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Robust decentralized control of structures using the LMI H_∞ controller with uncertainties

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Abstract. This paper investigates the operation of the H_∞ static output-feedback controller to reduce dynamic responses under seismic excitation on the five-story and benchmark 20 story building with parametric uncertainties. Linear matrix inequality (LMI) control theory is applied in this system and then to achieve the desired LMI formulations, some transformations of the LMI variables is used. Conversely uncertainties due to material properties, environmental loads such as earthquake and wind hazards make the uncertain system. This problem and its effects are studied in this research. Also to decrease the transition of large amount of data between sensors and controller, avoiding the disruption of whole control system and economy problems, the operation of the decentralized controllers is investigated in this paper. For this purpose the comparison between the performance of the centralized, fully decentralized and partial decentralized controllers in uncoupled and coupled cases is performed. Also, the effect of the changing the number of stories in substructures is considered. Based on the numerical results, the used control algorithm is very robust against the parametric uncertainties and structural responses are decreased considerably in all the control cases but partial decentralized controller in coupled form gets the closest results to the centralized case. The results indicate the high applicability of the used control algorithm in the tall shear buildings to reduce the structural responses and its robustness against the uncertainties.

Keywords: active control; decentralized control; robust control; uncertainty; earthquake excitation

1. Introduction

For a few decades, feedback control has attracted amount of interest in engineering fields. In the feedback structural control system, the array of sensors, actuators and controllers are used to reduce undesired vibrations during dynamic excitations such as earthquakes. When a dynamic excitation occurs, the sensors receive structural response data, and this data is transferred to controller, control commands are determined by controller and are delivered to actuators that are installed in some or all stories. The actuators apply control force to structure stories and reduce the structural response. Applying the control force to structure can be done directly (active control) or indirectly (semi-active control). Housner *et al*. (1997) have investigated structural control including active control, semi-active control and, etc. In the semi-active manner, Ghaffarzadeh (2013) has studied an optimal fuzzy logic control scheme for vibration mitigation of buildings using magneto-rheological dampers subjected to near-fault ground motions. The application of BPFs in the semi-active control algorithm concerning decrease the computational expenses is presented by Younespour and Ghaffarzadeh (2016). Two novel semi-active control methods for a seismically excited nonlinear benchmark building equipped with magnetorheological dampers are presented by Askari *et al*. (2016). Muthalif *et al.* (2017) have studied a new way to use MR damper for vibration control in semi-active manner. Braz-César and Barros (2018) have presented the application of a semi-active fuzzy based control system for seismic response reduction of a single degree-of-freedom (SDOF) framed structure. In the conventional control system, there is one controller that is named centralized control method. Manjunath and Bandyopadhyay (2005), Preumont and Seto (2008), Cheng *et al.* (2008), Ubertini (2008), Beheshti-Aval and Lezgy-Nazargah (2010), Dhanalakshmi *et al.* (2011), Korkmaz (2011), Cao and Lei (2014) have studied feedback and feedforward active controller in the centralized case.

In this case, the transition of large amounts of data between sensors and controller is difficult and lose of controller function may lead to disruption of the whole control system. In addition, because of communication requirements in the centralized control method, economical problems may be generated, especially when the large scale structural system should be controlled. Hence, decentralized control approach can be employed, so that a large scale structure is divided in to multiple substructures (Loh and Chang 2008). If a controller on a story only uses the sensor data from that story, it is named fully decentralized control but if the controller receives data from other sensors in the other substructures or stories, it is named partial decentralized control. The partial decentralized control method can be represented in some forms. When one substructure stories don't overlap with the other

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substructure stories, it is named as uncoupled partially decentralized control and in second form the non-overlapped substructure of the uncoupled method is modified into an overlapped case, and it is named as coupled partially decentralized control. Lynch and Law (2002, 2004), Wang *et al.* (2007), Johansen (2008), Bakule (2008), Chen and Nagarajaiah (2008), Lei and Lin (2009), Ma *et al*. (2010), Cha *et al*. (2013), Rubió-Massegú *et al.* (2012), Lei *et al*. (2012, 2013), Ruiz-Sandoval and Morales (2013), Yan *et al*. (2014), Yu *et al*. (2017) have studied decentralized algorithm with different methods and topics. The decentralized control creates suboptimal control, and this is a shortage of it compared to the centralized control. Therefore, choosing a suitable control algorithm in the decentralized case is necessary. This algorithm should be able to produce results in reducing the structural response toward the centralized control conclusions.

