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Decentralized seismic response control of a long span cable-stayed bridge for a benchmark problem

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Abstract

Complexity is a central problem in modern system theory and practice. The ability to study large complex systems is greatly enhanced by modern computing machinery. A theory of large-scale complex control systems is rapidly developing, supplying powerful tools that enable to solve effectively more and more practical problems in different areas.

Potential motivating advantages for using decentralized control schemes are in the reduction of transmission costs within the feedback loop, in the increasing of the reliability of the control operation in case of sensor/actuator/controller failures, the reduction of overall computational effort and the ability of parallel implementation in real time.

It is well known that the control of flexible structures represents a new, difficult and unique problem, with many difficulties in the processes of modeling, control design and implementation.

This investigation presents an overlapping decentralized control design for a cable-stayed bridge benchmark which was proposed within the structural control community to design and compare control schemes. The cable-stayed bridge has two towers as main structural elements. This naturally suggests the overlapping decomposition of a finite element overall dynamic model into two subsystems sharing a common part. Each subsystem is formed by a tower, adjacent cables and a part of the deck. The common shared part is formed by the central part of the deck.

The paper firstly describes the problem and the objectives of the control. Then the overlapping solution is proposed and the corresponding algorithm is shown.

The idea of decentralization of control has been numerically tested using a SIMULINK scheme and compared to the benchmark sample centralized control design using the LQG design.The performance of the overlapping decentralized control design has been assessed by means of given benchmark evaluation criteria, eigenvalue analysis and time responses. The dynamics of the closed-loop *benchmark model with the overlapping local controllers exhibits an acceptable behavior though slightly worse than in the centralized case.*

1. INTRODUCTION

Benchmark structural models have been proposed in recent years as challenging problems to the structural control community to design and compare control schemes for buildings and cable-stayed bridges subjected to seismic and wind excitations [1].

On the other hand, a theory of large-scale complex control systems is rapidly developing, supplying powerful tools that enable to solve effectively more and more practical problems in different areas. Particularly, the emphasis is laid on a theory synthesizing control laws under decentralized information structure constraints [2].

Overlapping decompositions and decentralized control schemes have been applied in different systems as buildings [3,4], bridges [5,6], car suspensions [7], telescopes [8], longitudinal motion control of a platoon of vehicles [9,10], etc.

In this paper, it is attempted to explore the possibility of applying overlapping decentralized control tools to the cable-stayed bridge benchmark control problem proposed in [1]. This problem deals with a long span cable-stayed bridge with two main towers, each one with over hundred cables attached to.

Among the wide variety of control methods available for decentralized control design, the overlapping decentralized LQG design with an infinite time horizon is adopted. Also, he expansion-contraction concept of extension has been employed. The sample LQG design in [1] has been selected as a reference case. Simultaneously, the control strategy implementation constraints and procedures required in [1] are a-priori satisfied when considering the overlapping decentralized LQG design. Further, the extension ensures contractibility of overlapping controllers [11].

The paper constructively describes a procedure in which the overall finite element model (FEM) of the benchmark cable-stayed bridge is decomposed into two overlapping subsystems. By expanding the original LQG problem into a larger space, the overlapping information sets become disjoint and the expanded LQG problem can be solved by standard decentralized methods. This design is made by performing a model reduction for each subsystem in expanded space. In this study the effectiveness of the overlapping decentralized control approach is tested by numerical simulations. To measure the performance, closed-loop eigenvalue analysis, calculation of evaluation criteria given in the benchmark problem, and

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analysis of time history response for selected earthquake excitations are used. The paper is an extention of the results presented in [12].

2. PROBLEM STATEMENT

Consider the cable-stayed bridge illustrated in Figure 1. It is composed of two towers and 128 cables. The bridge is excited by an earthquake longitudinal acceleration. Five accelerometers and four displacement sensors are used to supply feedback information for the control, which is produced by 24 hydraulic actuators located between the deck and the towers and the end supports acting to apply longitudinal forces on the deck. A complete physical description of the bridge, a finite element model and a MATLAB/SIMULINK simulation framework are given in [1] as a benchmark for control design. A centralized LQG control design is also presented in [13].

