Friction Based Semi-Active Control of Cable-Stayed Bridges

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With the rapid increase of bridge spans, research on controlling earthquake-induced vibration of long-span bridges has been a problem of great concern. The concept of varying the normal force in a frictional interface is investigated to enhance the energy dissipation from a vibrating structure and improve the seismic performance of bridge structures. A semi-active optimal control algorithm is formulated to determine the controllable clamping force of a variable friction device; this algorithm uses measurements of the absolute acceleration and device relative displacements for determining the control action to ensure that the algorithm would be implementable on a physical structure. The friction device UHYDE-fbr is designed and manufactured such that the normal force in the friction interface can be influenced with air pressure chamber, hence the normal force and friction damping can be controlled. The friction device is a controllable energy dissipation device that cannot add mechanical energy to the structural system; the proposed control strategy is fail-safe in that bounded-input, bounded-output stability of the controlled structure is guaranteed. The numerical results demonstrated that the performance of the presented control design is nearly the same as that of the active control system; and that the friction device can effectively be used to control seismically excited cable-stayed bridges with multiple-support excitations.

Key words: Cable-stayed bridges, seismic design, friction device system, control algorithm, semi-active control

1. Introduction

The control of long-span bridges represents a challenging and unique problem, with many complexities in modelling, control design and implementation[1) ~ 4)]. Cable-stayed bridges exhibit complex behaviour in which the vertical, translational and torsional motions are often strongly coupled. Through implementation of an appropriate adaptive control law, semi-active elements are able to adapt to different vibration environments and/or system configurations[5) ~ 7)], another advantage over passive damping elements is their ability to utilize sensor information from other parts of the structure. Passive control systems are relatively simple and easy to be complemented, but the effectiveness of passive devices is limited due to their passive nature and the random nature of earthquake events. Active control systems can offer the advantage of being able to dynamically modify the response of a structure in order to increase its safety and reliability. However, the engineering community has not yet fully embraced this technology because of questions of cost effectiveness, reliability, power requirements[5)]. An alternative approach is the semi-active control device system offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems, because semi-active control systems are inherently stable and require relatively much less power, the application of semi-active control system to civil engineering structures is very promising[8) ~ 9)]. Control forces are developed based on feedback from sensors that measure the excitation and/or the response of the structure, the feedback of the response may be measured at locations remote from the active control system. With the **Hy**steretic **De**vice **S**ystems; Hydes[10)] being independent of the vertical load bearing system, a wide variety of link hysteresis loops are possible for

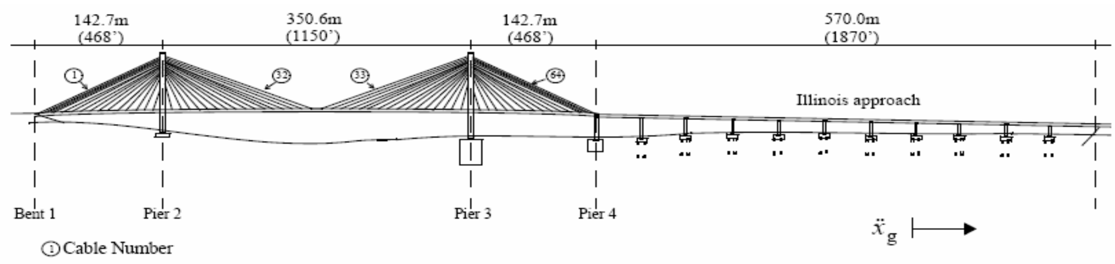

Fig. 1 View of the Cape Girardeau bridge

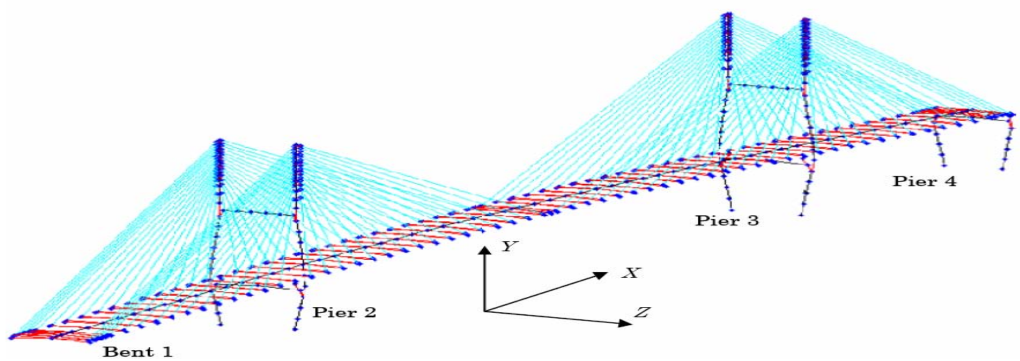

Fig. 2 Bridge finite element model and evaluation model

optimal performance, a complete control over the maximum forces is possible in the main horizontal load resisting system regardless of the type and severity of the earthquake.

Long-span cable-stayed bridges require special considerations in their analysis; design and construction. Typically, complicated nonlinear time-history analyses are involved in their design, which by itself is a challenge to bridge structural engineers. Due to a lack of knowledge about how to design earthquake response modification systems for these special bridges, it is difficult to develop standardized design procedures and specification provisions. To address this need, this study seeks to develop a cost-effective semi-active control system for seismic protection of the targeted bridges from destructive earthquakes by applying a concept of physical parameter modifications. The characteristics of an eventual earthquake can vary substantially from those used for design; structures which incorporate controllable elements can adapt their behaviour based on measurements of their motion and the motion of their supports.

