DESIGN OF ACTIVE CONTROLLER FOR BILL EMERSON MEMORIAL BRIDGE, MISSOURI, USA AGAINST SEISMIC EXCITATION USING UPDATED NUMERICAL MODEL

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ABSTRACT :

In this present work two active controllers have been designed against seismic excitation of benchmark cable-stayed bridge, the Bill Emerson Memorial Bridge, Missouri, USA, using an updated finite element model constructed in Matlab®. A linear evaluation model based on dead load deformed structure is arrived at by non linear static analysis. The model is reduced by static condensation. The reduced model is validated with transfer function to match its dynamic response with the original model. The model is transferred to state space and is further reduced with balance realization. This reduction is validated with transfer function again. Two active controllers, one against uniform support excitation and the other against multiple support excitations have been designed to control the response of the bridge against three representative earthquakes. Multiple support excitation case is considered with different angles of attack of earthquake excitation and corresponding time lag of incidence of earthquake wave in different supports. Performances of the controllers are checked by their efficiencies in reducing the peak pylon forces. It has been observed that the active controllers perform well against these criteria.
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KEYWORDS: Linear Evaluation model, Transfer function, Balance realization, Active controller.

1. INTRODUCTION

Cable-stayed bridges have gained popularity over the last three decades due to improved structural performance and aesthetic appeal. Active control of cable-stayed bridges represents a challenging problem and very little has been reported in the literature about active control strategy. Dyke *et. al.* (2000) introduced the phase-I benchmark control problem for seismic response control of a cable stayed bridge, the Bill Emerson Memorial Bridge, Missouri, USA, in which a sample LQG controller was presented and its efficacy was checked against select earthquake excitations. Later alternative control strategies such as hybrid, semiactive, passive, fuzzy, neurofuzzy were studied on the numerical model of this bridge by various researchers. This bridge has also been a subject of structural health monitoring [Caicedo (2003)] and structural identification [Song *et. al.* (2006)]. However, the FE model that was used for the aforesaid studies was found to be inadequate to simulate the dynamic characteristics of the bridge structure as studied previously by Giraldo *et. al.* (2006) and in Caicedo *et. al.* (2006). It is well appreciated that for any control strategy to be successful, the numerical model must correspond to the observed modal behaviour to the closest extent. In this paper, an updated model developed in Caicedo *et. al.* (2006) has been used to design two active controllers, one against uniform support excitation and the other corresponding to multiple support excitations and the efficacies of these have been tested against select seismic excitations. Multiple support excitation case has been considered for two different angles of attack of earthquake excitation and corresponding time lags of incidence of earthquake wave in different piers of the bridge. The procedure adopted for the design of the active controllers is the same as the one followed in Dyke *et. al.* (2000) and Caicedo *et. al.* (2003).

2. THE UPDATED NUMERICAL MODEL OF THE BRIDGE

The structural detail of the Bill Emerson Memorial Bridge, Missouri, USA, has been described in detail in Dyke *et. al.* (2000) and is not repeated here.

2.1. Finite Element Model

The finite element model adopted in the previous study by Dyke *et. al.* (2000) has been updated in Matlab® environment optimizing its mass, stiffness and model of bearings in Caicedo *et. al.* (2006) using system identification data. Fig. 2 shows the finite element model of the bridge.