To implement the decentralized control method, some approaches have been investigated such as Homotopy method (Wang 2011, Qu *et al.* 2013) and applying sparsity patterns to the gain matrices (Wang *et al*. 2009, Palacios-Quinonero *et al*. 2014). Decentralized control has been previously utilized based on the linear quadratic regulation (LQR) (Wang *et al.* 2007, Lei and Lin 2009, Palacios-Quinonero *et al.* 2014, Chu *et al.* 2017), Linear Gaussian regulation (LQG) (Loh and Chang 2008, Lei *et al*. 2013, Kohiyama and Yoshida 2014) and sliding mode control (Ma 2008, 2010) in the literature. Wang *et al.* (2009) have investigated the design of the decentralized H_∞ controller for the large-scale civil structures.

Linear matrix inequality (LMI) has been applied for feedback control of structures (Bakule 2008, Du *et al.* 2012, Pozo *et al.* 2016, Xu *et al*. 2018). The H_∞ control method with LMI constraints was applied to reduce the complexities in the control process (Wang 2011, Jiang and Li 2011, Rubió-Massegú 2012). It should be noted that the achievement of full state information is difficult in practice, especially in large scale structures. In this case, full state feedback controller can be replaced by static-output feedback controllers.

The main problem that involves the controller design of systems is the uncertainty issue. Generally, the existence of uncertainty in modeling of a system is undeniable fact. In the control process, the operation of the model and the real system is not the same and this can be the main source of uncertainty.

This kind of uncertainty is known as systematic uncertainty and can be diminished by applying two approaches. The first one is adaptive control (Tu *et al*. 2014, Ghaffarzadeh and Aghabalaei 2017), which identifies the continual process and adapts the controller to new conditions. The second method is robust control which protects the certain properties of the control loop for the whole family of controlled plants. Schmitendorf *et al*. (1994), Materazzi and Ubertini (2012), Giron and Kohiyama (2014), have studied robust control techniques for buildings, robust structural control with system constraints and a robust decentralized control method based on dimensionless parameters respectively. Jiang and Li (2011) evaluated the effect of uncertainty in decentralized robust control of structures. The active control of intelligent structures with uncertainty using a new method for analyzing the robustness of uncertain systems has been studied by Cao *et al.* (2003). Robust H_∞ feedback control presented to vibration active control of structural systems under the uncertainty by Zhang *et al.* (2014). The main characteristic of the robust control is its formulation in both frequency and time domains. The uncertainty in the control systems can be modeled as parametric and nonparametric uncertainties. When the accurate values of the real parameters of a system are not known, parametric uncertainty is introduced. Nonparametric uncertainty should be considered when fast dynamics and nonlinearities of a system should be neglected (Wang *et al.* 2004, Lim *et al*. 2006, Morales *et al.* 2012, Du *et al.* 2012).

In this study, by considering various types of decentralization, we investigate the using of the H_∞ method for controlling structural systems subject to earthquake excitation. The static-output feedback H_∞ controller incorporated with the novel LMI constraints was designed and to be used for the control of the tall shear buildings. The robustness and the uncertainty of the models to be imposed in state space representation of the models. The robustness of the applied methodology against the parametric uncertainties was investigated.

2. Problem formulations

2.1 Parametric uncertainty formulations of static output feedback controller

The equation of motion for building structures under earthquake excitation and control forces, is written as follows

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = Bu(t) + E\ddot{x}_g(t) \tag{1}$$

Where M, C and K are $n \times n$ mass, Rayleigh damping and stiffness matrices respectively. $x(t)$ is $n \times 1$ story displacement vector relative to the ground and $u(t)$ is $r \times 1$ control force vector. The location of control forces is represented by $n \times r. B$ Matrix, and E is $n \times 1$ coefficient vector for earthquake ground acceleration, $\ddot{x}_g(t)$. n , r are also number of degrees of freedom of structure and actuator numbers located at some stories, respectively.

