ROBUST HYBRID CONTROL OF A SEISMICALLY EXCITED CABLE-STAYED BRIDGE

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Summary

This paper presents a hybrid system combining lead rubber bearings and hydraulic actuators controlled by a μ-synthesis method for seismic response control of a cable-stayed bridge. A hybrid system could alleviate some of restrictions and limitations that exist when each system is acting alone because multiple control devices are operating. Therefore, the overall control performance of a hybrid system may be improved compared to each system, however the overall system robustness may be negatively impacted by active device in the hybrid system or active controller may cause instability due to small margins. Therefore, a μ-synthesis method that guarantees the robust performance is considered to enhance the possibility of real applications of the control system. The performances of the proposed control system are compared with those of passive, active, semiactive control systems and hybrid system controlled by a LQG algorithm. Furthermore, an extensive robust analysis with respect to stiffness and mass matrices perturbation and time delay of actuator is performed. Numerical simulation results show that the performances of the proposed control system is superior to those of passive system and slightly better than those of active and semiactive systems and two hybrid systems show similar control performances. Furthermore, the hybrid system controlled by a μ-synthesis method shows the good robustness without loss of control performances. Therefore, the proposed control system could be effectively be used to seismically excited cable-stayed bridge which contains many uncertainties.

1. Introduction

A hybrid control system is typically defined as one that employs a combination of passive and active devices. This system could alleviate some of the restrictions and limitations that exist when each system is acting alone, because multiple control devices are operating. Thus, higher level of performance may be achievable and the resulting hybrid control system may be more reliable and robust that a fully active control system. However, the overall system robustness may be decreased by the malfunction of active devices due to the differences between the numerical model and real structure and many uncertainties. Therefore, control algorithms that guarantee the controller robustness should be considered to improve the overall system robustness of the hybrid control system. In this study, a hybrid control system combining lead rubber bearings (LRBs) and hydraulic actuators (HAs) is used for seismic response control of a cable-stayed bridge. LRBs are used to reduce the earthquake-induced forces in the bridge and HAs are used to further reduce the bridge responses, especially deck displacements (i.e., deformation of LRBs). A μ-synthesis method is used for HAs to improve the controller robustness. The performances of the proposed control system are compared with those of passive, active, semiactive control systems and hybrid system controlled by a LQG algorithm and an extensive robust analysis with respect to stiffness and mass matrices perturbation and time delay of actuator is performed.

2. Hybrid Control System

2.1 Control devices and Sensors

The LRB of Park et al.[1)] are used as passive control device in this study. This LRB is designed by a recommended procedure proposed Ali and Abdel-Ghaffar[2)] and 24 LRBs are used in the bridge. For the active control devices, 24 HAs which are used in the benchmark problem[3)], are used. The actuator is assumed to have a capacity of 1000 kN without its dynamics. For feedback in the control algorithm, five accelerometers and four displacement sensors are used. All sensor measurements are obtained in the longitudinal direction to the bridge and the sensor dynamics are neglected.

2.2 μ-Synthesis Method

The hybrid control system is more robust than a fully active control system due to the passive devices which are robust inherently. However, the overall system robustness may be decreased by the malfunction of active devices due to the differences between the numerical model and real structure and many uncertainties. Therefore, a μ-synthesis method is used to improve the robustness of HAs. Robust performance which represents the performance and stability of the closed-loop system simultaneously can be evaluated using the structured singular value (SSV) for systems containing both structured and unstructured perturbations. A system in standard form shown in Figure 1 with normalized performance criteria and perturbations performs robustly if and only if following condition is satisfied[4].

$$\sup_{\omega}\left\{\mu_{\bar{\Delta}}\left[\mathbf{N}(j\omega)\right]\right\} < 1 \tag{1}$$

$\mu_{\bar{\Delta}}(\cdot)$: SSV,
$\mathbf{N}(j\omega)$: Closed-loop transfer function.