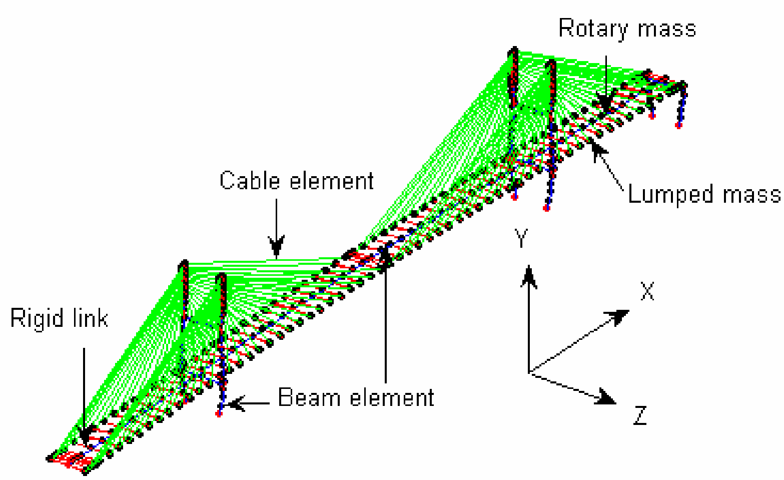

Figure 1 Finite Element Model of the bridge

2.2. Nonlinear static analysis

Nonlinear static analysis against dead load is conducted to arrive at a linear evaluation model. An incremental iterative scheme is adopted for conducting the nonlinear static analysis. This model is found to capture the modes observed in experimental study by Giraldo *et. al.* (2006) to the closest extent and hence is found to be more appropriate in designing an active controller. The first five modal frequencies (Hz) of this updated model are: 0.307 (flexural), 0.413 (flexural), 0.462 (torsional), 0.496 (mixed-torsional) and 0.635 (flexural).

2.3. Control Evaluation Model

The control evaluation model has been formed by replacing the constraint equations corresponding to the deck-abutment/pylon joints from the numerical model and replacing them with actuator connections. The procedure is as in Dyke *et. al.* (2000). The first seven frequencies (Hz) of this released structure are: 0.174, 0.303, 0.418, 0.437 and 0.490.

2.4. Problem formulation

The governing equation of motion for the undamped structure is of the form,

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{K}\mathbf{U} = -\mathbf{M}\Gamma\ddot{x}_g + \Lambda\mathbf{f} \tag{1}$$

where, $\mathbf{U}$ is the response vector and $\ddot{\mathbf{U}}$ is its second time derivative**,** $\mathbf{M}$ is the mass matrix and $\mathbf{K}$ is the stiffness matrix of the structure, $\mathbf{f}$ (N) is the control force vector, $\ddot{x}_g(m/\sec^2)$ is the ground acceleration, Γ is the influence vector indicating the input location of ground acceleration on the structure, and Λ is a vector indicating the input locations control forces to the structure.

2.5. Model Reduction

The Guyan reduction scheme has been implemented for reduction of the degrees of freedom of the finite element model to a manageable level for control studies. The procedure for reduction is in accordance with Dyke *et. al.* (2000). The reduction has been validated by the use of transfer function. In the case of multiple supports excitations the support dofs have been retained in the reduced model.

3. ANALYSIS TOOL

The linear dynamic model of the bridge is analyzed by a tool developed by Ohtori *et. al.* (1999). This tool enables the Matlab® user to interface with a complied C code for solving the dynamic equation Eq. [1] by Newmark-Beta method through Simulink® block. The input and output matrices of the system are found using the state space form

$$\dot{\mathbf{x}} = \mathbf{A}_e\mathbf{x} + \mathbf{B}_\mathbf{e}\begin{bmatrix}\ddot{x}_\mathbf{g}\\ \mathbf{f}\end{bmatrix}, \qquad \mathbf{y} = \mathbf{C}_e\mathbf{x} + \mathbf{D}_\mathbf{e}\begin{bmatrix}\ddot{x}_\mathbf{g}\\ \mathbf{f}\end{bmatrix} \tag{2}$$

where, $\mathbf{x} = \begin{bmatrix}\hat{\mathbf{U}}^T \dot{\hat{\mathbf{U}}}^T\end{bmatrix}^T$ represents the state vector, $\mathbf{A}_e$ is the state matrix, other system matrices $\mathbf{B}_e, \mathbf{C}_e, \mathbf{D}_e$ are determined by the selected outputs.

4. DESIGN OF CONTROLLER

The controller is designed with an aim to control the foundation forces at key locations of the bridge. The constraints and limitations in the control design for the problem have been maintained as in the benchmark case [Dyke *et. al.* (2000)]. The safe range for cable tensions (between 20% and 70% of ultimate tension) during excitation, prescribed by Dyke *et. al.* (2000) for the benchmark problem has been adopted for the present study too. The active controller is designed based on a LQG algorithm. Accelerometers and displacement sensors have been used as measurement devices while hydraulic actuators act as controlling devices. The configurations of the sensor and actuator have been kept same as the benchmark problem by Dyke *et. al.* (2000).

