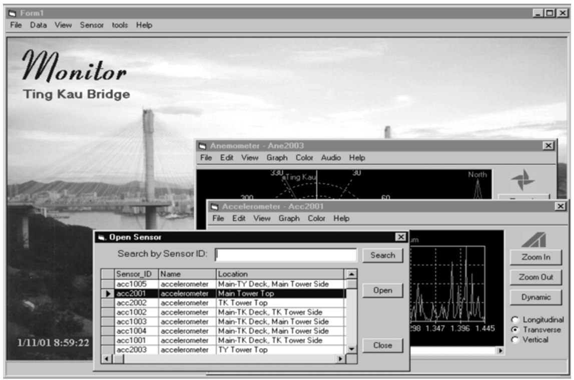


Fig. 1. GIS-Based Monitoring System

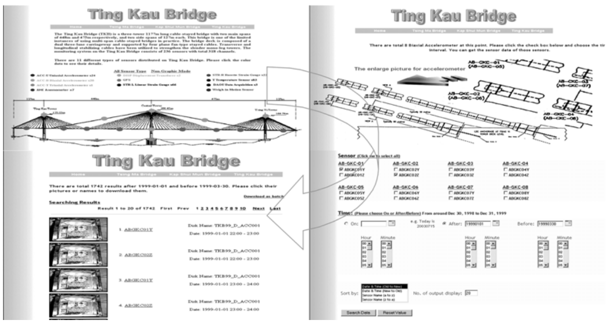


Fig. 2. Illustration of Data Management System

condition information in a multi-level format. One-year continuously collected data from 947 sensor channels of the WASHMS has been incorporated into the data management system. With this system, the data can be conveniently retrieved by clicking visualized sensor(s) and selecting desired time period as shown in Fig. 2.

From the point of view of structural health monitoring, raw data are rarely of direct benefit. Its true value is predicated on the ability to extract information and knowledge useful for decision support or exploration on structural health status. The emerging field of knowledge discovery in databases (KDD) provides such a tool to create an object-oriented information architecture for diagnostic inferring. The KDD technology allows automating the entire process of data analysis, implementing specific algorithms for pattern extraction from data, and integrating the inferred knowledge from data with damage-inferring indices for structural health assessment and decision making. Research effort is currently being devoted to integrating the KDD technology with the developed data management system.

2.3. Feasible Damage Detection Methodologies

Commissioned by the HKSAR Highways Department, a research team in The Hong Kong Polytechnic University has made a comprehensive feasibility study on using measured dynamic characteristics from the WASHMS to detect structural damage in the three bridges (Ko *et al.,* 2000a; Wang *et al.,* 2002). As part of the WASHMS sensory system, a considerable number of accelerometers (106 channels in total) have been permanently installed on the three bridges to measure dynamic characteristics of the three bridges. Fig. 3 illustrates the deployment of accelerometers in the Ting Kau Bridge, where 24 uni-axial accelerometers, 20 bi-axial accelerometers and 1 tri-axial accelerometer (a total of 67 channels) were installed at the deck of the two main spans and the two side spans, the longitudinal stabilizing cables, the top of the three towers, and the base of central tower to monitor ground excitation and dynamic response of the bridge. Besides these fixed vibration transducers, a 16-channel portable computer-controlled data acquisition system in operation with 5 uni-axial accelerometers and 8 bi-axial accelerometers have also been used as supplementary instrument for regular monitoring of local vibration characteristics of the bridges. Therefore, development of practical vibration-based damage detection methods in accordance with the WASHMS is an urgent need.

The feasibility study is conducted by the use of precise 3D finite element models of the bridges. The majority of

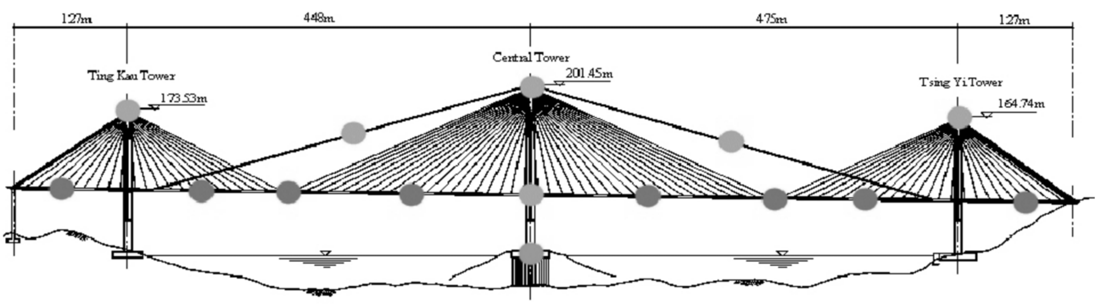


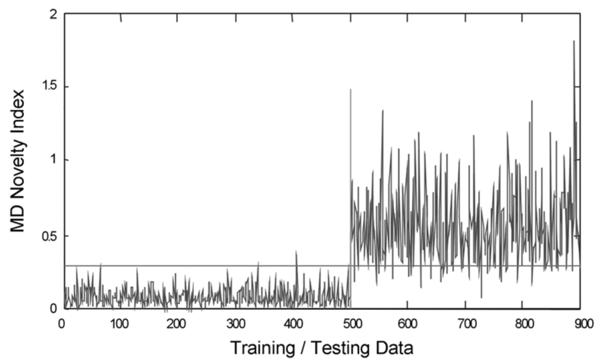
Fig. 3. Deployment of Accelerometers in Ting Kau Bridge for Long-Term Monitoring

vibration-based damage detection methods need a refined or validated analytical or finite element model as baseline reference. For long-span cable-supported bridges, however, developing a precise structural model suitable for damage detection use poses a difficult task. The concept of damage-detection-oriented modeling for large-scale structures has been proposed (Ko *et al.*, 1999). A damage-detection-oriented model should meet the requirements that: (i) the model is accurate enough through comparison of the computed and measured modal parameters; (ii) the spatial configuration (geometric and sectional properties, boundary and support conditions) of the original structure remains in the model; as a result, using this model will not blur the damage location in simulating any member-level damage; (iii) the stiffness contribution of all individual structural components is independently described in the model, so the sensitivity of global and local modal properties to the material or geometric parameters of any structural component can be computed accurately; consequently, damage occurring in any structural component can be directly simulated in the model.

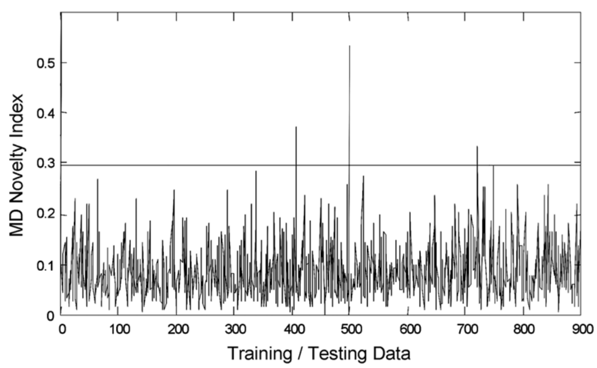
In the feasibility study, a neural network based hierarchical identification strategy has been proposed for structural damage detection of the three bridges instrumented with the WASHMS. This multi-stage diagnosis strategy aims at successive detection of the occurrence, type, location and extent of the structural damage (Ko *et al.*, 2002a). Because the bridges involve 5,000 to 20,000 structural components each, damage detection based on optimization and parameter identification procedures is almost impossible. When the conventional methods are applied to large-scale redundant structures, the ill-conditioning and non-uniqueness in the solution of inverse problems are inevitable difficulties. The proposed neural network based multi-stage diagnosis strategy is more feasible for the damage detection of large-scale bridges because: (i) different identification algorithms (different neural network architectures) and different sensor deployment schemes can be designed in view of the objectives of different stages; (ii) the hierarchical identification strategy can achieve Level-I (damage occurrence) or Level-I-and-II (damage occurrence and region) detection when only modal data from a few measurement points are available; (iii) the neural network based methods can use to the utmost extent, information from forward problems and avoid direct solution to inverse problems.

The feasibility study concludes that because of low modal sensitivity of the bridges to structural damage, only those methods which are highly tolerant of incompleteness of measured data, measurement noise, modeling error and structural uncertainty are applicable to large-scale bridge structures for vibration-based damage identification. Research emphasis has therefore been placed on designing modeling-error-insensitive neural network input vectors and devising noise-tolerant probability measures for damage detection purpose (Ni *et al.,* 2001a; 2002d). The feasibility study also indicates that the WASHMS suffices to provide measurement data for damage alarming by using a neural network based novelty detection technique that is highly tolerant of uncertainty/noise and independent of structural model (Ko *et al.*, 2000b).