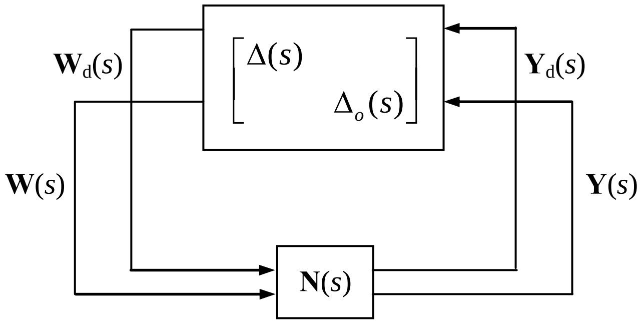


Figure 1. Standard form for robust performance analysis

In Figure 1, $\mathbf{W}(s), \mathbf{Y}(s), \mathbf{W}_d(s)$ and $\mathbf{Y}_d(s)$ are the Laplace transforms of disturbance, reference output, perturbation input and perturbation output, respectively. Δ and Δ_o are perturbation blocks for stability and performance, respectively. Unfortunately, the direct computation of the SSV is intractable in all but the simplest cases. Therefore, it is reasonable to minimize the upper bound on SSV as an alternative using **D**-**K** iteration[4].

$$J = \sup_{\omega} \min_{\substack{\{d_1 \; d_2 \; \cdots \; d_p\} \\ d_i \in (0,\infty)}} \bar{\sigma}\left[\mathbf{D}_{\mathrm{R}}(j\omega)\mathbf{N}(j\omega)\mathbf{D}_{\mathrm{L}}^{-1}(j\omega)\right] \tag{2}$$

$\bar{\sigma}(\cdot)$: Maximum singular value,
$\mathbf{D}_{\mathrm{R}}(j\omega),\ \mathbf{D}_{\mathrm{L}}(j\omega)$: Frequency dependent right and left **D**-scales.

D-**K** iteration performs ∞-norm optimization and **D**-scale optimization alternatively. Two perturbations are implemented into the design model to account for differences between design and evaluation models, and for uncertainty of control signal. First there is additive perturbation on the transfer function between the earthquake excitation and measurement to account for the difference between full-order model (i.e., evaluation model) and reduced-order model (i.e., design model). Therefore, the weight on this perturbation is included in the plant block chosen based on this uncertainty, so that the additive uncertainty could account for unmodelled dynamics in the system. The weighting function, $\mathbf{W}_{\ddot{x}_g \to \mathrm{y}}$, is obtained by comparing the singular value error between the design and evaluation models as shown in

Figure 2.