4.1. Control design model

The states space representation of the system has been made more compact to facilitate a practically implementable controller. This is done by removing the states with less controllability and observability grammians following the procedure as enumerated in Dyke *et. al.* (2000). The resulting system has been termed as the control design model. The remaining states after balance realization for uniform support excitation and multiple support excitations are 30 and 60 respectively. These models correspond to the original ones in terms of input as validated by transfer functions.

4.2. Control Algorithm

A linear quadratic gaussian (LQG) control design is used to minimize the cost function

$$\mathbf{J} = \lim_{\tau\to\infty}\frac{1}{\tau}\mathbf{E}\left[\int_0^{\tau}\left\{\left(\mathbf{C_r^z x^r} + \mathbf{D_r^z u}\right)^{\mathrm{T}}\mathbf{Q}\left(\mathbf{C_r^z x^r} + \mathbf{D_r^z u}\right) + \mathbf{u^T R u}\right\}(dt)\right] \tag{3}$$

where, $\mathbf{x^r}$ is the reduced state vector, z is the regulated output vector, $\mathbf{A_r}$ and $\mathbf{B_r}$ are the reduced state matrices and $\mathbf{C_r^z}$, $\mathbf{D_r^z}$ and $\mathbf{F_r^z}$ are the mapping matrices corresponding to control design model. The controlled cost matrix **R** is a [8×8] identity matrix, and the state weighting matrix is **Q**. Controller is of the form

$$\mathbf{u} = -\mathbf{K_u}\hat{\mathbf{x}}^{\mathbf{r}} \tag{4}$$

where, $\hat{\mathbf{x}}^{\mathbf{r}}$ is the Kalman Filter estimate of the state vector on the reduced order model. $\mathbf{K_u}$ is the full state feedback gain matrix for the deterministic regulator problem.

4.3. Sensors and actuators

Separate arrangements of sensors have been used for the control design against uniform support and multiple support excitations. Four displacement sensors and five accelerometers have been employed for measuring the responses to uniform support excitation and fourteen accelerometers and four displacement sensors have been used for measurement of responses to multiple support excitations. The accelerometers have a sensitivity of 7 V/*g* (*i.e.* 7 Volts = 9.81 m/sec^2) and thus are able to measure upto 1.42*g* within a range from -10 V to +10 V.

Twenty four numbers of hydraulic actuators have been employed for seismic response control in this study. These have been placed on the deck pylon interface and deck abutment/pier interface in the longitudinal direction. The actuator-sensitivity D_d for actuators have been selected as 155 kN/V allowing for the constraint of ±10 V = 1550 kN.

4.4. Control Simulation

Three representative earthquake excitations have been considered for checking the efficacy of the controller: (i) *El Centro.* Recorded at Imperial Valley, Valley Irrigation District substation in El Centro, California, during Imperial Valley, California earthquake of 18th of May, 1940; (ii) *Mexico City.* Recorded at Galeta de Campos station with site geology of meta-andesite breccia on the 19th of September, 1985; (iii) *Gebze, Turkey.* The Kocaeli earthquake recorded at the Gebze Tubitak Marmara Arastirma Merkezi on the 17th of August, 1999. The simulation is done using Simulink® within the control system toolbox of Matlab®. Time lag of arrival of earthquake waves is calculated for the supports from left to right for the multiple support excitation. It is [0 0.05 0.16 0.20] sec for 15^0 incidence angle and [0 0.03 0.12 0.15] sec for 45^0.

5. RESULTS AND DISCUSSION

5.1. Uniform support excitation

The efficiency of control for uniform support excitation has been presented in Table 1. These results correspond to a value of the state weighting matrix $\mathbf{Q} = 10^4 \mathbf{I}_{4\times4}$. The controller reduces the responses of base shear and overturning moment of the pylon to considerable extent. The control performances of base shear and in case of the left pylon corresponding to El Centro earthquakes have been presented in Fig. 2. The reduction of base shear and overturning moment of the pylon is of great practical importance as these are significant criteria for pylon design and can reduce the cost of pylon considerably. In addition to reducing the peak responses at strategic locations, the controller effectively reduces the norm of base shear and overturning moment significantly indicating that the controller is effective over the entire excitation period. The actuator requirements have been shown in Table 2 and are realistic for the geometry of the bridge.