The neural network based novelty detection technique shows great promise for structural damage occurrence detection in the three bridges in operation with noisy measurement data. When using only measured natural frequencies, the novelty detector is able to signal the damage occurrence even if the damage-caused frequency change level is less than the corrupted noise level (Chan *et al.*, 2000). When both measured frequencies and a few modal components are used, the proposed method can alarm minor structural damage. Working towards practical use, this technique has been improved applicable for damage region identification (Ni *et al.*, 2001b) and, more importantly, capable of distinguishing anomaly due to

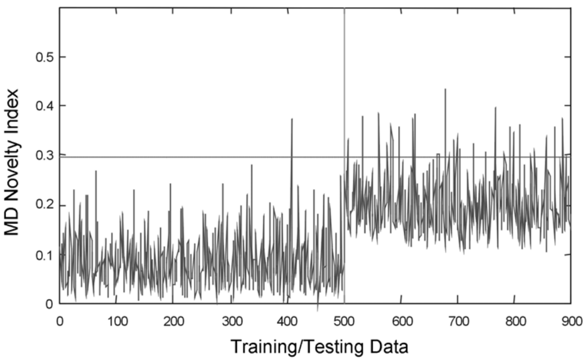


(a) Original Novelty Index

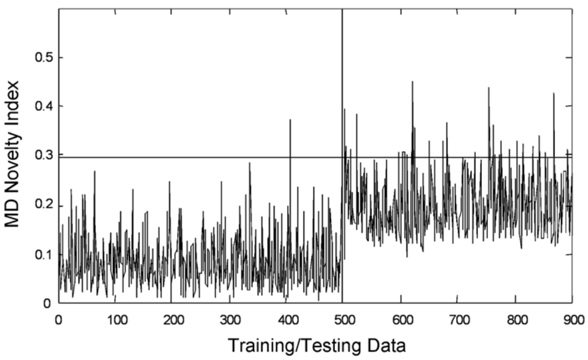


(b) Improved Novelty Index

Fig. 4. Influence of Noise on Novelty Index Performance in the Absence of Damage



(a) Identical Noise Level in Training and Testing



(b) Different Noise Levels in Training and Testing

Fig. 5. Performance of Improved Novelty Index for a Damage Scenario

structural damage from that due to alteration of noise conditions (Ni *et al.*, 2002c). Fig. 4 illustrates a comparison of performance of the original and improved novelty indices in the absence of damage but different noise levels in training and testing. The former wrongly displays shift even when only noise level alters between the two phases, whereas the latter does not exhibit shift unless damage occurs. Fig. 5 shows the performance of the improved novelty index for a specific damage case. It is seen that the predicted shift (damage severity) in the case of identical noise level for training and testing is the same as that in the case of different noise levels for training and testing, indicating the capacity of eliminating noise influence in damage alarming.

2.4. Modeling of Environmental Variability

Vibration-based structural health monitoring approaches use measured change in modal parameters to evaluate change in physical properties that may indicate structural damage or degradation. In reality, however, a civil structure is subjected to varying environmental and operational conditions such as traffic, humidity, wind, solar-radiation and most important, temperature. These environmental

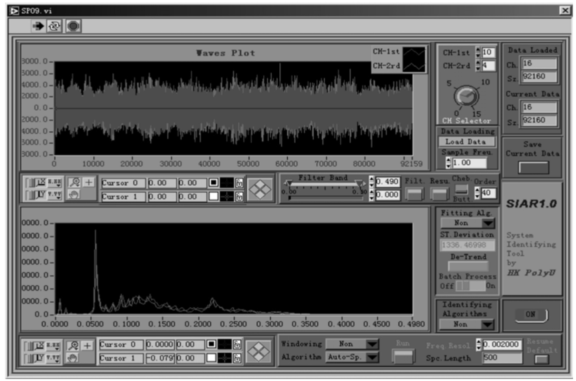
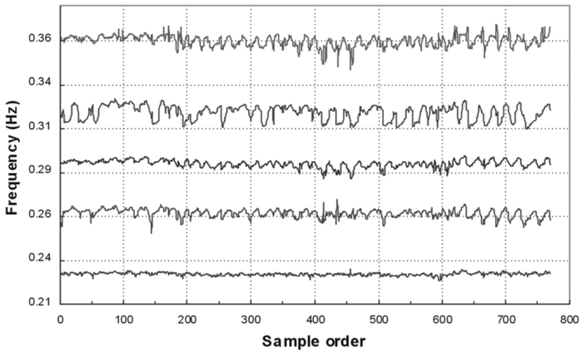


Fig. 6. Automatic Modal Identification Software in VI Style

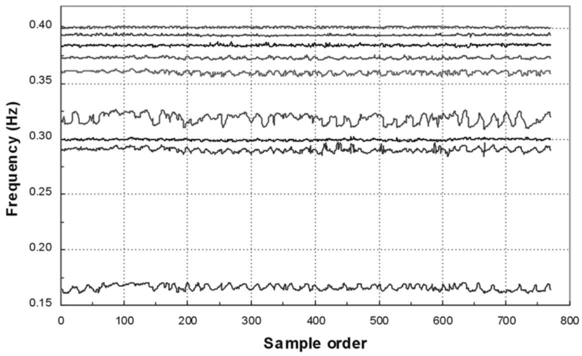
effects also cause changes in modal properties which may mask the changes caused by structural damage. For reliable performance of damage detection algorithms, it is of paramount importance to discriminate abnormal changes in dynamic features resulting from structural damage from normal changes due to the natural variability. Because the three bridges are instrumented with a wide variety of sensors, it is possible to quantitatively understand the effects of various environmental and operational factors (temperature, wind, traffic, etc.) on the modal properties, and a multivariate correlation analysis can formulate a variability model to simultaneously account for all the environmental effects. Such a variability model is extremely useful for vibration-based damage detection of real-world civil structures with uncertainty.

In order to study the environmental variability of modal properties, an automatic modal identification program is developed for continuous extraction of modal parameters of the three bridges (Ni *et al.*, 2003b). The program employs Complex Modal Indication Function algorithm for identifying modal properties from continuous ambient vibration measurements in an on-line manner. As shown in Fig. 6, the software realizes the algorithm in Virtual Instrument (VI) style with the aid of LabVIEW.

Then one-year measurement data, which represent a full cycle of in-service/operating conditions, are recovered from the established data management system for the observation of environmental variability and the correlation study. A total of 770-hour data are used for this purpose, which cover measurements in February, March, June, July, August and December of 1999. Fig. 7 shows the variation of measured modal frequencies from vertically and laterally oriented accelerometers on the Ting Kau Bridge. For this bridge, it is found that the normal environmental change accounts for variation in modal frequencies with variance error from 0.11% to 1.43% for the first ten modes. Fig. 8



(a) From Vertically Oriented Accelerometers



(b) From Laterally Oriented Accelerometers

Fig. 7. Variation of Measured Modal Frequencies

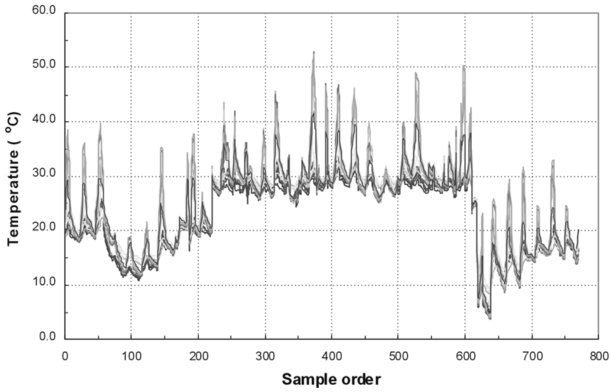


Fig. 8. Variation of One-Hour Average Temperatures from 20 Temperature Sensors

shows the variation of measured one-hour average temperatures at different locations of the Ting Kau Bridge.

The correlation of the measured fourth mode frequencies with the corresponding one-hour average temperatures is illustrated in Fig. 9. It is found that for the first ten modes of the Ting Kau Bridge, the normal variations of the modal properties, due to environmental change, show an inversely proportional trend in modal frequencies with temperature (Ko *et al.*, 2003a).