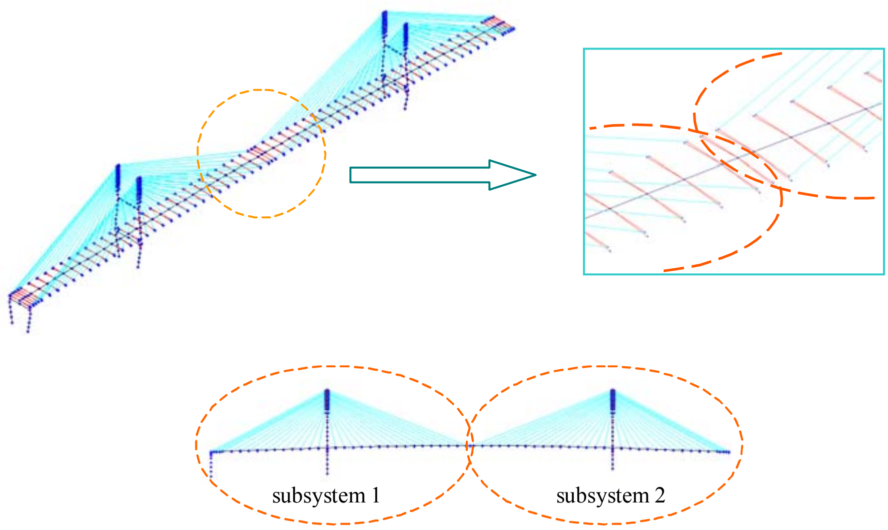

Figure 1. Bridge model and its overlapping decomposition structure

The objectives of this study are the following:

1. To propose a convenient overlapping decomposition of the bridge structure with overlapping subsystems.
2. To design an overlapping decentralized LQG active control strategy.
3. To perform simulations to assess the dynamic behavior of the benchmark bridge model when using the implemented decentralized control.

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4. To assess the performance of the overlapping decentralized control by checking eigenvalues for the closed-loop system, calculating benchmark evaluation criteria and analyzing dynamic responses under selected benchmark earthquake excitations in comparison with results obtained with the sample centralized control design.

3. SOLUTION

This section is divided into three parts: Overlapping decomposition, Overlapping decentralized control design and Simulation results

Overlapping decomposition

The decomposition of the bridge model into two subsystems is proposed. Each subsystem corresponds to one of the towers, the cables attached to it and the part of the deck where the cables are attached. This is illustrated in Figure 1. Both subsystems are interconnected through the center of the bridge. It corresponds with the part of the deck where no cable is attached. The overlapping decomposition procedure considers the towers strongly connected via deck in the part where no cable is attached. When the original model is extended, it defines a state space model in a larger space with the structure of disjoint subsystems and interconnections.

More precisely, the overall original FEM model consists of 838 states. By properly re-arranging the components of the state, input and output vectors, the overall model can be split into two overlapping subsystems. These subsystems have 414 and 434 states. The overlapping subsystem has 10 states. The overlapping common part includes one sensor but no actuator.

Overlapping decentralized control design

First, the benchmark sample LQG design has been selected as a reference. Further, the control subsystems have been defined with the same locations and models of sensors and actuators as in the reference case. The global model has 8 control inputs and 13 measured outputs. The expanded system has two subsystems with 414 and 434 states, 4 and 4 control inputs, and 7 and 7 measured outputs, respectively. There are 14 measured outputs in the expanded space because the overlapped part includes a sensor that is also expanded, i.e. doubled in the expanded space.

A decentralized control law is proposed for each free subsystem by combining its model reduction and the LQG design on the reduced order subsystems. Model reduction first forms a balanced realization and then condenses out the states with relatively small controllability and observability grammians. An algorithm follows:

Algorithm

1. Expand the original LQG problem with identified overlapping subsystems into a larger expanded space.
2. Perform model reduction for each subsystem. Select a minimal order of the subsystem's states ensuring the stability of the reduced-order models.
3. Perform the LQG with preselected weighting matrices for reduced order subsystems.
4. Contract and implement the local controllers into the original overall FEM model and run simulations.
5. Evaluate the results by computing the given benchmark evaluation criteria, the closed-loop system eigenvalues and the dynamic responses, all in comparison to the centralized control design reference case.
6. Tune the control laws by repeating the simulations for different weighting matrices until acceptable results are reached.