Since in the most control schemes the actuators not to be located in all stories of structures, the control force vector $\{u(t)\}_{r\times 1}$ can be related to the $\{u(t)\}_{n\times 1}$ control force vector using the matrix $[\theta]_{n\times r}$ in which its members corresponding to non-zero members of $\{u(t)\}_{n\times 1}$are 1 and other members are zero. By taking this matrix, the B matrix will be as

$$[B]_{n\times r} = [B]_{n\times n}[\theta]_{n\times r} \tag{2}$$

The Eq. (1) can be represented in the state-space form as

$$\begin{cases} \dot{X}(t) = AX(t) + B_u u(t) + E_w \ddot{x}_g(t) \\ y(t) = C_y\, X(t) \end{cases} \tag{3}$$

Where

$$A = \left[\frac{[0]}{-[M]^{-1}[K]}\middle|\frac{[I]}{-[M]^{-1}[C]}\right]$$
$$B_u = \left[\frac{[0]}{[M]^{-1}[B]}\right] \tag{4}$$

In the Eq. (3), $X(t)$ is the state vector and A, B_u and E_w are plant, control force coefficients and external excitation matrices, respectively. C_y is the $p \times n$ matrix, where p is the number of output. $y(t)$ is output vector. In the output feedback control theory, using the output gain matrix k, the control force. $u(t)$. is computed based on the observed output $y(t)$

$$u(t) = ky(t) \tag{5}$$

And then by substituting $y(t) = C_y X(t)$, the control force feedback is calculated

$$u(t) = kC_y X(t) = GX(t) \tag{6}$$

Where, G is the $r \times n$ state gain matrix. By substituting the control force in Eq. (3) and considering the perturbed model, the perturbed closed loop form of state equations is formed.

$$\begin{cases}\dot{X}(t) = A_{ucl}X(t) + E_w\ddot{x}_g(t)\\ y(t) = C_{ucl}X(t)\end{cases} \tag{7}$$

Where A_{ucl} and C_{ucl} are perturbed closed loop system matrices. By considering parameter uncertainties in the mass, stiffness and control force matrices, the uncertain parameters of system can be displayed as follows

$$A_{ucl} = A + \Delta A + B_u G + \Delta B_u G \tag{8}$$

$$C_{ucl} = C_z + D_z G \tag{9}$$

ΔA and ΔB_u are the additive uncertainties.

$$\Delta A = \left[\frac{[0]}{-\Delta D_k}\middle|\frac{[I]}{-\Delta D_c}\right] \tag{10}$$

$$\Delta B_u = \left[\frac{[0]}{[M]^{-1}[\Delta B]}\right] \tag{11}$$

In which $[M]^{-1}[K] = D_k$ and $[M]^{-1}[C] = D_c$. *Also*, ΔD_c *and* ΔB are perturbation time varied matrices with appropriate dimensions. In some cases of structured uncertainties, the norm bounded unstructured uncertainties are used and the norm-bounded unstructured uncertainties are described as

$$\|\Delta \boldsymbol{D}_k\| \le \delta_{a1} \,.\, \|\Delta \boldsymbol{D}_c\| \le \delta_{a2}.\, \|\Delta B_u\| = \|\Delta B\| \le \delta_{bu} \tag{12}$$

Where two-norm bounds of the uncertain stiffness and uncertain damping matrices are displayed with δ_{a1} and δ_{a2} respectively and a two norm is displayed with $\| \quad \|$. The Lagrangian representation of configuration in Eq. (7) can be described as a matched uncertain system. It should be considered that the matched uncertainties are located inside the range of the nominal control input matrix, B_u. Hence, the uncertainties that are previously discussed are expressed in the following form

$$\Delta A = B_u.\Delta A_B \,, \Delta B_u = B_u.\Delta B_{Bu} \tag{13}$$

From Eqs. (4), (10) and (12) it can be described

$$\Delta A_B = [-\Delta D_{Bk} \ - \Delta D_{Bc}].\, \|\Delta D_{Bk}\| \le \delta_{ma_1}.\, \|\Delta D_{Bc}\| \le \delta_{ma2} \tag{14}$$

$$\Delta B = B\Delta B_B \,.\, \Delta B_{Bu} = \Delta B_B \,.\, \|\Delta B_{Bu}\| \le \delta_{mbu} \tag{15}$$