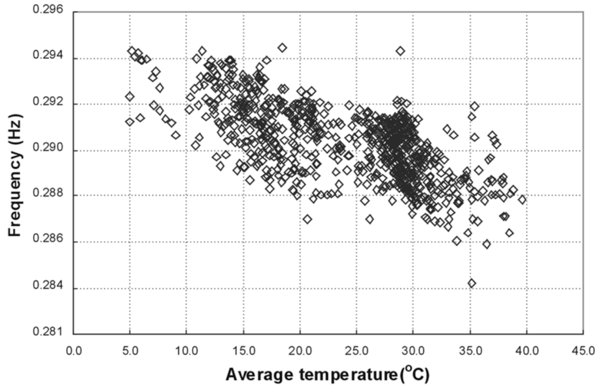
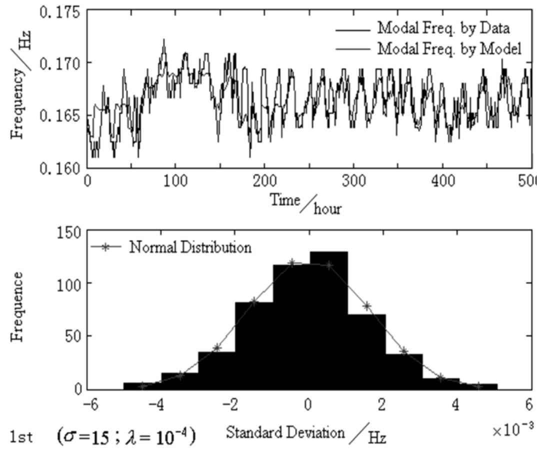
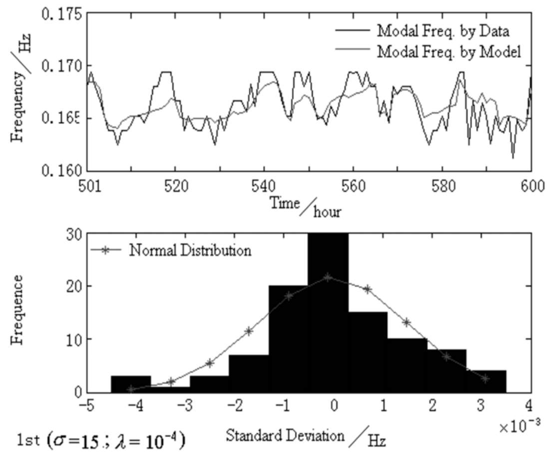


Fig. 9. Measured Fourth Modal Frequency versus Temperature



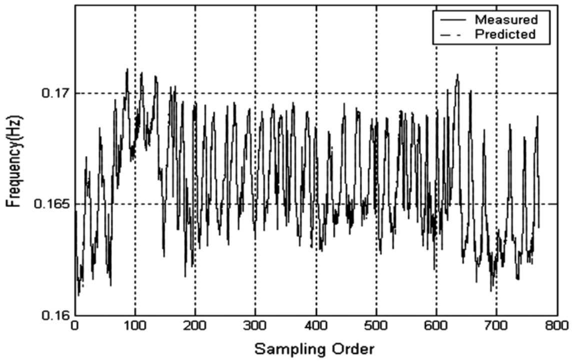
(a) Training Data Set



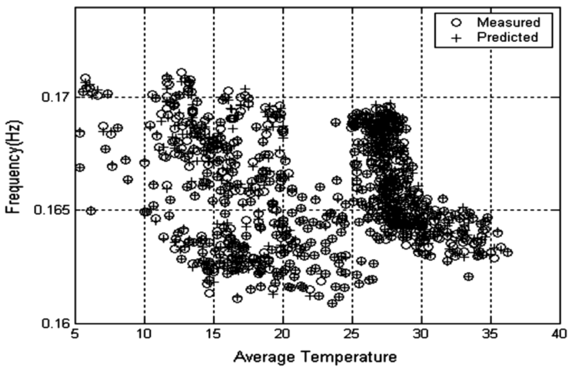
(b) Testing Data Set

Fig. 10. Training and Prediction Using a Nonlinear Regression Model

For comparison, correlation between the measured modal frequencies and temperatures has been analyzed by means of regression models, neural network models, and support vector machine (SVM) models, respectively. Fig. 10 shows

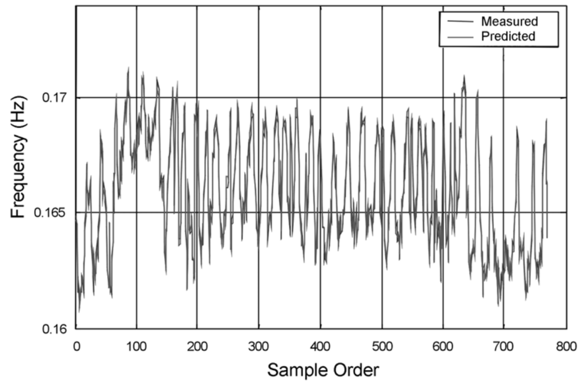


(a) Frequency Sequence

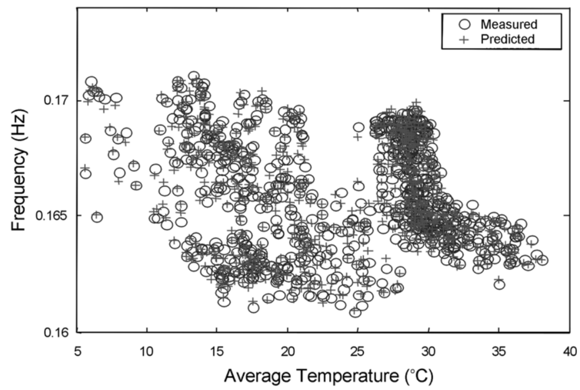


(b) Frequency Versus Temperature

Fig. 11. Measured and Predicted Results by Neural Network



(a) Frequcy Sequence



(b) Frequency Versus Temperature

Fig. 12. Measured and Predicted Results by Support Vector Machine

the training and prediction results for the first modal frequency based on a nonlinear regression model. This model is obtained by ridge regression analysis in kernel feature space using the radial basis kernel function. As illustrated in the figure, the first 500-hour data are used to train the model, while the other 100-hour data are used to examine prediction capacity of the developed model. Fig. 11 shows the measured and predicted natural frequencies for the first mode based on a correlation model in terms of neural network, and Fig. 12 shows the measured and predicted results based on a correlation model in terms of support vector machine. Both the neural network model and the support vector machine model show good capabilities for mapping between the temperatures and modal frequencies for all the one-year measurement data. The well-defined nature of temperature effect on modal properties means that this effect can be eliminated or separated from the measurements, giving the potential for subtle structural damage to be detected.

2.5. Local Damage Detection

For the suspension Tsing Ma Bridge, local damage detection using the measured dynamic strain caused by railway traffic from the WASHMS has been studied (Wang *et al.*, 2003). Measurement data verify that the railway traffic under service conditions affords a localized excitation with statistical uniformity. Dynamic strain data recorded from strain gauges deployed at waybeams supporting the railway track-form are used in this study. Strain time-history segments containing railway traffic induced vibration are separated from the original records for the analysis of strain energy and segmental statistics. The results are then used to extract pattern features and construct statistical parameters.

Cross-energy index and normalized cross-energy index have been formulated in the context of statistical recognition paradigm for local damage detection. The bootstrap method is adopted for estimating confidence intervals of the extracted parameters. Fig. 13 illustrates the cross-energy index for 30 selected strain gauges deployed along the Tsing Ma Bridge deck. Fig. 14 shows the evolution of cross-energy index for some selected strain gauges. An abnormal change is alarmed in the figure for the signal from the strain gauge 'SSTLS05' between signal segments 59 and 60. Mean-value confidence intervals of the cross-energy index from bootstrap analysis are plotted in Fig. 15. This figure also indicates the abnormal change of the 24th