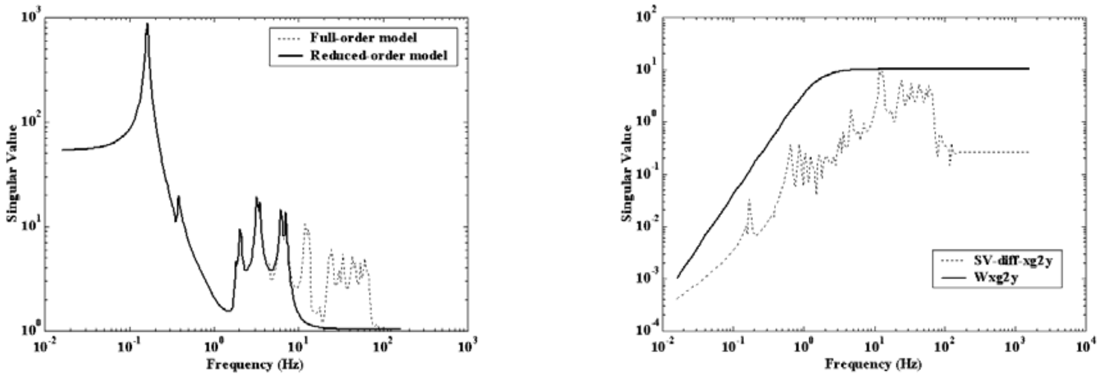


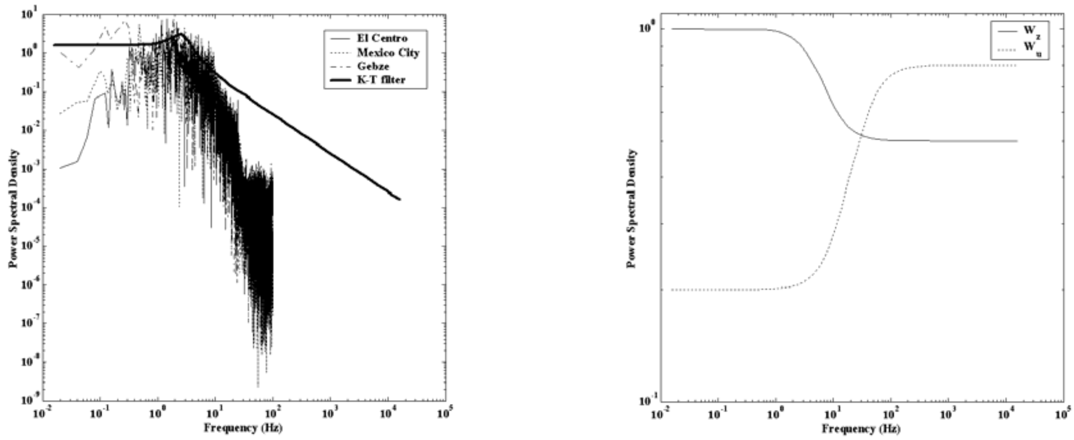
Figure 2. Unmodelled dynamics of the evaluation model and the designed additive uncertainty filter

Furthermore, multiplicative uncertainty is considered to account for the interaction between the bridge model and control device, difference of input signal due to the error of mechanical and electrical models, and so on. The weighting function, $\mathbf{W}_{\mathbf{u}\to\mathbf{u}}$, on this perturbation is simply chosen to include 1% uncertainty. In addition to uncertainty filters, three frequency dependent weighting filters are considered to improve the control performance and controller robustness. In the LQG algorithm, the earthquake excitation is taken to be a stationary white noise. However, the energy of earthquake is concentrated in the low frequency in general as shown in Figure 3(a). Therefore, *Kanai-Tajimi* filter is considered to capture the characteristics of input earthquakes. Furthermore, a high-pass filter is adopted for control inputs to prevent spillover effects of controller caused by difference error of the designed and evaluation models, and a low-pass filter is used for regulated outputs to control low frequency responses effectively. Theses control force and regulated output filters are shown in Figure 3(b). Figure 4 shows the block diagram of the μ-controller incorporated with frequency dependent weighting and uncertainty filters. In this study, *maximum response approach*[1)] is used to obtain the appropriate response weighting matrix, **Q**.

3. Numerical Examples

3.1 Bridge Model

The bridge model considered in this study is that of a benchmark control problem[3)] which is provided as a testbed structure for the development of strategies for the control of cable-stayed bridges. This benchmark bridge is composed of two towers, 128 cables, and two additional piers. To evaluate the effectiveness of various control systems and algorithms, 18 evaluation criteria are presented in the benchmark control problem[3)]. The first six evaluation criteria, J_1 ~ J_6, are related to the peak responses, the second five ones, J_7 ~ J_{11}, represent the norm of bridge response quantities, and the last seven ones, $J_{12} \sim J_{18}$, are related the control system itself.



(a) Earthquakes and *Kanai-Tajimi* filter (b) Control force and regulated output filters