The focus of this study is to use the benchmark bridge model[11) ~ 12)] to investigate the effectiveness of UHYDE-fbr friction device system strategy for seismic protection of cable-stayed bridges under multiple support excitations. For vibration suppression and improvement of the seismic performance of bridge structures, the friction device system is designed such that the normal force in a frictional interface is controlled to enhance the dissipation of energy from a vibrating structure. A semi-active optimal control algorithm is formulated to determine the controllable clamping force of a variable friction device. This algorithm uses measurements of the absolute acceleration and device relative displacements for determining the control action to ensure that the algorithms would be implementable on a physical structure. Since the friction device is an energy-dissipative device that cannot add mechanical energy to the structural system, the proposed control strategy guarantees the bounded-input, bounded-output stability of the controlled structure. Numerical results indicate that response quantities of the bridge can be reduced to a level comparable to that of the sample active controller by installing semi-active friction device system. Also, the friction device system could effectively be used to control cable-stayed bridges subjected to multiple-support seismic excitations.

2. Bridge Finite Element Model

The cable-stayed bridge, shown in Fig. 1, which is located in Cape Griardeau, Missouri, USA, is considered. Based on detailed drawings of the bridge, a three-dimensional finite element model has been developed in the cable-stayed bridge benchmark[11)~12)] to represent the complex behaviour of the full-scale benchmark bridge, shown in Fig. 2. The linear evaluation model was developed and used as a basis of comparison of the performances using various protective systems. Three earthquake records, each scaled to peak ground accelerations of 0.36g or smaller, used for numerical simulations are (i) El Centro NS (1940), (ii) Mexico City (1985), and (iii) Gebze N-S (1999). To evaluate the ability of various control systems to reduce the peak responses, the normalised responses over the entire time record, and the control requirements, evaluation criteria J_1 to J_{18} that have been presented in the benchmark[8), 11 ~ 12)] are considered, however, only the evaluation criteria J_1 to J_{13} are relevant to semi-active and passive systems and hence used in the present study, these evaluation criteria have been normalized by the corresponding response quantities for the uncontrolled bridge. Evaluation criteria J_1–J_6 are related to peak response quantities, where J_1 = the peak base shear of towers, J_2 = the peak shear force of towers at the deck level, J_3 = the peak overturning moment at the bases of towers, J_4 = the peak moment of towers at the deck level, J_5 = the peak deviation in cable tension, and J_6 = the peak displacement of the deck at the abutment. Evaluation criteria J_7–J_{11} are related to normed response quantities corresponding to response quantities for J_1–J_5. Evaluation criteria J_{12}–J_{13} are related to control system requirements; J_{12} = the peak control force, J_{13} = the peak device stroke.

2.1 Equation of motion of controlled bridge structure

The general equation of motion for a cable-stayed bridge subjected to uniform seismic loads can be written as

$$\mathbf{M}\ddot{\mathbf{U}}+\mathbf{C}\dot{\mathbf{U}}+\mathbf{K}\mathbf{U}=-\mathbf{M}\Gamma\ddot{\mathbf{x}}_{\mathbf{g}}+\Lambda\mathbf{f} \tag{1}$$

where U is the displacement response vector, M, C and K are the mass, damping and stiffness matrices of the structure, **f** is the vector of control force inputs, $\ddot{\mathbf{x}}_{\mathbf{g}}$ is the longitudinal ground acceleration, Γ is a vector of zeros and ones relating the ground acceleration to the bridge degrees of freedom (DOF), and Λ is a vector relating the force produced by the control device to the bridge DOFs. However, for the analysis of the bridge with multiple-support excitation, the model must include the supports degrees of freedom. The equation of dynamic equilibrium for all the DOFs is written in partitioned form[8), 11 ~ 12)]

$$\begin{bmatrix}\mathbf{M} & \mathbf{M}_{\mathbf{g}}\\ \mathbf{M}_{\mathbf{g}}^{\mathbf{T}} & \mathbf{M}_{\mathbf{gg}}\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{U}}^{\mathbf{t}}\\ \ddot{\mathbf{U}}_{\mathbf{g}}\end{bmatrix}+\begin{bmatrix}\mathbf{C} & \mathbf{C}_{\mathbf{g}}\\ \mathbf{C}_{\mathbf{g}}^{\mathbf{T}} & \mathbf{C}_{\mathbf{gg}}\end{bmatrix}\begin{bmatrix}\dot{\mathbf{U}}^{\mathbf{t}}\\ \dot{\mathbf{U}}_{\mathbf{g}}\end{bmatrix}+ \begin{bmatrix}\mathbf{K} & \mathbf{K}_{\mathbf{g}}\\ \mathbf{K}_{\mathbf{g}}^{\mathbf{T}} & \mathbf{K}_{\mathbf{gg}}\end{bmatrix}\begin{bmatrix}\mathbf{U}^{\mathbf{t}}\\ \mathbf{U}_{\mathbf{g}}\end{bmatrix}=\begin{bmatrix}0\\ \mathbf{P}_{\mathbf{g}}\end{bmatrix}+\begin{bmatrix}\Lambda\mathbf{f}\\ 0\end{bmatrix} \tag{2}$$

Where U_t and U_g are the superstructure absolute displacement vector and the supports displacement vector, respectively; M_g, C_g and K_g are the mass, damping and elastic-coupling matrices expressing the forces developed in the active DOFs by the motion of the supports. M_{gg}, C_{gg} and K_{gg} are the mass, damping and stiffness matrices of the supports, respectively. It is desired to determine the displacement vector U_t in the superstructure DOFs and the support forces P_g. Since the control forces **f** are only applied to the superstructure DOFs. The total displacement U_t is expressed as its displacement U_s due to static application of the ground motion, plus the dynamic displacement U relative to the quasi-static displacement.