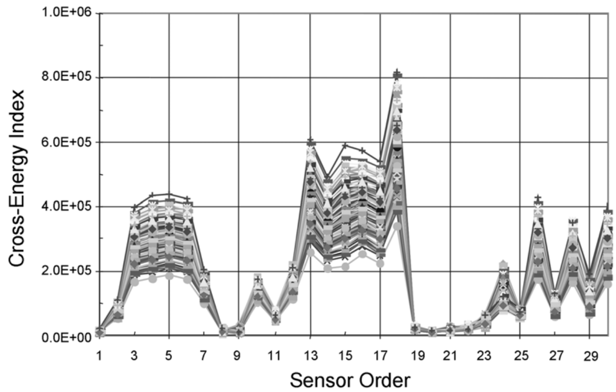


Fig. 13. Cross-Energy Index for Different Strain Gauges

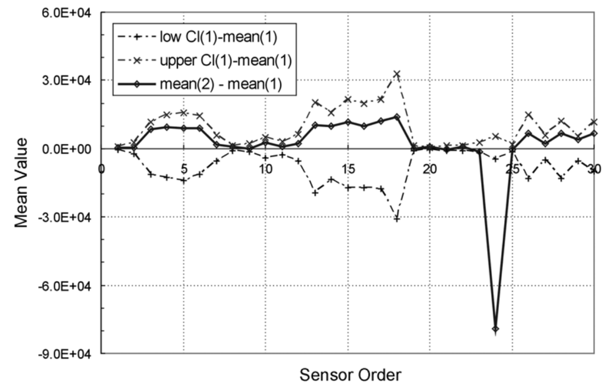


Fig. 15. Bootstrap Value of Cross-Energy Index

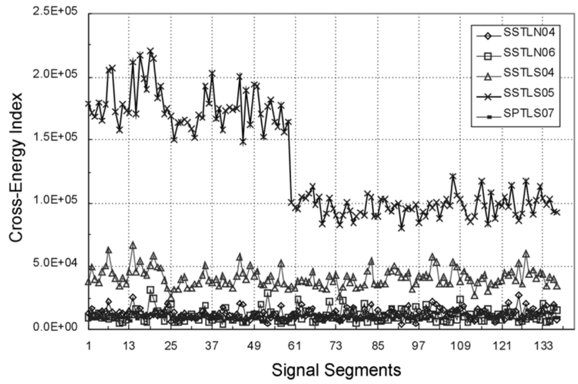


Fig. 14. Evolution of Cross-Energy Index for Selected Sensors

sensor, which is just the strain gauge 'SSTLS05'. All these results show that the proposed energy-based method is capable of alarming anomaly which is caused by either local structural damage or sensor fault.

2.6. Implementation of Optical Fiber Sensors to Tsing Ma Bridge

Optical fiber sensors have the potential to provide true real-time condition monitoring for civil engineering structures. They have several inherent advantages over conventional electrical sensors such as small size, light weight, non-conductivity, fast response, resistance to corrosion, higher temperature capability, and immunity to electromagnetic noise and ratio frequency interferences. Their multiplexing capability makes it practical to undertake distributed sensing and measurements within a structure. Because the WASHMS was implemented six years ago, it has not benefited from the newly commercialized optical fiber sensor technology. To keep up the advancement of this system, a research team from The Hong Kong Polytechnic University in collaboration with the HKSAR Highways Department has recently installed fiber Bragg Grating sensor systems on the Tsing Ma Bridge as supplement to the existing monitoring system (Chan *et al.,* 2003). As shown in Fig. 16 (where the circles indicate the structural regions with optical fiber sensors), a total of 30 Bragg Grating sensors have been installed at the deck cross sections, rocker bearing and suspender of the Tsing Ma Bridge for dynamic strain measurement. Fig. 17 shows the

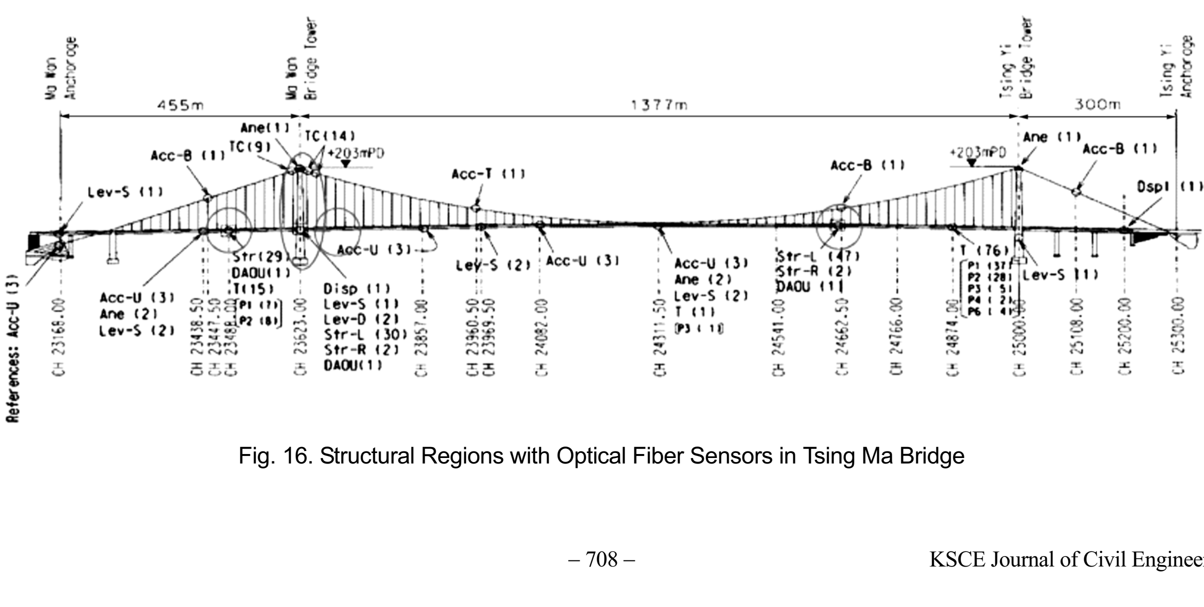


Fig. 16. Structural Regions with Optical Fiber Sensors in Tsing Ma Bridge

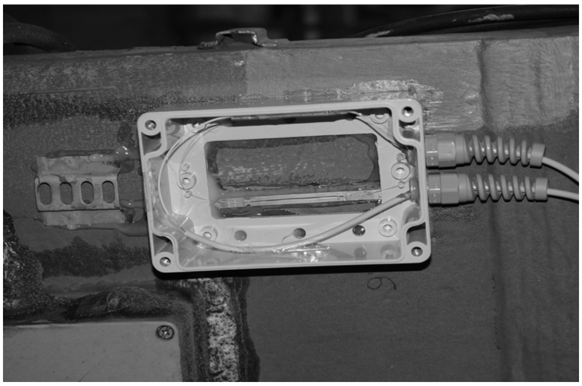


Fig. 17. Attachment of Optical Fiber Sensor to Bridge Deck

attachment of an optical fiber sensor to the bridge deck. All the optical fiber sensors are deployed nearby the existing strain gauges of the WASHMS for comparative study.

3. Intelligent Vibration Control of Cable-Supported Bridges

3.1. Background

Due to large flexibility, relatively small mass and extremely low damping, cables in cable-supported bridges are susceptible to vibration caused by wind, rain and support motion. Unexpectedly large oscillation occurring in cables under specific combinations of wind and rain has been observed in a number of cable-stayed bridges worldwide (Poston, 1998). The large-amplitude vibration may induce undue stresses and fatigue in the cables and in the connections with bridge deck and towers, and invoke the risk of losing public confidence in the bridges. In order to suppress harmful vibration of bridge cables, passive viscous and viscoelastic dampers (hydraulic dampers, oil dampers and rubber dampers) have been used in a number of cable-stayed bridges.

A recent research interest for cable vibration control has been given to semi-active control using magneto-rheological (MR) dampers (Johnson *et al.,* 1999; Lou *et al.*, 2001; Ni *et al.,* 2002a; Johnson *et al.*, 2003). The research has resulted in practical application of 312 MR dampers in the cable-stayed Dongting Lake Bridge for rain-wind-induced cable vibration control (Ni *et al.*, 2003c). The semi-active MR dampers possess some salient advantages over passive viscous dampers for cable vibration mitigation. Firstly, due to different geometric configurations of stay cables on a cable-stayed bridge, the passive dampers of same size can only afford optimal damping to one or a few cables while the vibration in other cables attached with the same dampers may still fail to be suppressed due to insufficient damping. However, the MR dampers of same size can provide optimal or sub-optimal damping to each of the cables by tuning the damper voltage input to proper values (Ni *et al.*, 2003a). This opinion has been evidenced by an observation on the Dongting Lake Bridge during the rain-wind excitation that the MR dampers failed to control some of the cables when they acted as passive dampers without voltage input, and were able to control all the cables when appropriate voltages were applied to the dampers.

Secondly, passive viscous dampers can achieve optimal damping ratio in only one mode of vibration. It is known that rain-wind-induced vibrations in bridge cables are dominated by one of the first few in-plane modes with low frequencies (Poston, 1998; Main and Jones, 2001; Ni *et al.,* 2002b). However, it is currently unclear how to specify *a priori* the preferred mode for a given cable in which optimal performance should be achieved. It was reported that passive dampers used in several cable-stayed bridges were designed with optimal performance for cable vibration mitigation in the first mode but the rain-wind-induced vibrations occurred there in the second or third mode. It was also observed that even two adjacent cables with similar configurations may vibrate in different modes during rain-wind excitation (Ni *et al.,* 2002b). Designing a passive viscous damper for optimal performance in a non-dominant mode may leave the cable susceptible to vibration in dominant mode under rain-wind-excited conditions. Contrarily, the performance of MR dampers can be adjusted even after installation through altering the voltage input to achieve optimal or sub-optimal damping for any desired mode.