Table 1 Performance of the active controller against uniform support excitation

Nature of force	% reduction			
	El Centro	Mexico	Gebze	Maximum
Base shear	68.86	47.40	56.16	68.86
Overturning moment	64.09	11.33	12.64	64.09
Norm base shear	72.16	59.03	61.47	72.16
Norm overturning moment	72.11	59.25	54.22	72.11

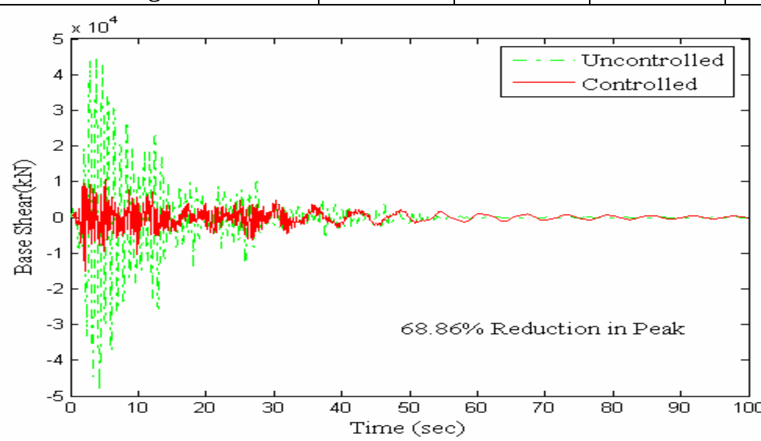

Figure 2 Time history of base shear in pylon I against uniform support excitation against El Centro earthquake.

Table 2 Actuator Requirements

Response	El Centro	Mexico	Gebze	Max
Force (kN)	889.78	330.78	901.03	901.03
Stroke (m)	0.1367	0.0756	0.2998	0.2998
Velocity (m/sec)	0.7543	0.4529	0.6324	0.7543

5.2. Multiple support excitations

5.2.1 Angle of attack: 15^0

The performance of the controller against different evaluation parameters have been presented in Table 3. It has been observed that the controller reduces the response of base shear and overturning moment of the pylons to considerable extent in the direction of its orientation (global *X*) but at the cost of slight increase of respective key responses in the transverse direction (global *Z*) indicated by the negative(-) signs in Table 3. The control performances of base shear for pylon-I against the El Centro earthquake have been presented in Fig. 3. The actuator requirement is shown in Table 4.

Table 3 Reduction in peak response (%) against multiple support excitation (attack angle: 15^0)

Nature of force	Direction	El Centro	Mexico	Gebze	Maximum
Base shear	*X*	62.24	55.77	67.63	67.63
	Z	-2.87	-1.17	-1.04	-2.87
Overturning moment	*X*	67.77	59.75	58.64	67.77
	Z	-1.09	-1.06	-1.04	-1.09
Norm Base shear	*X*	76.02	70.46	70.07	76.02
	Z	-1.01	-1.04	-1.05	-1.05
Norm Overturning moment	*X*	76.46	70.14	61.25	76.46
	Z	0.00	-1.03	-1.03	-1.03

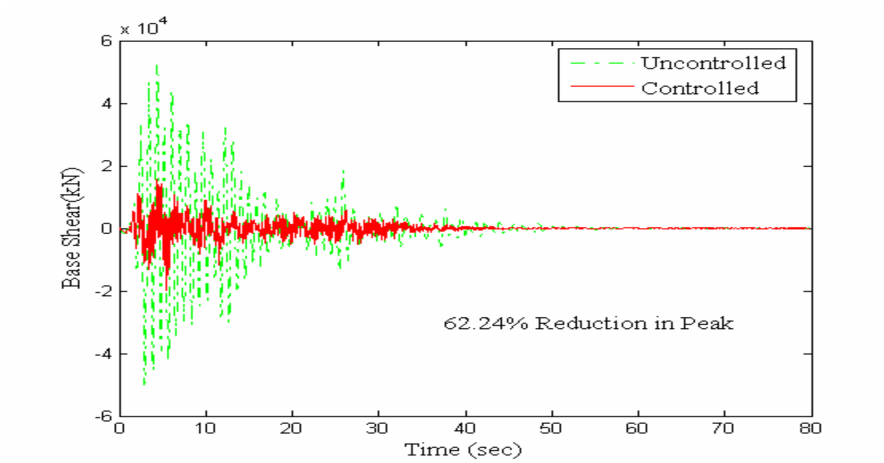

Figure 3 Time history of base shear in pylon I against multiple support excitation(attack angle: 15^0) aginst El Centro Earthquake