For a non-singular value of B_u, the following matched forms occur

$$\Delta D_{Bk} = B_u^{-1}\Delta D_k \,.\, \Delta D_{Bc} = B_u^{-1}\Delta D_c \,.\Delta B_{Bu} = B_u^{-1}\Delta B_u \tag{16}$$

2.2 Optimal designs of the $\boldsymbol{H}_\infty$ controller with LMI

Based on the Lyapunov's theorem, for a linear system with the plant matrix A, the system is stable if there exists a positive definite matrix P($P > 0$) such that

$$A^T P + PA < 0 \tag{17}$$

The mentioned condition in Eq. (17) is named a Lyapunov inequality on P and is a special form of a LMI (linear matrix inequality). By using a family of linear systems in Eq. (7), the transfer function can be expressed as

$$H(s) \triangleq C_z(sI - A_{ucl})^{-1}E_w \tag{18}$$

From the bounded-real lemma, the H_∞ norm of the static output feedback controller is less than a prescribed $\gamma > 0$ if and only if there exists $P \ge 0$ such that

$$\begin{bmatrix} A_{ucl}^T P + PA_{ucl} + C_{ucl}^T C_{ucl} & PE_w \\ E_w^T P & -\gamma^2 I\end{bmatrix} \le 0 \tag{19}$$

Then, the existence of $P > 0$ satisfying (19) is equivalent to the existence of $Q > 0$ satisfying

$$\begin{bmatrix} A_{ucl}^T Q + QA_{ucl} + E_w E_w^T/\gamma^2 & QC_{cl}^T \\ C_{ucl}Q & -I\end{bmatrix} \le 0 \tag{20}$$

Eq. (20) is used to controller design. By substituting the values of Cucl and Aucl from Eqs. (8) and (9), Eq. (20) is changed as

$$\begin{bmatrix} QA^T + Q\Delta A^T + AQ + \Delta AQ + QG^T B_u^T + QG^T \Delta B_u^T + B_u GQ + \Delta B_u GQ + EE_w^T/\gamma^2 & QC_z^T + QG^T D_z^T \\ C_z Q + D_z GQ & -I \end{bmatrix} \le 0 \tag{21}$$

To convert the nonlinear matrix inequality (21) to the LMI problem, the new variables should be defined. For this purpose, it is supposed that $GQ = Y$ and $\gamma^{-2} = \eta$. Now, the condition (21) takes the following form

$$\begin{bmatrix} QA^T + Q\Delta A^T + AQ + \Delta AQ + Y^T B_u^T + Y^T \Delta B_u^T + B_u Y + \Delta B_u Y + EE_w^T \eta & QC_z^T + Y^T D_z^T \\ C_z Q + D_z Y & -I \end{bmatrix} \le 0 \tag{22}$$

Where Q and Y are the optimization variables. To design the output-feedback H_∞ controller with unmatched uncertainty, the LMI optimization problem can be formulated as follows

$$\begin{cases} maximize\ \eta \\ subject\ to\ Q > 0.\eta > 0\ and\ the\ LMI\ in\ Eq. (22)\end{cases} \tag{23}$$

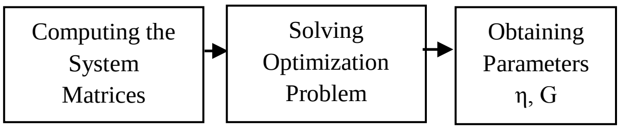


Fig. 1 The controller design algorithm with LMI

In the LMI problem it is to be supposed that $Y = kC_yQ$, hence $YQ^{-1} = kC_y$. When the optimization problem in Eq. (23) is solved, the optimal value for η is computed. The robust controller design algorithm is shown in a simple manner in Fig. 1.