In addition to the above advantages when MR dampers are utilized in open-loop control mode, it has also been shown that the semi-active MR dampers with the aid of an appropriate real-time control strategy are able to offer much better damping performance than optimal passive devices for cable vibration mitigation (Johnson *et al.,* 2000, Duan *et al.,* 2003). Dampers are often attached to stay cables unobtrusively near the anchorage at the deck and thus detract minimally from the aesthetics of the bridge. When attached at a reasonable distance from the cable anchorage, even optimal passive dampers may be not sufficient to suppress rain-wind-induced vibration of long-span cables like those on the Stonecutters Bridge with a main span of 1018 m (536 m for the longest stay cable) and the Sutong Bridge with a main span of 1088 m (577 m for the longest stay cable). A recent feasibility study on the Stonecutters Bridge showed that when the damper is installed at 1.0% of the cable length (5.36 m away from the lower end), the maximum damping ratio achieved by

Fig. 18. Cable-Stayed Dongting Lake Bridge

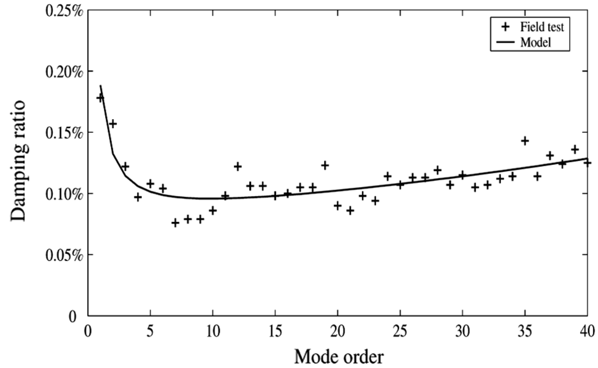


Fig. 19. Modal Damping Ratio of Free Cable

optimal passive damper is only about 0.3%, which is deemed to be not enough for rain-wind-induced vibration control. In comparison with optimal passive control, however, when semi-active MR damper is instead used at the same location and commanded by an appropriately implemented control system, the cable RMS displacement response can be further decreased by 72% in low noise case and by 66% in high noise case (Ni *et al.,* 2003d).

The Dongting Lake Bridge, as shown in Fig. 18, is a three-tower cable-stayed bridge in Hunan, China. It has a total length of 880 m consisting of two main spans of 310 m each and two side spans of 130 m each. Since its open to traffic in the end of 2000, the bridge has been observed several times to exhibit severe cable vibration under low wind speed and light to moderate rain. The frequent occurrence of such wind-rain-induced cable oscillation has agitated the bridge administrative authority and management engineers who finally accepted to adopt MR-based smart damping technology proposed by the authors for cable vibration mitigation. In order to realize this pioneering application, a series of in-situ vibration tests were conducted before the full implementation. After completing the full implementation, field measurements and real-time semi-active control tests lasting 45 days have also been carried out in the bridge site.

3.2. In-Situ Experiments before Full Implementation

In recognizing that this is the world's first time implementation of MR-based smart damping technique in bridge structures, a series of in-situ experimental investigations have been carried out before the full implementation to understand actual damping performance of the cables before and after using MR dampers, to determine the preferred damper setup, and most importantly, to demonstrate to the bridge owner the control effectiveness of this unprecedented damping technique. The field experimental study covers: (i) modal testing of undamped cables, (ii) vibration tests of an MR-damped trial cable, (iii) field measurements of damped and undamped cables under rain-wind-excited conditions, and (iv) comparative tests of cable-damper systems under different damper setups.

In order to understand the dynamic characteristics of undamped cables, six typical cables were selected to carry out ambient vibration testing and sinusoidal-decay excitation testing (Ko *et al.,* 2002b). Accelerometers were installed in both in-plane and out-of-plane directions at two or three locations for each cable. Based on the measured acceleration response, natural frequencies and damping ratios of the first 40 in-plane modes and the first 40 out-of-plane modes have been identified for each cable by spectral analysis. Fig. 19 shows the modal damping of one free cable. It is observed that the modal damping ratios of the cable are less than 0.2% for all the measured forty modes. According to the Irwin's criterion (Irwin, 1997), the minimum damping ratio in need for suppressing rain-wind-induced cable vibration, which produces the Scruton number greater than 10, is obtained to be ξ_{min}=0.35% for this cable. It is therefore concluded that the inherent structural damping of the cable is insufficient to suppress rain-wind-induced vibration.

One of the six cables was then equipped with two RD-1005 MR dampers for trial testing. As shown in Fig. 20, the two dampers in the angle of 72 degrees with each other were connected with the cable through a supporting pole at the position of 4.2 m (3.7% of the cable length) away from the cable lower end. Four accelerometers, two at the damper location and the other two at 17 m from the cable lower end, were deployed for cable vibration measurement. Movement of the damper piston was measured by two displacement transducers as shown in the figure.

Equivalent modal damping of the cable-damper system was experimentally identified using both ambient vibration

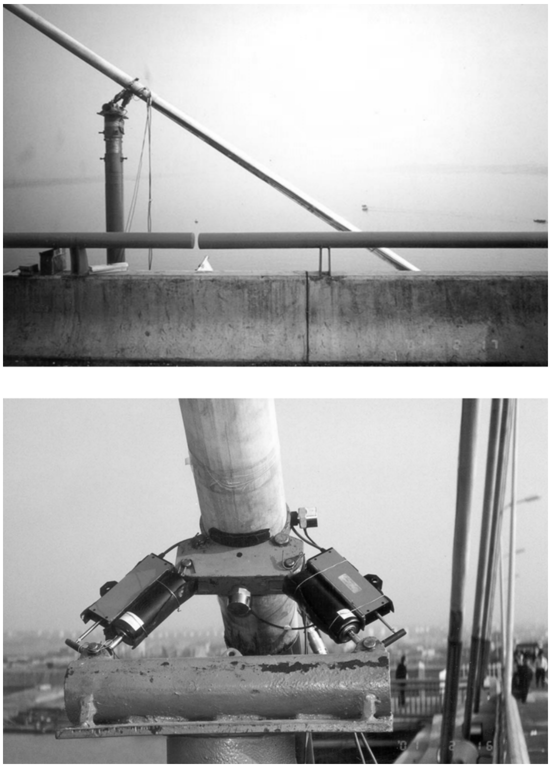


Fig. 20. Cable Incorporating MR Dampers for Trial Testing

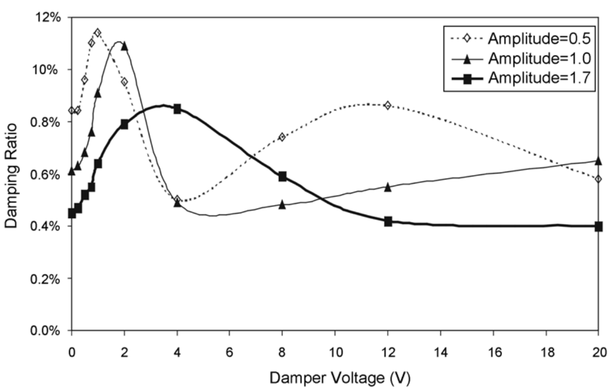


Fig. 21. Damping Ratio of Second Mode versus Voltage Input to Damper

excitation and sinusoidal-decay excitation. In order to study the dependency of modal damping on vibration level and voltage input strength, the tests were conducted under different vibration amplitudes and using a series of voltage inputs to the dampers. Fig. 21 shows the identified damping ratio versus damper voltage strength for the second mode. It is seen that there is an optimal voltage input that achieves maximum modal damping. With the increase of vibration amplitude, the maximum damping value has a slight reduction. Accordingly, the optimal voltage input increases with the increase of vibration amplitude. As a result,

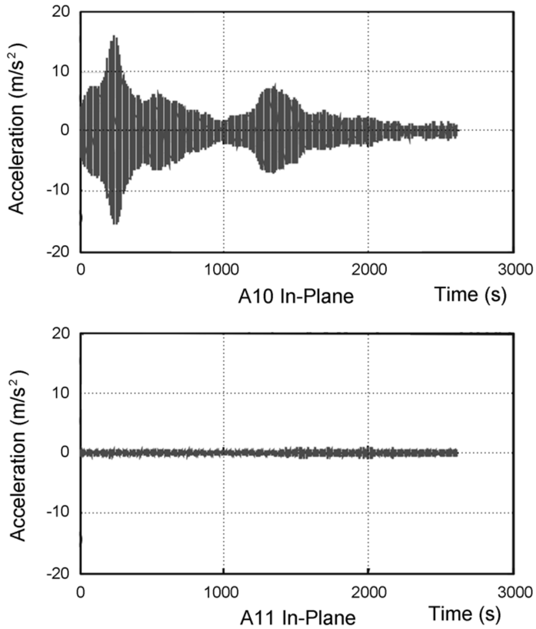
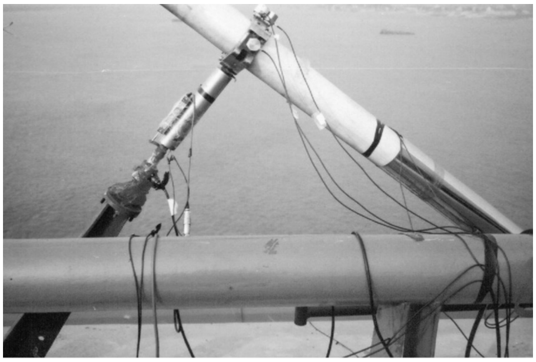


Fig. 22. Response Comparison of Undamped and MR-Damped Cables

damping of the MR-damped cable can be adjusted by changing the voltage input to achieve an optimal value for a specific mode. Obtaining such an optimal voltage input is essential for developing a cost-effective multi-switch control strategy (Ni *et al.*, 2003a).