$$\mathbf{U}^{\mathbf{t}}=\mathbf{U}^{s}+\mathbf{U} \tag{3}$$

$$\mathbf{K}\,\mathbf{U}^{s}+\mathbf{K}_{g}\,\mathbf{U}_{g}=0 \tag{4}$$

In which the displacement U_s by definition is the pseudo-static vector. Solving for these displacements leads to define the pseudo-static influence vector as follow

$$\mathbf{R}_{s}=-\mathbf{K}^{-1}\mathbf{K}_{g} \tag{5}$$

Finally; substituting (3), (4) and (6) into the first row of (2) gives

$$\begin{aligned}\mathbf{M}\,\ddot{\mathbf{U}}+\mathbf{C}\,\dot{\mathbf{U}}+\mathbf{K}\,\mathbf{U}=\Lambda\mathbf{f}-(\mathbf{M}\,\mathbf{R}_{s}+\mathbf{M}_{\mathbf{g}})\,\ddot{\mathbf{U}}_{\mathbf{g}}\\ -(\mathbf{C}\,\mathbf{R}_{s}+\mathbf{C}_{\mathbf{g}})\dot{\mathbf{U}}_{\mathbf{g}}\end{aligned} \tag{6}$$

If the ground accelerations and velocities are prescribed at each support, this completes the formulation of the governing equation.

2.2 Evaluation model

The model resulting from the finite element formulation, which is modelled by beam elements, cable elements, and rigid links as shown in Fig. 2, has a large number of degrees-of freedom and high frequency dynamics. Thus, some assumptions are made regarding the behaviour of the bridge to make the model more manageable for dynamic simulation while retaining the fundamental behaviour of the bridge. Application of static condensation reduction scheme to the full model of the bridge resulted in a 419 DOF reduced order model, the first 100 natural frequencies of the reduced model (up to 3.5 Hz) were compared and are in good agreement with those of the 909 DOF structure. The damping in the system is defined based on the assumption of modal damping, the damping matrix was developed by assigning 3% of critical damping to each mode, and this value is selected to be consistent with assumptions made during the bridge design.

$$\mathbf{C}=\mathbf{M}\;\Phi\begin{bmatrix}2\zeta_{1}\omega_{1} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \cdots\cdots & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & 2\zeta_{n}\omega_{n}\end{bmatrix}\Phi^{-1} \tag{7}$$

where Φ is the modal matrix, and ω_i and ζ_i are the natural frequency [rad/sec] and modal damping ratio of the i^{th} mode, respectively. The evaluation model is considered to portray the actual dynamics of the bridge and will be used to evaluate various control systems. Because the evaluation model is too large for control design and implementation, a reduced-order model (i.e., design model) of the system should be developed. The design model[8), 11 ~ 12)], which has 30 states, was derived from the evaluation model by forming a balanced realization of the system.

3. Semi-Active Control Strategy

The trade-off is that large relative displacement is inevitable in the passive seismic isolation system in order to decrease the response acceleration of the superstructures. To solve this trade-off problem, a semi-active seismic control system using a controllable friction device is developed in which the damping force is controlled by varying the pressure between the friction materials, the implementation of variable friction devices for vibration mitigation of seismic structures generally requires an efficient semi-active control law. Semi-active optimal control method is considered to determine the controllable clamping force of friction device system.

3.1 Structural mathematical modelling

Optimal control algorithms are based on the minimization of a performance index that depends on the system variables, while maintain a desired system state and minimize the control effort. According to classical performance criterion, the active control force f_c is found by minimizing the performance index subjected to a second order system. For a seismically excited structure controlled with variable friction device system, the equations of motion can be described in the state-space form as follow:

$$\dot{x} = \mathbf{A}x + \mathbf{B}f + \mathbf{E}\left[\ddot{U}_g^T \ \ \dot{U}_g^T\right]^T \tag{8}$$

$$y_m = \mathbf{C}_y x + \mathbf{D}_y f + v \tag{9}$$

$$z = \mathbf{C}_z x + \mathbf{D}_z f \tag{10}$$

In which x is the state vector, y_m is the vector of measured outputs, z is the regulated output vector and v is the measurement noise vector. The measurements typically available for control force determination include the absolute acceleration of selected points on the structure, the relative displacement of each control device, and a measurement of each control force.

3.2 Control algorithm

The H2/LQG control algorithm is used for the controller design using the reduced order model of the system, which is derived from the evaluation model by forming a balanced realization of the system and condensing out the sates with relatively small controllability and observability grammians.

3.3 Design of controller

A nonlinear control law is derived to maximize the energy dissipated from a vibrating structure by the frictional interface using the normal force as control input. The level of normal force required is determined using optimal controller; modified LQG control problem is to devise a control law with constant gain to minimize the quadratic cost function in the form

$$f_c = -\mathbf{K}\, x \tag{11}$$

In the design of the controller, the disturbances to the system are taken to be identically distributed, statistically independent stationary white noise process. An infinite horizon performance index is chosen that weights the regulated output vector, z

$$J = \lim_{\tau\to\infty}\frac{1}{\tau}\mathbf{E}\left[\int_{\mathbf{0}}^{\tau}\left\{(\mathbf{C}_z x + \mathbf{D}_z f)'\mathbf{Q}(\mathbf{C}_z x + \mathbf{D}_z f) + f_c^T\mathbf{R}f_c\right\}dt\right] \tag{12}$$

where **Q** and **R** are weighting matrices for the vectors of regulated responses and control forces, respectively. Further, the measurement noise is assumed to be identically distributed, statistically independent Gaussian white noise process, with $S_w / S_v = \gamma = 25$. **K** is the full state feedback gain matrix for the deterministic regulator problem given by