3. Decentralized H_∞ controller

From the control theory, unlike the decentralized control method, for a fully centralized control of the structure, both the whole structural system and all control forces should be identified. In decentralized control, just a part of the structural information is available for local controllers but in the centralized approach, the system plant's information (a priori information) and the state data (a posteriori information) to be considered completely. The non-classical information configuration of the decentralized control approach can be identified based on the amount and type of available information to each sub-system controller. Three types of decentralized information configurations can be defined: full, partial and hierarchical decentralized control configurations. Fig. 2 illustrates the three forms of the decentralized information configuration.

In a fully decentralized control configuration, there is access to local posteriori information for each controller without any transformation of data between local controllers. If there occurs data exchange between local controllers, it is named as partially decentralized control. In the hierarchical decentralized control, as illustrates in figure 2(c), there is an additional layer of vertical information is situated besides the local controllers. In fact, the controllers of latest level create balanced relation between former layer local controllers.

In this paper, to apply the decentralized control algorithms to the static output feedback control system, the sparsity patterns are used. For this reason, some new variables are presented by using the condition (23) to produce a simple term of the controller gain matrix k. Using these new variables, it is possible to apply zero and nonzero configuration of the LMI variables that lead to creation of full decentralized and a partial decentralized controllers in coupled and uncoupled forms. The variables are defined as follows:

$$Q = SQ_SS^T + RQ_RR^T. \quad Y = Y_RR^T \tag{24}$$

Q_S and Q_R are symmetric matrices with $(n-p)\times(n-p)$ and $p \times p$ dimensions, respectively and Y_R is a general matrix with $m \times p$ dimension. S and R matrices in the Eq. (24) are $n \times (n-p)$ and $n \times p$ matrices, respectively in which S is the kernel of C_y and R is calculated as follows

$$R = C_y^T\,(C_yC_y^T)^{-1} \tag{25}$$

Now, these variables are imported in the LMI condition (22), then the LMI converts to

$$\begin{bmatrix} SQ_SS^TA^T + SQ_SS^T\Delta A^T + RQ_RR^TA^T + RQ_RR^T\Delta A^T + ASQ_SS^T + \Delta ASQ_SS^T + & * \\ ARQ_RR^T + \Delta ARQ_RR^T + RY_R^TB_u^T + RY_R^T\Delta B_u^T + B_uY_RR^T + \Delta B_uY_RR^T + EE_w^T\eta & \\ C_zSQ_SS^T + C_zRQ_RR^T + D_zY_RR^T & -I \end{bmatrix} \le 0 \tag{26}$$

Now static output feedback controller can be calculated as follows

$$\begin{cases} maximize\ \eta \\ subject\ to\ Q_s > 0.\ Q_R > 0.\ \eta > 0\ and\ the\ LMI\ in\ Eq. (26) \end{cases} \tag{27}$$

By solving the above problem, the output gain matrix is calculated as

$$k = Y_RQ_R^{-1} \tag{28}$$

By considering Eq. (28), by imposing appropriate zero-nonzero configuration on the Q_R and Y_R matrices, by using the output gain matrix, desired algorithm can be created for the structure. If we consider a five-story structure for as example, the algorithm will be as follows.

$$k = \begin{bmatrix} k_{11} & 0 & 0 & 0 & 0 \\ 0 & k_{22} & 0 & 0 & 0 \\ 0 & 0 & k_{33} & 0 & 0 \\ 0 & 0 & 0 & k_{44} & 0 \\ 0 & 0 & 0 & 0 & k_{55} \end{bmatrix} \tag{29}$$