The MR-damped cable and its two neighboring undamped cables were permanently installed by accelerometers for long-term monitoring and comparative study (Ni *et al.,* 2002b). After instrumentation, a number of rain-wind-induced cable vibration events have been observed. It was observed that during the rain-wind-excited conditions the peak-to-peak amplitude of the undamped cables exceeded 800 mm, while the maximum amplitude of the MR-damped cable was less than 50 mm. This demonstrated the effectiveness of MR dampers in suppressing rain-wind-induced cable vibration. Fig. 22 illustrates the time history of the in-plane and out-of-plane acceleration response for undamped and MR-damped cables. The maximum acceleration response amplitude of the MR-damped cable is about 2.5% of its neighboring undamped cable.

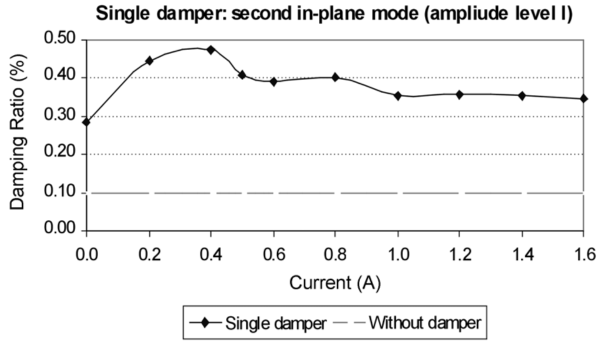
Some important observations were made. By spectral analysis of the measured responses, it is found that during the rain-wind-excited events, one neighboring undamped cable vibrates predominantly in the second mode while the other neighboring undamped cable vibrates predominantly in the third mode, although these two free cables have similar configurations. For the MR-damped cable, several modes participate in the response, but all these modal



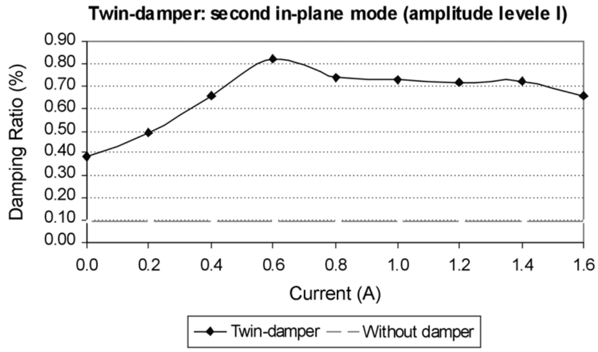
(a) Single-Damper Setup

(b) Twin-Damper Setup

Fig. 23. Damper Setups for Performance Comparative Tests



(a) Single-Damper Setup



(b) Twin-Damper Setup

Fig. 24. Comparison of Damping Ratios of Second Mode

response components are very small in comparison with the dominant modal response components of the undamped cables. It is interesting to note that the fundamental mode (first mode) does not participate in the rain-wind-induced vibration for both the undamped cables and the damped cable.

In order to figure out optimal damper installation configuration, in-situ comparative tests using different damper setups have been carried out. Both single- and twin-damper setups as shown in Fig. 23 were used in the tests. During the tests, the dampers in both setups were installed between the cable and bridge deck at the positions of 4.3 m (2.9% of the cable length) and 2.3 m (2.0% of the cable length) away from the cable lower end, respectively. In the single-damper setup, one damper was attached perpendicular to the cable axis within the cable plane. In the twin-damper setup, two dampers were diagonally installed in an angle of 60 to 72 degrees with each other, both being perpendicular to the cable axis. Sinusoidal-decay testing was carried out by exciting different modes under a lot of excitation amplitudes and a wide range of voltage/current input to the dampers. Fig. 24 shows a comparison of damping ratios of the second mode achieved in single- and twin-damper setups. It is seen that the maximum damping ratio achieved in twin-damper setup is significantly larger than that in single-damper setup.

3.3. Full Implementation of MR Dampers

Full implementation of MR dampers in the Dongting Lake Bridge was completed in May 2002. A total of 312 dampers have been installed on 156 stay cables of the bridge. Fig. 25 shows the MR-damped cables and the damper supporting setup in twin-damper configuration finally used. All the dampers were installed at a same height of 1.8 m from the deck level. Each damper was protected by a specifically designed double-tube steel cover to prevent the damper from adverse environmental conditions. For each cable a DC adapter was served to supply current to the MR dampers. The 156 cables are classified into five categories each of which is applied with a same optimal current when rain-wind-induced vibration is coming. Field observations under rain-wind-excited conditions after the full implementation indicated that, when no current input was applied to MR dampers, about 10 out of the 156 cables failed to be controlled under rain-wind excitation; whereas, when optimal currents were switched on, the vibration in all 156 cables was suppressed. It is therefore concluded that the designed damper setup can completely mitigate rain-

Fig. 25. Full Implementation of MR Dampers in Dongting Lake Bridge

Fig. 26. Setup for In-Situ Real-Time Control Test

wind-induced vibration of the cables in the Dongting Lake Bridge.

3.4. In-Situ Experiments after Full Implementation

After the full implementation, a series of field vibration measurements and tests lasting 45 days have been conducted in the bridge site with the purposes: (i) in-situ experimental verification of developed real-time feedback control strategies; (ii) identification of the exciting mechanism of rain-wind-induced cable vibration based on simultaneous measurement of wind, rain and cable response; and (iii) identification of dynamic interaction among cables, deck and towers by simultaneous measurement of dynamic response in these parts.

The real-time control system dSPACE has been used in-situ for experimental validation of a developed semi-active feedback control strategy, called state-derivative feedback control (Duan *et al.*, 2003). This control strategy is accomplished using only one MR damper and one accelerometer collocated near the lower end of the cable. Before the in-situ test, control simulation for the tested cable under both sweeping sine excitation and sinusoidal step relaxation excitation is conducted. Under both excitation conditions, the method for evaluating equivalent damping ratio resulting from real-time semi-active control has been devised, making it possible to use existing passive design criterion for semi-active control design of the rain-wind-induced vibration problem. It also facilitates wide acceptance of the semi-active control technology by civil engineers. The real-time control test on the prototype cable in the bridge site was carried out under sinusoidal step relaxation excitation. Fig. 26 illustrates the setup for semi-active feedback vibration control test. The experiment shows that the damping capacity obtained from semi-active feedback control test agrees very well with the simulation result. It is also found from the test that implementing in-plane semi-active control not only significantly enhances the cable in-plane damping capacity, but also acts favorably in reducing cable out-of-plane response. It is greatly meaningful for rain-wind-induced vibration control problem.

In order to identify the exciting mechanism of rain-wind-induced cable vibration, 3D anemometers and rain gauges together with the vibration sensors were installed on the bridge for the measurement of wind velocity, wind direction, rainfall, cable response as well as bridge deck and tower response under rain-wind-excited conditions. For several selected cables, the MR dampers are intentionally dismantled from the cables to motivate large-amplitude cable vibration. Fig. 27 shows the measured wind velocity, wind direction, rainfall and in-plane acceleration response of an undamped cable under a rain-wind-excitation event. The diagrams of cable in-plane RMS response versus 1-munite mean wind velocity, 1-munite mean wind direction and rainfall are plotted in Fig. 28. It is revealed that the large-amplitude rain-wind-induced cable vibration occurs in the bridge only when the mean wind velocity at the deck level ranges from 6 to 14 m/s, the wind attack angle ranges from 10 to 50 degrees, and the rainfall is light to moderate (less than 8 mm/h) (Ni *et al.,* 2003e).