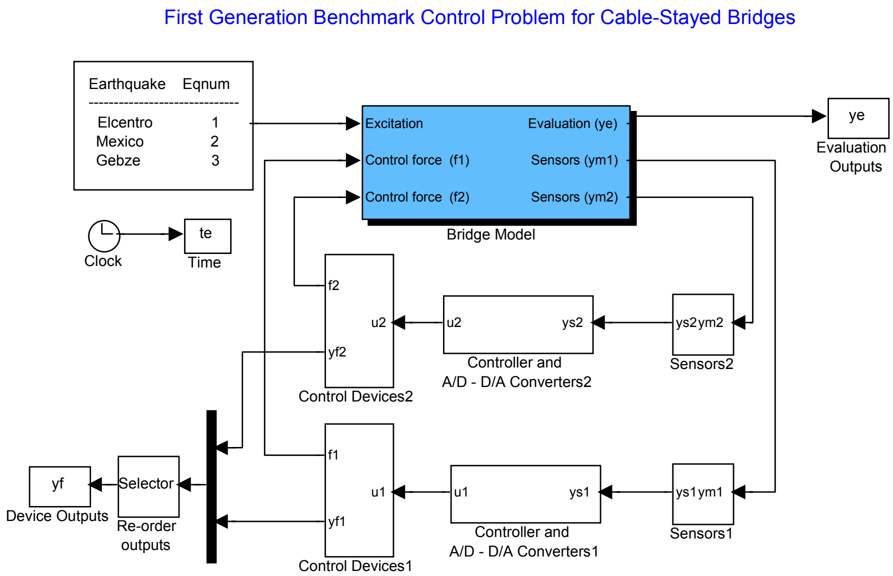

Figure 2. SIMULINK diagram of the decentralized control scheme

The expansion/contraction process with extension, the model reduction and the LQG design are performed using well-known algorithms. MATLAB/SIMULINK and Control System Toolbox are used to help in this design and also to perform the numerical evaluations. Figure 2 shows the SIMULINK diagram with the two overlapping decentralized controllers. Overlapping does not appear in the resulting controller because there is no actuator in the overlapped part. However, a common part of both subsystems formed by a part of the deck is actuated twice.

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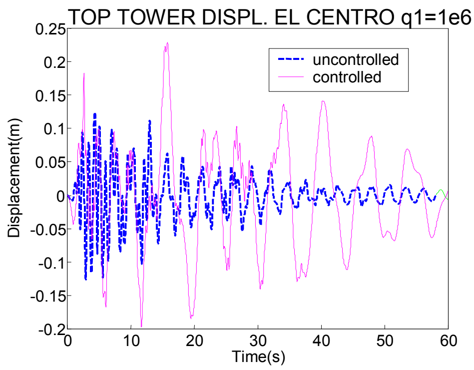

Figure 3: Tower top displacements

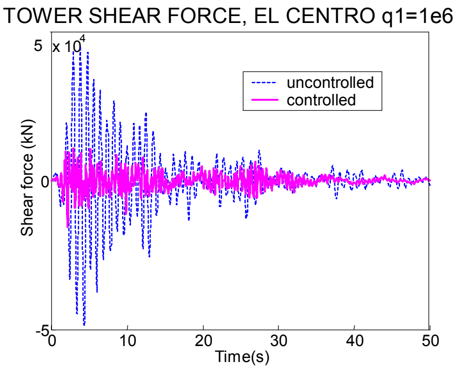

Figure 4: Tower base shear forces

Simulation results

For the overlapping decomposition of the FEM model described above, the model reduction results in reduced-order stable subsystems with a minimal dimension of 34 states for each subsystem. The decentralized LQG control design has been performed with the weighting on the state defined by the identity matrix multiplied by a scalar q_1. Some results are summarized in the following.

For one of the towers, Figures 3 and 4 show the top displacement and the base shear force, respectively, for q_1=1e6 in comparison with the uncontrolled case. The excitation is the acceleration of El Centro earthquake. From Figures 3 and 4, it is observed that the improvement achieved in reducing the tower base shear force is obtained in exchange for an increase (within an acceptable range) in the top tower displacement response with respect to the case without control.