Figure 3. Power spectral density of various filters

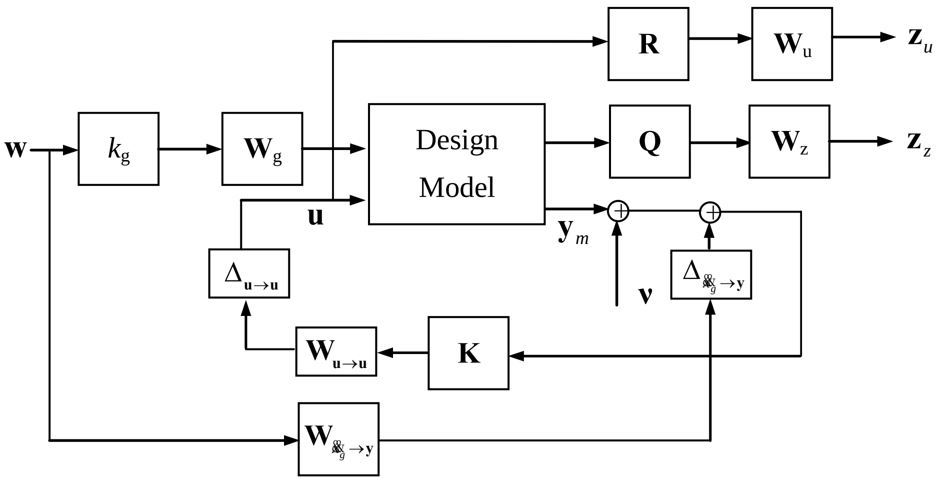


Figure 4. Block diagram of μ-controller with various filters

3.2 Analysis Results

3.2.1 Control Performances

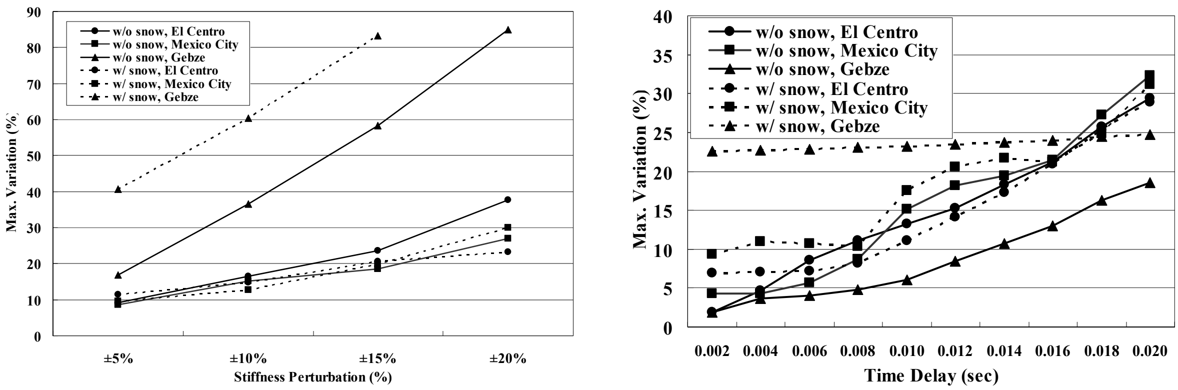
Table 1 shows the maximum values of evaluation criteria for all three earthquakes (i.e., El Centro, Mexico City and Gebze earthquakes). In Table 1, ‘Passive’ is the passive system using LRBs, ‘Active’ is the active system using HAs controlled by a μ-synthesis method, ‘Semiactive’ is the semiactive system using magnetorheological fluid dampers (MRDs) controlled by sliding mode control[5], ‘Hybrid I’ is the hybrid system using LRBs with HAs controlled by a LQG algorithm, and ‘Hybrid II’ is the hybrid system using LRBs with HAs controlled by a μ-synthesis method, respectively. As shown in Table 1, the performances of the proposed control system (i.e., Hybrid II) are superior to those of passive system and slightly better than active and semiactive systems. Furthermore, 'Hybrid II' shows similar control performances with 'Hybrid I' which uses performance-oriented control algorithm. For all considered control system satisfy the actuator requirements presented by Dyke et al.[3] (i.e., peak control force = 1000 kN, peak stroke = 0.2, peak velocity = 1 m/sec).

Table 1. Maximum evaluation criteria for all three earthquakes

Criterion	Passive	Active	Semiactive[5]	Hybrid I	Hybrid II
J_1- peak base shear	0.546	0.523	0.468	0.485	0.497
J_2- peak shear at deck level	1.462	1.146	1.283	0.921	1.170
J_3- peak overturning mom.	0.619	0.416	0.485	0.443	0.454
J_4- peak mom. at deck level	1.266	0.821	1.184	0.656	0.752
J_5- peak dev. of cable tension	0.208	0.154	0.219	0.143	0.144
J_6- peak deck displacement	3.830	1.465	3.338	1.553	1.117
J_7- normed base shear	0.421	0.368	0.370	0.377	0.360
J_8- normed shear at deck level	1.550	1.005	1.351	0.899	0.976
J_9- normed overturning mom.	0.482	0.316	0.404	0.338	0.307
J_{10}- normed mom. at deck level	1.443	0.682	1.607	0.728	0.617
J_{11}- normed dev. of cable tension	0.022	0.016	0.019	0.017	0.015
J_{12}- peak control force	2.16e-3	1.96e-3	1.96e-3	2.628e-3	2.93e-3
J_{13}- peak stroke	-	0.803	1.830	0.852	0.613
J_{14}- peak power	-	8.69e-3	-	9.35e-3	0.010
J_{15}- peak total power	-	8.19e-4	-	1.19e-3	9.51e-4
J_{16}- no. of control devices	24	24	24	48	48
J_{17}- no. of sensors	-	9	17	9	9
J_{18}- no. of resources	-	48	30	30	80