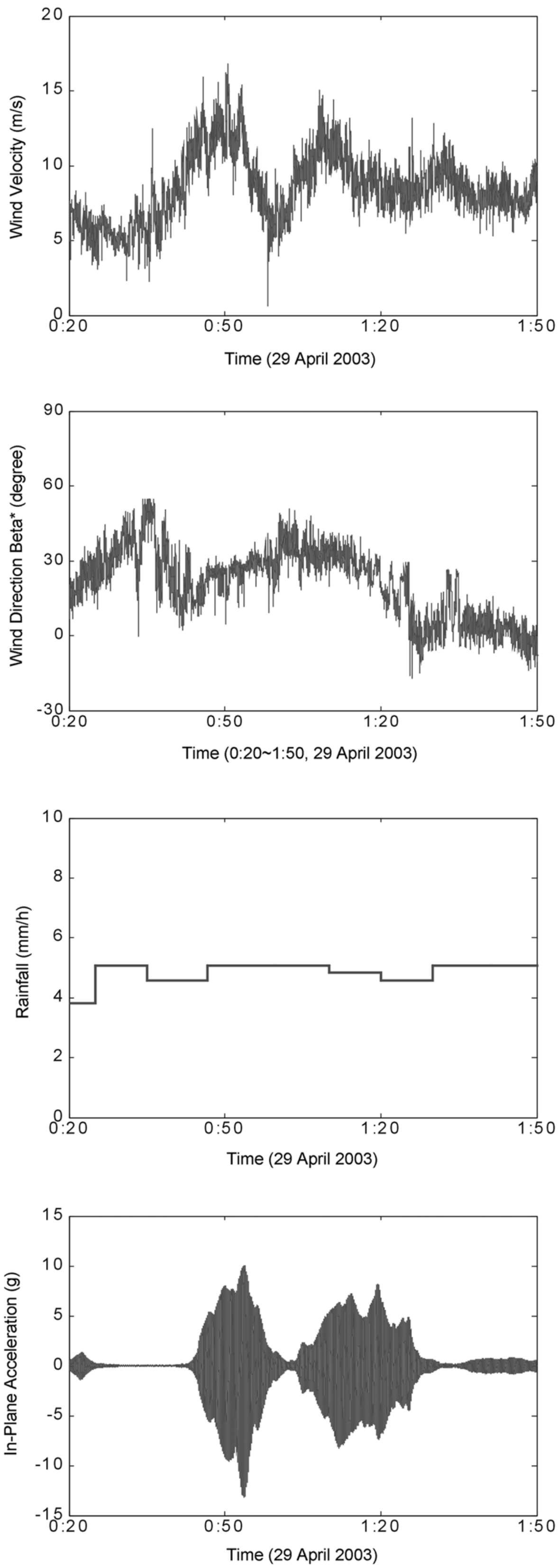


Fig. 27. Measured Wind, Rain and Cable Response during Rain-Wind Excitation

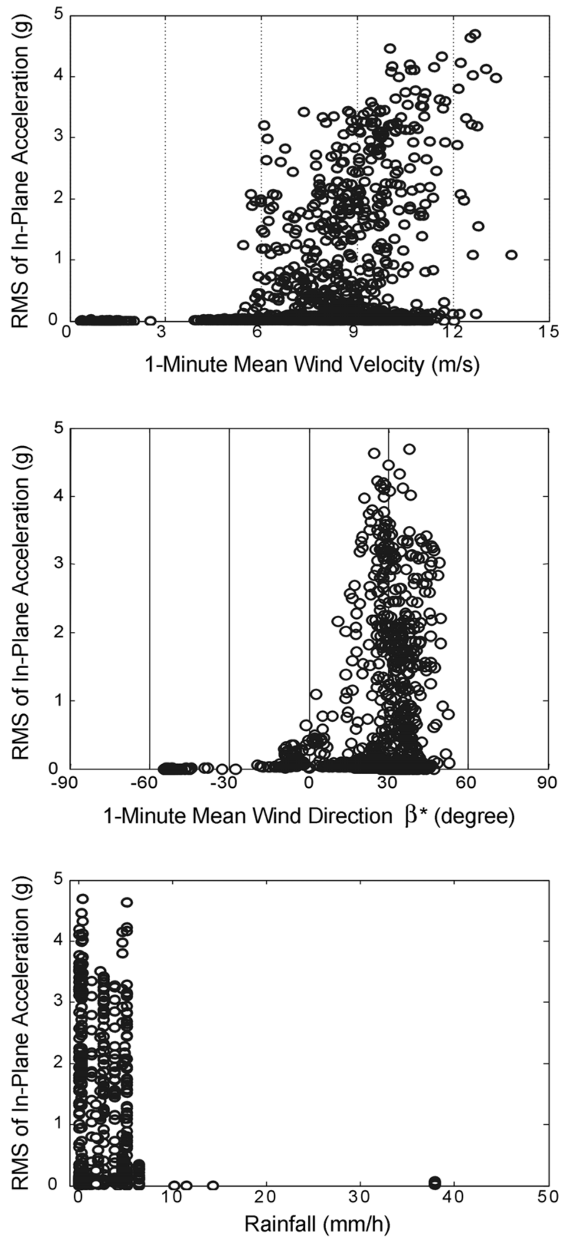


Fig. 28. Cable Response versus Wind Velocity, Wind Direction and Rainfall

4. Conclusions

This paper outlines research activities in The Hong Kong Polytechnic University on structural health monitoring and intelligent vibration control of cable-supported bridges. The development of long-term monitoring systems for three existing cable-supported bridges and two new cable-supported bridges in Hong Kong greatly promotes the academic research in these fields. Instrumentation-based monitoring has been a widely accepted technology to diagnose and assess structural health and conditions of civil infrastructure systems. Current hardware allows efficient data acquisition for sophisticated monitoring systems. However, our ability to analyze and understand the massive datasets with the intention of structural health monitoring lags far behind our ability to gather and store the data. It is therefore desirable to develop an interactive framework for the overall process of inferring knowledge from data and to formalize a comprehensive computational environment for effective data manipulation, retrieval, reliable interpretation and decision making from massive measurement data. Research activities in The Hong Kong Polytechnic University have been devoted to this direction.

Cable vibration in cable-stayed bridges induced by a combination of specific circumstances of light rain and moderate wind is a main concern of design and a conundrum to civil engineers. Newly emerging smart materials offer enormous potential for developing control devices in reducing cable vibration caused by various exciting mechanisms. Summarized in this paper are a series of experimental studies in the cable-stayed Dongting Lake Bridge site, which have resulted in the world's first time practical application of MR-based smart technology in bridge structures. Success of this engineering project shows a great promise of the unprecedented smart control technology for protecting and revitalizing our civil infrastructure systems.

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References

Chan, T.H.T., Ko, J.M., Ni, Y.Q., Lau, C.K., and Wong, K.Y. (2000). "A feasibility study on damage detection of three cable-supported bridges in Hong Kong using vibration measurements." *Proceedings of the International Workshop on Research and Monitoring of Long Span Bridges*, Hong Kong, pp. 204-211.

Chan, T.H.T., Tam, H.Y., Ni, Y.Q., and Ko, J.M. (2003). "Using optical fibre sensors for structural health monitoring of Tsing Ma Bridge." *Proceedings of the International Workshop on Advanced Smart Materials and Smart Structures Technology*, Hawaii, USA.

Duan, Y.F., Ni, Y.Q., and Ko, J.M. (2003). "State-derivative feedback control of cable vibration using semi-active MR dampers." Submitted to *Computer-Aided Civil and Infrastructure Engineering*, in review.

Irwin, P.A. (1997). "Wind vibrations of cables on cable-stayed bridges." *Building to Last Structures Congress: Proceedings of the 15th Structures congress*, ASCE, Vol. 1, pp. 383-387.

Johnson, E.A., Spencer Jr., B.F., and Fujino, Y. (1999). "Semiactive damping of stay cables: a preliminary study." *Proceedings of the 17th International Modal Analysis Conference*, Kissimmee, Florida, pp. 417-423.

Johnson, E.A., Baker, G.A., Spencer Jr., B.F., and Fujino, Y. (2000). "Mitigating stay cable oscillation using semiactive damping." *Smart Structures and Materials 2000: Smart Systems for Bridges, Structures, and Highways*, S.-C. Liu (ed.), SPIE, Vol. 3988, pp. 207-216.

Johnson, E.A., Christenson, R.E., and Spencer Jr., B.F. (2003). "Semiactive damping of cables with sag." *Computer-Aided Civil and Infrastructure Engineering*, Vol. 18, pp. 132-146.