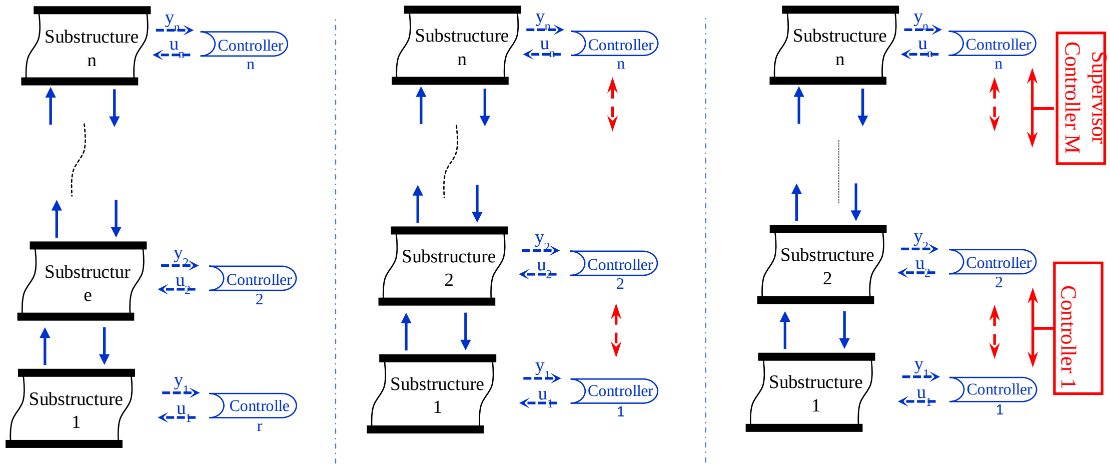
Based on the linear feedback control law, $u(t) = kC_yX(t) = GX(t)$, when the sparsity pattern in Eq. (29) is used to determine control force at each story, only state space variables on the same story are needed. For this purpose, the Q_R and Y_R matrices in Eq. (2) can be considered as

$$Q_R = \begin{bmatrix} Q_{R11} & 0 & 0 & 0 & 0 \\ 0 & Q_{R22} & 0 & 0 & 0 \\ 0 & 0 & Q_{R33} & 0 & 0 \\ 0 & 0 & 0 & Q_{R44} & 0 \\ 0 & 0 & 0 & 0 & Q_{R55} \end{bmatrix}$$
$$Y_R = \begin{bmatrix} Y_{R11} & 0 & 0 & 0 & 0 \\ 0 & Y_{R22} & 0 & 0 & 0 \\ 0 & 0 & Y_{R33} & 0 & 0 \\ 0 & 0 & 0 & Y_{R44} & 0 \\ 0 & 0 & 0 & 0 & Y_{R55} \end{bmatrix} \tag{30}$$

In the uncoupled case, the control force on one story in each substructure is determined based on the state space variables of stories in the same substructure. The output gain matrix in the static-output feedback controller should take the following configuration

$$k = \begin{bmatrix} k_{11} & k_{12} & 0 & 0 & 0 \\ k_{21} & k_{22} & 0 & 0 & 0 \\ 0 & 0 & k_{33} & k_{34} & k_{35} \\ 0 & 0 & k_{43} & k_{44} & k_{45} \\ 0 & 0 & k_{53} & k_{54} & k_{55} \end{bmatrix} \tag{31}$$

In this special case, the five-story building structure is divided in to the two substructures that one of the substructures has two stories and the other one has three



(a) fully decentralized control (b) partially decentralized control (c) hierarchical decentralized control

Fig. 2 Configuration of the decentralized information

stories. Hence, the variable matrices should get the form that is adopted with the output gain matrix. Therefore, we have

$$Q_R = \begin{bmatrix} Q_{R11} & 0 & 0 & 0 & 0 \\ 0 & Q_{R22} & 0 & 0 & 0 \\ 0 & 0 & Q_{R33} & 0 & 0 \\ 0 & 0 & 0 & Q_{R44} & 0 \\ 0 & 0 & 0 & 0 & Q_{R55} \end{bmatrix}$$

$$Y_R = \begin{bmatrix} Y_{R11} & 0 & 0 & 0 & 0 \\ 0 & Y_{R22} & 0 & 0 & 0 \\ 0 & 0 & Y_{R33} & 0 & 0 \\ 0 & 0 & 0 & Y_{R44} & 0 \\ 0 & 0 & 0 & 0 & Y_{R55} \end{bmatrix} \tag{32}$$