$$\mathbf{K} = \tilde{\mathbf{R}}^{-1}\mathbf{B}^T\mathbf{P} \tag{13}$$

where **P** is the symmetric positive definite solution of the algebraic Riccati equation given by

$$\mathbf{PA} + \mathbf{A}^T\mathbf{P} - \mathbf{PB}\tilde{\mathbf{R}}^{-1}\mathbf{B}^T\mathbf{P} + \mathbf{C}_z^T\mathbf{QC}_z = 0 \tag{14}$$

$$\tilde{\mathbf{R}} = \mathbf{R} + \mathbf{D}_z^T\mathbf{QD}_z \tag{15}$$

3.4 Design of observer

The problem with state feedback control is that every element of the state vector is used in the feedback path and, clearly, many states in realistic systems are not easily measurable. In many cases, only a few states are readily available from physical or economical concerns. One way around this dilemma is to use an estimate of the unmeasurable states using a mathematical simulation of the system. With this approach, it is needed to implement a state estimation routine or state observer into the overall system model, being sure to account for the fact that some states are measurable and may be used to improve the computed estimate. The optimal controller (11) is not implemental without the full state measurement. However, a state estimate can be formulated $\hat{x}$ such that $f_c = -\mathbf{K}\,\hat{x}$ remains optimal based on the measurements and could be generated by the Kalman filter

$$\begin{aligned}\dot{\hat{x}} &= \mathbf{A}\hat{x} + \mathbf{B}f + \mathbf{L}(y_m - \mathbf{C}_y\hat{x} - \mathbf{D}_y f) \\ &= (\mathbf{A} - \mathbf{L}\mathbf{C}_y)\hat{x} + \begin{bmatrix}\mathbf{L} & \mathbf{B} - \mathbf{L}\mathbf{D}_y\end{bmatrix}\begin{Bmatrix} y_m \\ f \end{Bmatrix}\end{aligned} \tag{16}$$

In which $\hat{x}$ is the Kalman filter optimal estimate of the state space vector x. L is the gain matrix for state estimator, with the state observer technique, a seismic response control system is more effective and less complicated because full-state feedback seismic control algorithms can be implemented by means of acceleration sensors, and a smaller number of sensors is required. The filter gain L is determined by solving an algebraic Riccati equation. This estimator uses the known inputs f_c and the measurements ym to generate the output and state estimates $\hat{y}$ and $\hat{x}$. A Kalman filter is used to estimate states of the reduced-order model required for the applications of semi-active controllers using selected acceleration and displacement measurements. The Kalman filter estimator is given by

$$\mathbf{L} = \mathbf{S}\mathbf{C}_y^T\mathbf{R}^{-1} \tag{17}$$

The estimation error variance S is a solution of the filter Riccati algebraic equation given by

$$\mathbf{SA} + \mathbf{A}^T\mathbf{S} - \mathbf{S}\mathbf{C}_y^T\mathbf{R}^{-1}\mathbf{C}_y\mathbf{S} + \gamma\,\mathbf{E}\mathbf{E}^T = 0 \tag{18}$$

Calculations to determine K_u and L are performed using the control toolbox in MATLAB.

3.5 Control law design

The proposed approach is to append a force feedback loop to induce the friction device to produce approximately a desired control force f_c. A linear optimal controller $K_c(s)$ is then designed that provides the desired control force f_c based on the measured responses y_m, and the measured force f as follow

$$f_c = L^{-1}\left\{-K_c(s)L\left(\begin{bmatrix} y_m \\ f \end{bmatrix}\right)\right\} \tag{19}$$

where L (.) is the Laplace transform. Although the controller $K_c(s)$ can be obtained from a variety of synthesis methods, the H2/LQG strategies are advocated herein because of the stochastic nature of earthquake ground motions and because of their successful application in other civil engineering structural control applications.

The force generated by the friction device cannot be commanded; only the voltage v, applied to the current driver for the friction device, consequently the air pressure could be linearly changed. To induce the friction device to generate approximately the desired optimal control force f_c, new selection algorithm of the command signal v is considered[13)], when the friction device is providing the desired optimal force ($f = f_c$), the voltage applied to the friction device should remain at the present level. If the magnitude of the force produced by the device is smaller than the magnitude of the desired optimal force and the two forces have the same sign, the voltage applied to the current driver, hence air pressure is increased proportional to the desired force so as to increase the force produced by the device to match the desired control force. Otherwise, the commanded voltage is set to zero. The algorithm for selecting the command signal is graphically represented in Fig. 3 and can be concisely stated as

$$v = (V_{\max} / f_{\max})\,|\,f_c\,|\,H(\{f_c - f\}f) \tag{20}$$

where V_{max} and f_{max} is the device maximum voltage and force, and H(.) is the Heaviside step function.

4. Semi-Active Variable Friction Device (UHYDE-fbr)

Several approaches have been taken in past research to vary the friction damping of mechanical systems through semi-active control. The normal force applied by the device at the contact area is given as a function of slip and slip rate which are multiplied by gain coefficients. The controller essentially combines the effects of a viscous and a non-linear Reid damping, creating a nearly rectangular hysteretic loop. Therefore, the energy dissipation from the system is maximized.