Ko, J.M., Ni, Y.Q., and Chan, T.H.T. (1999). "Dynamic monitoring of structural health in cable-supported bridges." *Smart Structures and Materials 1999: Smart Systems for Bridges, Structures, and Highways*, S.C. Liu (ed.), SPIE, Vol. 3671, pp. 161-172.

Ko, J.M., Ni, Y.Q., Wang, J.Y., Sun, Z.G., and Zhou, X.T. (2000a). "Studies of vibration-based damage detection of three cable-supported bridges in Hong Kong." *Civil Engineering in the 21st Century*, J. Song and G. Zhou (eds.), Science Press, Beijing, pp. 105-112.

Ko, J.M., Ni, Y.Q., Zhou, X.T., and Wang, J.Y. (2000b). "Structural damage alarming in Ting Kau Bridge using auto-associative neural networks." *Advances in Structural Dynamics*, J.M. Ko and Y.L. Xu (eds.), Elsevier, Oxford, Vol. 2, pp. 1021-1028.

Ko, J.M., Ni, Y.Q., Sun, Z.G., and Chan, T.H.T. (2001). "Remote visualized health monitoring of cable-supported bridges." *Health Monitoring and Management of Civil Infrastructure Systems*, S.B. Chase and A.E. Aktan (eds.), SPIE, Vol. 4337, pp. 368-378.

Ko, J.M., Sun, Z.G., and Ni, Y.Q. (2002a). "Multi-stage identification scheme for detecting damage in cable-stayed Kap Shui Mun Bridge." *Engineering Structures*, Vol. 24, pp. 857-868.

Ko, J.M., Zheng, G., Chen, Z.Q., and Ni, Y.Q. (2002b). "Field vibration tests of bridge stay cables incorporated with magneto-rheological (MR) dampers." *Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways*, S.-C. Liu and D.J. Pines (eds.), SPIE, Vol. 4696, pp. 30-40.

Ko, J.M., Chak, K.K., Wang, J.Y., Ni, Y.Q., and Chan, T.H.T. (2003a). "Formulation of an uncertainty model relating modal parameters and environmental factors by using long-term monitoring data." *Smart Systems and Nondestructive Evaluation for Civil Infrastructures*, S.-C. Liu (ed.), SPIE, Vol. 5057, pp. 298-307.

Lau, C.K., Mak, W.P.N., Wong, K.Y., Chan, W.Y.K., and Man, K.L.D. (1999). "Structural health monitoring of three cable-supported bridges in Hong Kong." *Structural Health*

Monitoring 2000, F.-K. Chang (ed.), Technomic, Lancaster, pp. 450-460.

Lou, W.J., Ni, Y.Q., and Ko, J.M. (2001). "Modal damping and stepping-switch control of stay cables with magneto-rheological fluid dampers." *Smart Structures and Materials 2001: Smart Systems for Bridges, Structures, and Highways*, S.-C. Liu (ed.), SPIE, Vol. 4330, pp. 354-365.

Main, J.A. and Jones, N.P. (2001). "Evaluation of viscous dampers for stay-cable vibration mitigation." *ASCE Journal of Bridge Engineering*, Vol. 6, pp. 385-397.

Ni, Y.Q., Jiang, S.F., and Ko, J.M. (2001a). "Application of adaptive probabilistic neural network to damage detection of Tsing Ma suspension bridge." *Health Monitoring and Management of Civil Infrastructure Systems*, S.B. Chase and A.E. Aktan (eds.), SPIE, Vol. 4337, pp. 347-356.

Ni, Y.Q., Ko, J.M., and Zhou, X.T. (2001b). "Damage region identification of cable-supported bridges using neural network based novelty detectors." *Structural Health Monitoring: The Demands and Challenges*, F.-K. Chang (ed.), CRC Press, Boca Raton, Florida, pp. 449-458.

Ni, Y.Q., Chen, Y., Ko, J.M., and Cao, D.Q. (2002a). "Neuro-control of cable vibration using semi-active magneto-rheological dampers." *Engineering Structures*, Vol. 24, pp. 295-307.

Ni, Y.Q., Duan, Y.F., Chen, Z.Q., and Ko, J.M. (2002b). "Damping identification of MR-damped bridge cables from in-situ monitoring under wind-rain-excited conditions." *Smart Structures and Materials 2002: Smart Systems for Bridges, Structures, and Highways*, S.-C. Liu (ed.), SPIE, Vol. 4696, pp. 41-51.

Ni, Y.Q., Li, H., Wang, J.Y., and Ko, J.M. (2002c). "Implementation issues of novelty detection technique for cable-supported bridges instrumented with a long-term monitoring system." *Nondestructive Evaluation and Health Monitoring of Aerospace Materials and Civil Infrastructures*, A.L. Gyekenyesi, S.M. Shepard, D.R. Huston, A.E. Aktan and P.J. Shull (eds.), SPIE, Vol. 4704, pp. 225-236.

Ni, Y.Q., Wang, B.S., and Ko, J.M. (2002d). "Constructing input vectors to neural networks for structural damage identification." *Smart Materials and Structures*, Vol. 11, pp. 825-833.

Ni, Y.Q., Chen, Y., Ko, J.M., and Zheng, G. (2003a). "Optimal voltage/current input to ER/MR dampers for multi-switch control of stay cable vibration." *Proceedings of the 3rd World Conference on Structural Control*, F. Casciati (ed.), John Wiley & Sons, Chichester, Vol. 3, pp. 767-775.

Ni, Y.Q., Fan, K.Q., Zheng, G., Chan, T.H.T., and Ko, J.M. (2003b). "Automatic modal identification of cable-supported bridges instrumented with a long-term monitoring system." *Smart Systems and Nondestructive Evaluation for Civil Infrastructures*, S.-C. Liu (ed.), SPIE, Vol. 5057, pp. 329-339.

Ni, Y.Q., Ko, J.M., Chen, Z.Q., Wang, X.Y., and Spencer Jr., B.F. (2003c). "Implementation of smart MR dampers to Dongting Lake Bridge for mitigating rain-wind-induced cable vibration." Submitted to *Journal of Wind Engineering and Industrial Aerodynamics*, in review.

Ni, Y.Q., Ko, J.M., Duan, Y.F., and Wang, X.Y. (2003d). "Feasibility study on intelligent control of wind-rain-induced cable vibration in cable-stayed Stonecutters Bridge." Accepted to *Proceedings of the International Workshop on Advanced Smart Materials and Smart Structures Technology*, Hawaii, USA.

Ni, Y.Q., Wang, X.Y., Ko, J.M., and Chen, Z.Q. (2003e). "Field observations of rain-wind-induced cable vibration in cable-stayed Dongting Lake Bridge." Submitted to *Journal of Wind Engineering and Industrial Aerodynamics*, in review.

Poston, R.W. (1998) "Cable-stay conundrum." *ASCE Civil Engineering*, Vol. 68, No. 8, pp. 58-61.

Teng, J.G., Ko, J.M., Chan, H.T.H., Ni, Y.Q., Xu, Y.L., Chan, S.L., Chau, K.T., and Yin, J.H. (2003). "Third-generation structures: intelligent high-performance structures for sustainable urban systems." *Proceedings of the International Symposium on Diagnosis, Treatment and Regeneration for Sustainable Urban Systems*, Ibaraki, Japan, pp. 41-55.

Wang, J.Y., Ni, Y.Q., Ko, J.M., and Chan, T.H.T. (2002). "Damage detection of long-span cable-supported bridges." *Proceedings of the 1st International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures*, A.A. Mufti (ed.), ISIS Canada Corporation, Winnipeg, pp. 299-308.

Wang, J.Y., Ni, Y.Q., and Ko, J.M. (2003). "Local damage detection of bridges using signals of strain measurements." *Proceedings of the 1st International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Tokyo, Japan, Vol. 2, pp. 1081-1088.

Wong, K.Y. (2003). "Instrumentation and health monitoring of cable-supported bridges." Accepted to *Journal of Structural Control*, in press.

Wong, K.Y., Lau, C.K., and Flint, A.R. (2000). "Planning and implementation of the structural health monitoring system for cable-supported bridges in Hong Kong." *Nondestructive Evaluation of Highways, Utilities, and Pipelines IV*, A.E. Aktan and S.R. Gosselin (eds.), SPIE, Vol. 3995, pp. 266-275.

Wong, K.Y., Man, K.L., and Chan, W.Y. (2001). "Application of global positioning system to structural health monitoring of cable-supported bridges." *Health Monitoring and Management of Civil Infrastructure Systems*, S.B. Chase and A.E. Aktan (ed.), SPIE, Vol. 4337, pp. 390-401.