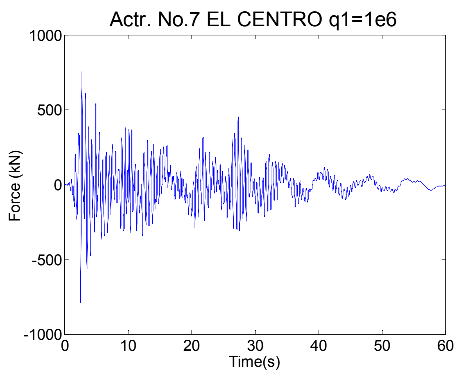

Figure 5: Actuator control force

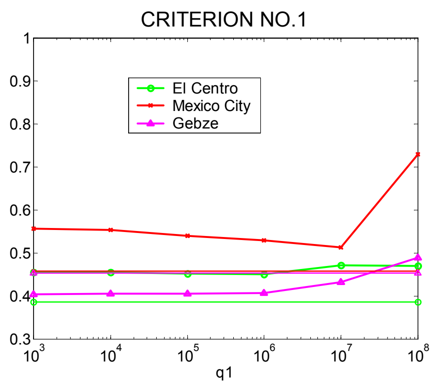

Figure 6: Benchmark criterion No.1

Figure 5 displays the control force supplied by one of the actuators located at the connection between the tower and the deck. Figure 5 shows that the control force is

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acceptable since it will always remains without reaching the saturation value of 1000 kN defined as a maximum in the benchmark sample application.

Table 1: Eigenvalues comparison (Hz)

Freq. no.	Open loop	Closed loop centralized	Closed loop overlapping
1	0.1619	0.1619	0.1619
2	0.2667	0.2667	0.2667
3	0.3725	0.2682	0.3725
4	0.4547	0.3617	0.3852
5	0.5017	0.3724	0.3877
6	0.5652	0.4547	0.4547
7	0.6190	0.5017	0.4864
8	0.6489	0.5653	0.5017
9	0.6968	0.6190	0.5054
10	0.7097	0.6489	0.5653

In order to compare the results obtained with the overlapping decentralized control with those given in the centralized reference case [1], Table 1 gives the first ten eigenvalues of the closed-loop system modes. The overlapping decentralized case corresponds to q_1=1e6.

The first two modes remain unchanged by the proposed feedback controllers. The third mode is changed in the centralized sample control design case, but it remains unchanged in the case of overlapping decentralized controllers. The other modes are in close range. This may be interpreted as a slightly better performance of the centralized control as compared to the overlapping decentralized control case.

The benchmark evaluation criterion No. 1 is presented in Figures 6 for the overlapping decentralized LQG control design with varying scalar q_1. Direct comparison with the benchmark sample centralized LQG control design case given by Table 4 in [1] is included by horizontal lines in this graph. This comparison is made for the three different earthquakes provided by the benchmark. The thick horizontal lines show the nominal (uncontrolled) values.

Criterion No. 1 is a ratio between the maximum absolute shear force at the bridge tower base over the same for the situation without control.

From Figure 6, it is observed that the overlapping decentralized control acted worse than the centralized control in the cases of earthquakes Mexico and El Centro and better in the case of Gebze Earthquake. Also, from the same Figure 6, it

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is very useful to identify an "optimal" value for the parameter q_1, in this case 1e6 has been selected.

4. CONCLUSIONS

The paper has presented simulation results of the overlapping decentralized LQG design for the cable-stayed bridge benchmark performed in a SIMULINK/MATLAB scheme. Two overlapping subsystems are considered, where each subsystem is composed of a tower, part of the deck and the set of corresponding attached cables.

The overlapping decentralized model has used the same locations and models for sensors and actuators as the reference (benchmark) case. Then the original model is expanded into a larger state space model with disjoint subsystem-interconnection structure by using the notion of extension. The proper decentralized design starts with free subsystems model reduction in expanded space. It includes also the expansion of a sensor appearing in the overlapped part. The reduced order subsystems are used as control design models.

The results look promising and confirm expectations. They are slightly worse than in the case of the sample centralized case but lie within acceptable ranges. They satisfy also the requirements on cable tensions that are known a-posteriori. This encourages applying other overlapping decentralized control design methods to this problem in the future.

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