4.1 UHYDE-fbr friction device modelling

The friction device UHYDE-fbr dissipates energy as a result of solid sliding friction[13) ~ 15)]. The name is an abbreviation for

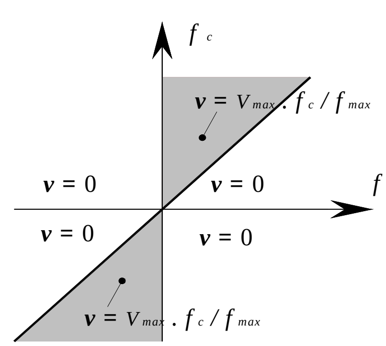

Fig. 3 Selection algorithm of the command signal graphical representation

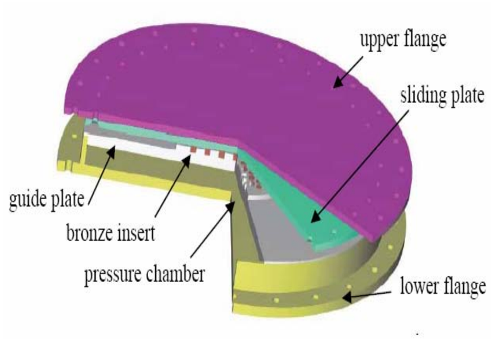

Fig. 4 UHYDE-fbr friction device construction scheme

Uwe´s Hysteretic Device, f for friction and br for bridges, since it is intended for application in bridges where displacements of ±500 mm and more must be accommodated. The patented sliding mechanism consists of two steel plates and a set of bronze inserts. One of the steel plates serves as guidance for the bronze inserts. The other plate has a specially prepared surface which is in contact with the inserts forming the sliding surface, Fig. 4. As long as the design limit displacement is not exceeded, the device suffers no damage. Once the wear due to friction has an influence on the device characteristics, the bronze inserts and sliding plate can be exchanged.

The structural implementation of these devices as well as the experimental verification and evaluation of semi-active control in bridges have been experimentally investigated at the European Laboratory for Structural Assessment within the "Testing of Algorithms for Semi-Active Control of Bridges (TASCB)" project, financed under the "European COnsortium of Laboratories for Earthquake And Dynamic Experimental Research - JRC" (ECOLEADER) within the Fifth Framework Program of the European Commission. The hysteresis loops measured for the device with constant gas pressure, ± 90 mm amplitude and random excitation from EU-ECOLEADER TASCB Project show perfect elasto-plastic behaviour. In a well designed control system, the input energy due to an earthquake is largely dissipated in the control devices through friction. The devices limit the motion of the mechanism which leads to minimized stresses in the structure.

Adequate modeling of the control devices is essential for the accurate prediction of the behavior of the controlled system. A simple phenomenological model for UHYDE-fbr device is adopted based on the Bouc-Wen model, which is shown to accurately predict the behavior of a UHYDE-fbr device over a wide range of inputs. By adjusting the parameters of the model, one can control the degree of linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region. The device exhibits ideal elasto-plastic behavior. Easy adjustment of the friction force is accomplished by gas pressure. A control algorithm may manipulate the gas pressure such that, a wide range of different force-displacement characteristics, including viscous damping, may be achieved; in this case the device becomes semi-active.

4.2 Biaxial Bouc-Wen model for UHYDE-fbr

In a well designed control system, the input energy due to an earthquake is largely dissipated in the control devices through friction. The devices limit the motion of the mechanism which leads to minimized stresses in the structure. The forces mobilized in the friction device UHYDE-fbr can be modelled by biaxial model as follow:

$$\begin{aligned} f_x &= c_0\dot{u}_x + k_0 u_x + \alpha z_x \\ f_y &= c_0\dot{u}_y + k_0 u_y + \alpha z_y \end{aligned} \tag{21}$$

where z_i is an evolutionary shape variable, internal friction state, bounded by the values ± 1; and account for the conditions of separation and reattachment (instead of a signum function) and the directional/ biaxial interaction of frictional forces. The model for biaxial interaction of the resultant hysteretic forces is given as first order differential equation[16),

$$\begin{bmatrix} \dot{z}_x \\ \dot{z}_y \end{bmatrix} = \begin{bmatrix} A\dot{u}_x \\ A\dot{u}_y \end{bmatrix} - \begin{bmatrix} z_x^2(\gamma sign(z_x\dot{u}_x)+\beta) & z_x z_y(\gamma sign(z_y\dot{u}_y)+\beta) \\ z_x z_y(\gamma sign(z_x\dot{u}_x)+\beta) & z_y^2(\gamma sign(z_y\dot{u}_y)+\beta) \end{bmatrix} \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} \tag{22}$$

The parameter c_0, k_0, β, γ and A are called the characteristic parameters of the Bouc-Wen model. In equation shown in (21), the first term describes the force associated with viscous dissipation, the second term represents the linear force portion due to compressed gas and the last term is the evolutionary force due to hysteresis portion of the total restoring force, α is function of the coefficient of sliding friction and the clamping force that linearly dependent on the input voltage. From displacement controlled tests on the friction device under constant pressure and varying frequency, no significant dependency of the friction coefficient on the excitation frequency is observed and the average friction coefficient is determined to be 0.45. In this paper, the dynamic behaviour will be neglected, so the normal force is proportional to the input voltage. In addition, the dynamics involved in the UHYDE-fbr pneumatic servo system equilibrium are accounted for through the first order filter

$$\dot{u} = -\eta(u - v) \tag{23}$$

where v is the command voltage applied to the control circuit,

η = 50 sec^{-1} is time constant associated with filter. Analog voltage control, cover range 0 - 10 Volt is applied to air pressure regulator to set the desired analog output air pressure signal. The functional dependence of the device parameters on the command voltage u is expressed as:

$$\alpha = \alpha_a + \alpha_b u \,;\; c_0 = c_{0a} + c_{0b} u \tag{24}$$

5. Numerical results and discussion

To verify the effectiveness of the presented semi-active control design, simulations were done for the three earthquakes specified in the benchmark problem statement. In this study, a total of 24 friction devices with maximum capacity of 1000 kN are installed at eight locations in the bridge as shown in Fig. 5, eight between the deck and pier 2, eight between the deck and pier 3, four between the deck and bent 1, and four between the deck and pier 4. In addition to fourteen accelerometers, eight displacement transducers and eight force transducers to measure control forces applied to the structure are used for feedback to the clipped optimal control algorithm. The parameters of the UHYDE-fbr device are selected so that the device has a capacity of 1000 kN and maximum displacement of 500 mm (the tested friction device scaled: 2.5 for the frictional force; 1.5 for displacement), as follow: A = 10 cm^{-1} and $\gamma = \beta$ = 5 cm^{-1}, c_{0a} = 10 kN.s/m, c_{0b} = 25 kN.s/m.V, k_0 = 25 kN/m, α_a = 22.5 kN, α_b = 101.25 kN/V.

To evaluate the ability of the friction device system to achieve the performance of a comparable fully active control system, the device is assumed to be ideal, can generate the desired dissipative forces with no delay, hence the actuator/sensor dynamics are not considered. Appropriate selection of parameters (z, Q, R) is important in the design of the control algorithm to achieve high performance controllers. The weighting coefficients of performance index are selected such that; R is selected as an identity matrix; z is comprised of different important responses for the overall behaviour of the bridge including deck displacement, mid deck acceleration/velocity, tower top displacement, velocity and acceleration, shear force and overturning moment at base/deck level that are constructed by the Kalman filter from selected measurements. In this study, a variety of control weighting cases and weighting values are considered, Extensive simulations have been conducted to find the most effective weighting values corresponding to each regulated response, then the least squares minimization is used to estimate the values of the weighting values for the combined regulated responses, and accordingly the optimized weighting matrix Q can be selected for different cases as follows:

(1) *Sample active control* with feedback corresponding to deck displacement and mid span acceleration regulated output response and weighting values as follow:

$$Q_{dd\&da} = \begin{bmatrix} q_{dd}\mathbf{I}_{\mathbf{4x4}} & \mathbf{0} \\ \mathbf{0} & q_{da} \end{bmatrix} \quad q_{dd} = 3500,\ q_{da} = 350.$$

(2) *Semi-active control* with feedback corresponding to deck displacement and tower top velocity regulated output response and weighting values as follow:

$$Q_{dd\&tv} = \begin{bmatrix} q_{dd}\mathbf{I}_{\mathbf{4x4}} & \mathbf{0} \\ \mathbf{0} & q_{tv}\mathbf{I}_{\mathbf{4x4}} \end{bmatrix} \quad q_{dd} = 41408,\ q_{tv} = 105.39.$$

(3) *Passive-on control* without feedback with the voltages to all UHYDE-fbr devices held at maximum (saturated) value 10 Volts.
(4) *Passive-off control* without feedback with the voltages to all UHYDE-fbr devices held at minimum value 0 Volts.

Simulation results of the proposed semi-active control design are compared to those of a passive and sample active control designs. Table 1 shows the evaluation criteria for all the three earthquakes, the responses in the transverse direction z are not presented because they change insignificantly compared with the longitudinal responses. As shown in the table, the semi-active control strategy has nearly the same effectiveness as the sample active control system (Dyke et al., 2000) for seismic protection of the benchmark cable-stayed bridge model. Furthermore, the selection of the weight parameters and regulated response has significantly effect on the controller performance. The proposed semi-active control system significantly reduces the entire peak and normalized responses, except the maximum shear at deck level under Gebze earthquake is slightly increased compared with the uncontrolled bridge including shock transmission devices. The maximum deck displacement is less than allowable displacement (0.3 m), the tension in the stay cables remains within allowable values. The performance is outstanding in comparison with that of sample active control, although the peak control force is much higher.

In particular, the peak deck displacement, J6, of the bridge and those of the shear and moment at the base of the towers using UHYDE-fbr devices are simultaneously reduced; moreover the friction device system is shown to effectively reduce both the peak and *rms* responses due to a broad class of seismic excitations. The proposed semi-active strategy can maintain the seismic