3.2.2 Controller Robustness

The evaluation model with the hybrid system controlled by a μ-synthesis method produces desirable results based on the performance criteria. However, the dynamics of the real bridge may not be expected to be identical to the numerical model, thus the robustness of the proposed control system is investigated with respect to uncertainties of stiffness and mass matrices and time delay of HAs. The stiffness perturbation of ±5%, ±10%, ±15%, and ±20% are considered and the additional mass on the bridge deck caused by snow and/or rain based on the UBC code are added in the mass matrix. The time delay of 0.002 sec ~ 0.02 sec which is 10% ~ 100% of sampling time is considered in the HAs. It is assumed that the control system fails to obtain the robustness if the maximum variation is greater than 100% and/or additional constraints (i.e., tension in the stay cable and actuator requirements) are violated. Figure 5 shows that the maximum variation of evaluation criteria versus variation of stiffness perturbation and time delay of HAs under each earthquake. As shown in Figure 5(a), the control system obtains the robustness for the stiffness perturbation without the mass perturbation. However, the control system fails to obtain the robustness with -20% stiffness perturbation and mass perturbation simultaneously under Gebze earthquake. However, for the time delay of HAs, the proposed control system obtains the robustness regardless of the mass perturbation as shown in Figure 5(b). Furthermore, the variations of evaluation criteria with respect to time delay of HAs are smaller than those with respect to stiffness perturbation in general. This is why the civil-infra structure is much massive than the electrical and mechanical structures, so the effect of time delay of actuator is smaller than when compared to electrical and mechanical control problems.



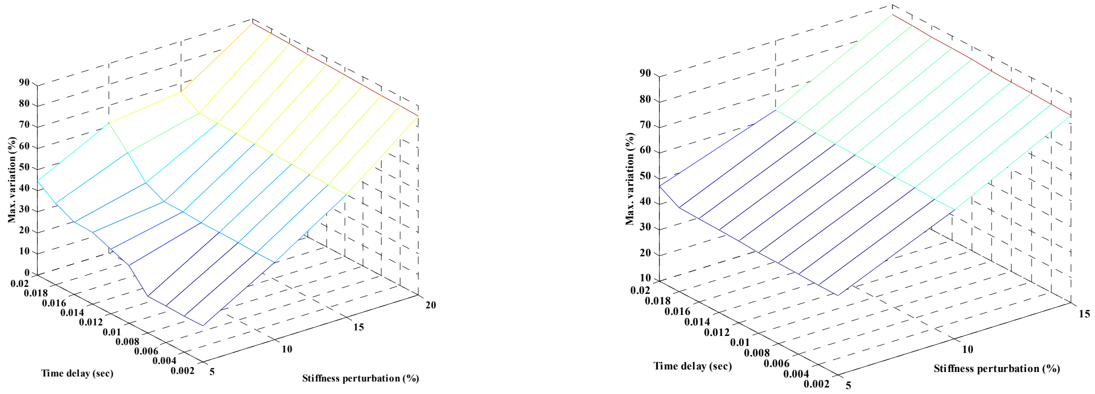
(a) Stiffness perturbation (b) Time delay of actuators

Figure 5. Robustness with respect to the stiffness perturbation and time delay of actuators

Figure 6 shows that the maximum variation of evaluation criteria for all three earthquakes when there exists stiffness perturbation and time delay of actuator simultaneously. The control system obtain the robustness without mass perturbation as shown in Figure 6(a), however, the control system fails to obtain the robustness under ±20% stiffness perturbation when there exists mass perturbation.

4. Conclusions

In this study, a hybrid control system which is composed of LRBs to reduce the earthquake-induced forces in the bridge and HAs to further reduce the bridge responses has been proposed by investigating the benchmark control problem for seismic response of cable-stayed bridges. The μ-synthesis method is used for HAs to improve the overall system robustness. Numerical simulation results show that the performances of the proposed control system is superior to those of passive system and slightly better than those of active and semiactive systems and two hybrid systems show similar control performances. Furthermore, the hybrid system controlled by a μ-synthesis method shows the good robustness without loss of control performances. Therefore, the proposed control system could be effectively be used to seismically excited cable-stayed bridge which contains many uncertainties.



(a) Without mass perturbation (b) With mass perturbation

Figure 6. Robustness with respect to the stiffness perturbation and time delay of actuators

5. Acknowledgements

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