Table 4 Actuator Requirements

Response	Direction	El Centro	Mexico	Gebze	Max
Force (kN)	*X*	1503.98	865.36	1490.75	1503.98
Stroke (m)	*X*	0.1156	0.0935	0.2638	0.2638
Velocity (m/sec)	*X*	0.7878	0.5439	0.5870	0.7878

5.2.2 Angle of attack: 45^0

The performance of the controller against different evaluation criteria have been presented in Table 5. The table has been prepared as in cased of previous subsection. A typical controller performance is presented in Fig. 4. The actuator requirements have been presented in Table 6

Table 5 Reduction in peak response (%) against multiple support excitation (attack angle: *45^0*)

Nature of force	Direction	El Centro	Mexico	Gebze	Maximum
Base shear	*X*	63.36	55.21`	65.16	65.16
	Z	-1.03	-1.12	-1.03	-1.12
Overturning moment	*X*	67.77	57.42	58.42	67.77
	Z	-1.09	-1.03	-1.04	-1.09
Norm base shear	*X*	73.36	68.13	67.13	73.36
	Z	0.01	-1.01	-1.01	-1.01
Norm overturning moment	*X*	74.09	68.94	59.25	0.4075
	Z	0.01	-1.00	-1.01	-1.01

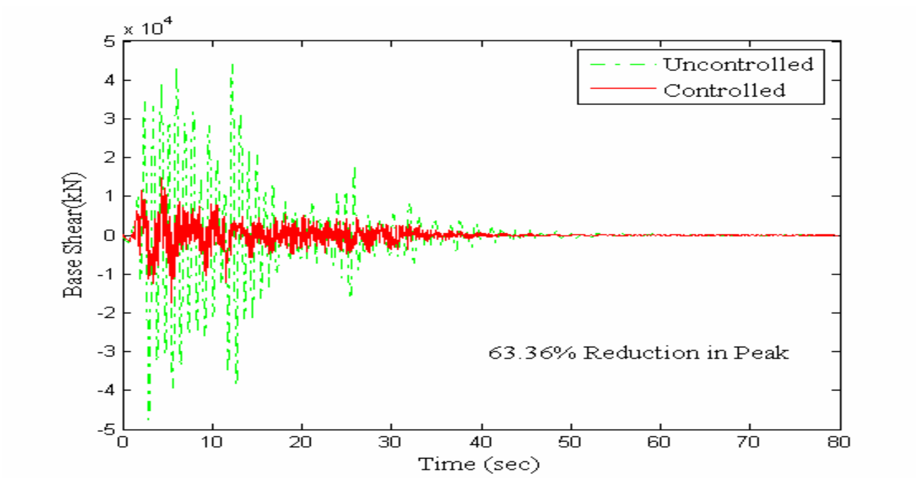

Figure 4 Time history of base shear in pylon I against multiple support excitation (attack angle: *45^0*) against El Centro earthquake.

Table 6 Actuator Requirements

Response	Direction	El Centro	Mexico	Gebze	Max
Force (kN)	*X*	1389.06	895.05	1178.46	1389.06
Stroke (m)	*X*	0.1384	0.0945	0.2432	0.2432
Velocity (m/sec)	*X*	0.5693	0.5926	0.4893	0.5926

6. CONCLUSION

Two active controllers have been designed to control seismic response of the Bill Emerson Memorial cable-stayed bridge against select earthquakes. An updated finite element model has been used in this study to arrive at the linear evaluation model, reduced model and finally the state space model that has been used to construct the control design model. The active controllers show effective control capability in controlling key pylon responses against the selected earthquake. The controllers have been found to be realistic as they are based on an updated finite element model of the cable-stayed bridge.

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