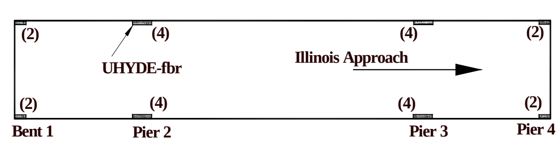

Fig. 5 Locations of UHYDE-fbr devices in the cable-stayed bridge

Table 1 Evaluation criteria for three input earthquakes

Evaluation Criteria		Sample active control	Semi-active control	Passive-on control	Passive-off control
- El Centro earthquake					
J_1	Max Base Shear (*X*)	0.331	0.312	0.344	0.305
J_2	Max Deck Shear (*X*)	0.810	0.959	1.123	0.921
J_3	Max Base Moment (*X*)	0.324	0.285	0.307	0.246
J_4	Max Deck Moment (*X*)	0.612	0.511	0.642	0.565
J_5	Max Cable Deviation	0.248	0.232	0.283	0.272
J_6	Max Deck Displacement	1.028	0.870	1.013	1.266
J_7	Norm Base Shear (*X*)	0.267	0.227	1.018	0.221
J_8	Norm Deck Shear (*X*)	0.869	0.807	2.885	1.038
J_9	Norm Base Moment (*X*)	0.248	0.212	0.635	0.240
J_{10}	Norm Deck Moment (*X*)	0.636	0.539	1.529	0.752
J_{11}	Norm Cable Deviation	2.35E-02	2.40E-02	6.78E-02	2.84E-02
J_{12}	Max Control Force (*X*)	2.66E-03	1.96E-03	1.96E-03	1.76E-04
J_{13}	Max Device Stroke (*X*)	0.630	0.533	0.621	0.775
- Mexico earthquake					
J_1	Max Base Shear (*X*)	0.415	0.364	0.641	0.340
J_2	Max Deck Shear (*X*)	0.828	0.840	1.715	1.093
J_3	Max Base Moment (*X*)	0.396	0.320	0.465	0.367
J_4	Max Deck Moment (*X*)	0.766	0.638	0.964	0.881
J_5	Max Cable Deviation	0.121	0.119	0.191	0.148
J_6	Max Deck Displacement	1.783	1.179	1.344	2.226
J_7	Norm Base Shear (*X*)	0.327	0.274	1.833	0.234
J_8	Norm Deck Shear (*X*)	0.964	0.831	4.848	1.122
J_9	Norm Base Moment (*X*)	0.319	0.265	1.143	0.285
J_{10}	Norm Deck Moment (*X*)	0.793	0.624	2.619	0.920
J_{11}	Norm Cable Deviation	1.46E-02	1.32E-02	6.58E-02	1.85E-02
J_{12}	Max Control Force (*X*)	1.67E-03	1.96E-03	1.96E-03	1.67E-04
J_{13}	Max Device Stroke (*X*)	0.971	0.642	0.732	1.212
- Gebze earthquake					
J_1	Max Base Shear (*X*)	0.474	0.441	0.506	0.358
J_2	Max Deck Shear (*X*)	0.941	1.088	1.278	1.932
J_3	Max Base Moment (*X*)	0.456	0.389	0.446	0.798
J_4	Max Deck Moment (*X*)	0.955	0.838	0.954	3.284
J_5	Max Cable Deviation	0.182	0.189	0.218	0.375
J_6	Max Deck Displacement	2.403	2.363	2.276	12.010
J_7	Norm Base Shear (*X*)	0.320	0.285	1.614	0.328
J_8	Norm Deck Shear (*X*)	0.956	0.978	6.704	2.566
J_9	Norm Base Moment (*X*)	0.400	0.346	0.961	1.144
J_{10}	Norm Deck Moment (*X*)	0.780	0.867	2.217	4.295
J_{11}	Norm Cable Deviation	1.50E-02	1.59E-02	5.33E-02	3.89E-02
J_{12}	Max Control Force (*X*)	2.83E-03	1.96E-03	1.96E-03	2.10E-04
J_{13}	Max Device Stroke (*X*)	1.048	1.031	0.993	5.241

effectiveness of active control for seismic protection of the benchmark cable-stayed bridge model while it requires significantly less external power to operate. Furthermore, if the weight parameters of the nominal controller are not selected appropriately, the control systems with UHYDE-fbr devices perform much better than active control systems. The comparison of the passive on control system evaluation criteria for different input earthquakes to those of active and semi-active control cases reflects the non-adaptability of passive device system to different earthquakes. A more interesting comparison occurs between the semi-active strategy and the two passive strategies. Table 1 show that the semi-active control scheme is better at reducing vibration of the benchmark than either of the corresponding passive approaches, increased passive stiffness/friction force result in increased superstructure accelerations, thus undermining the beneficial effects of friction control system.

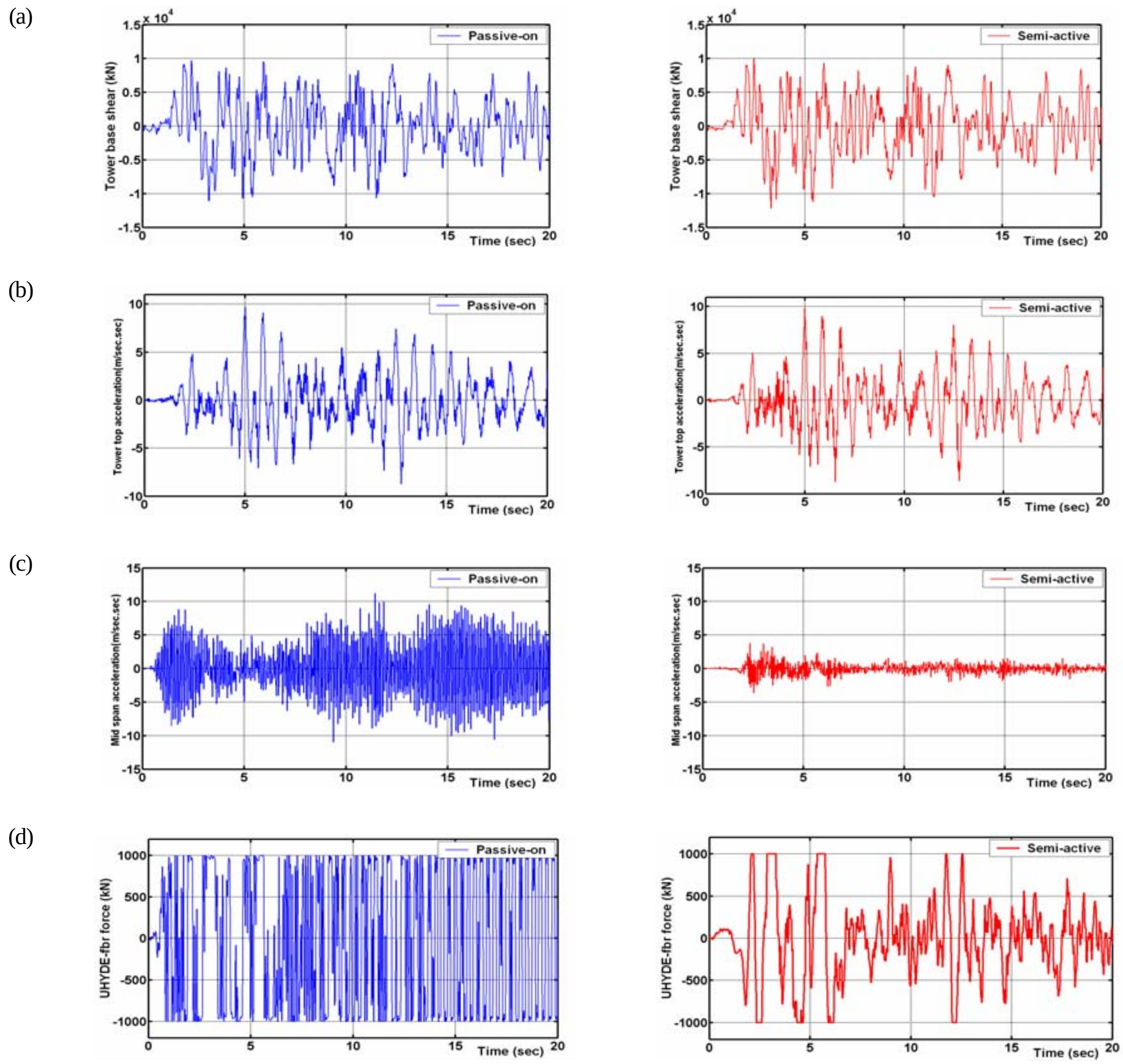

Fig. 6 Time history responses due to El Centro earthquake

The time-history responses of the semi-active controlled bridge are compared to those of the passive-on controlled bridge for the three different earthquakes, but due to limited space, only El-Centro earthquake results are presented in Fig. 6 (a, b, c and d), showing that the semi-active controller can achieve a significant reduction in the tower base shear force and tower top/mid-span acceleration responses simultaneously as compared to the passive-on controlled system. The passive-on control system creates a larger deck displacement reduction response compared to active controlled system, while sacrificing the acceleration and force responses of the bridge structure. By the proper selection of the slip load, it is therefore possible to tune the response of the structure to an optimum value. A semi-active control device is one that has properties that can be adjusted in real time but cannot input energy into the system being controlled. The energy dissipative properties of semi-active controller compared to passive-on control are investigated through driven force time history of the friction device the hysteresis loops of friction device as shown in Figs. 6(d) and 7.

During severe earthquake excitations, the friction device slips and a large portion of the vibrational energy is dissipated mechanically in friction rather than inelastic yielding of the main structural components, with the implementation of the UHYDE-fbr device system, the base shear force transmitted to the superstructure is limited to the maximum frictional force of the sliding bearings, regardless of the severity of earthquakes. Active systems generate a control force based on measurements of the structure responses at designated points. Because active systems have the ability to measure the response of the structure and can be designed to accommodate a variety of disturbances, they are

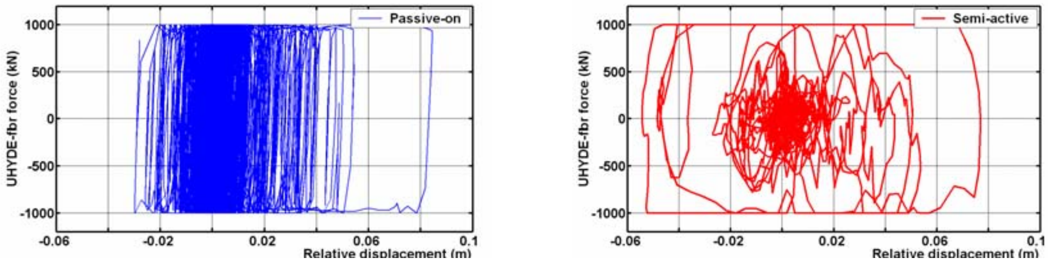

Fig. 7 Force displacement loops for UHYDE-fbr device

expected to achieve higher performance levels than passive systems. The energy dissipated by a friction device system is proportional to the device slip force; therefore, passive friction device may not be efficient if the level of the slip force is set too high, the device will not slip for most of the earthquake duration. A well-designed semi-active control scheme could balance benefits of the different objectives within the requirements of the specific design scenario.

6. Conclusions

The effectiveness of the optimal semi-active control strategy using friction device system in reducing structural responses for a wide range of seismic loading conditions has been investigated through a numerical study of the ASCE benchmark cable-stayed bridge problem. The modified Bouc-Wen model is considered as a dynamic model of UHYDE-fbr device, a modified LQG-clipped optimal control algorithm is used to determine the control action for each friction device. The proposed control design employs five accelerometers, four displacement transducers and 24 force transducers as sensors, a total of 24 UHYDE-fbr friction devices with a maximum capacity of 1000 kN each as control device.

The frictional hysteresis system is effective for optimal performance over a wide range of frequency input and it ensures maximum acceleration transmissibility equal to maximum limiting frictional force regardless of the severity of earthquakes and the friction device only dissipates energy from the system hence it cannot cause instabilities to occur, furthermore the semi active control strategy has bounded-input, bounded-output stability and small energy requirements. The presented results show that variable, controlled normal force friction UHYDE-fbr device system can substantially improve the performance and could effectively be used for control of seismically excited cable-stayed bridges; the proposed control design with appropriate selection of weighting parameters and regulated responses is capable of not only approaching, but surpassing the performance of the active control system for the seismic protection of the benchmark cable-stayed bridge model, while only requiring a small fraction of the power that required by the active controller.

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