For the coupled case, that occurs overlapping between substructures, the state variables from both the ith story and neighboring stories are used to determine the control force of the ith story. For the five-story building structure with two substructures including three stories, the output gain matrix in the static-output feedback controller will have the following form

$$\mathrm{k} = \begin{bmatrix} \mathrm{k}_{11} & \mathrm{k}_{12} & \mathrm{k}_{13} & 0 & 0 \\ \mathrm{k}_{21} & \mathrm{k}_{22} & \mathrm{k}_{23} & 0 & 0 \\ \mathrm{k}_{31} & \mathrm{k}_{32} & \mathrm{k}_{33} & \mathrm{k}_{34} & \mathrm{k}_{35} \\ 0 & 0 & \mathrm{k}_{43} & \mathrm{k}_{44} & \mathrm{k}_{45} \\ 0 & 0 & \mathrm{k}_{53} & \mathrm{k}_{54} & \mathrm{k}_{55} \end{bmatrix} \tag{33}$$

Similarly, to compute control static-output feedback controller gain matrices for this case, variable matrices should be defined that satisfy the gain matrix (33). Then, there were

$$Q_R = \begin{bmatrix} Q_{R11} & 0 & 0 & 0 & 0 \\ 0 & Q_{R22} & 0 & 0 & 0 \\ 0 & 0 & Q_{R33} & 0 & 0 \\ 0 & 0 & 0 & Q_{R44} & 0 \\ 0 & 0 & 0 & 0 & Q_{R55} \end{bmatrix} \tag{34}$$

$$Y_R = \begin{bmatrix} Y_{R11} & Y_{R12} & Y_{R13} & 0 & 0 \\ Y_{R21} & Y_{R22} & Y_{R23} & 0 & 0 \\ Y_{R31} & Y_{R32} & Y_{R33} & Y_{R34} & Y_{R35} \\ 0 & 0 & Y_{R43} & Y_{R44} & Y_{R45} \\ 0 & 0 & Y_{R53} & Y_{R54} & Y_{R55} \end{bmatrix}$$

Now the state gain matrix can be computed as follows: $G = kC_y$

4. Numerical example

4.1 Five-story building structure

In order to demonstrate the procedure for the use of decentralized H_∞ control and its advantages for the robust control against matched case uncertainties, the numerical example of a five-degree-freedom structure, equipped with active tendons in all its stories, is considered. As shown in Fig. 3, in the shear model of the structure, one actuator is considered between two adjacent stories. The actuators at each floor produce a pair of adversary control forces. Earthquake ground acceleration, $\ddot{x}_g$, is applied at the base of the structure.

The mass and stiffness matrices in Eq. (1) for the structure are assumed as the following.

$$M = 10^3 \times \begin{bmatrix} 215.2 & 0 & 0 & 0 & 0 \\ 0 & 209.2 & 0 & 0 & 0 \\ 0 & 0 & 207 & 0 & 0 \\ 0 & 0 & 0 & 204.8 & 0 \\ 0 & 0 & 0 & 0 & 266.1 \end{bmatrix} kg$$

$$K = 10^6 \times \begin{bmatrix} 260 & -113 & 0 & 0 & 0 \\ -113 & 212 & -99 & 0 & 0 \\ 0 & -99 & 188 & -89 & 0 \\ 0 & 0 & -89 & 173 & -84 \\ 0 & 0 & 0 & -84 & 84 \end{bmatrix} \frac{N}{m} \tag{35}$$

By considering a 5% damping ratio between two first modes of the structure the Rayleigh damping matrix is determined.

$$C = 10^5 \times \begin{bmatrix} 6.5042 & -2.3111 & 0 & 0 & 0 \\ -2.3111 & 5.4894 & -2.0248 & 0 & 0 \\ 0 & -2.0248 & 4.9864 & -1.8203 & 0 \\ 0 & 0 & -1.8203 & 4.6675 & -1.7180 \\ 0 & 0 & 0 & -1.7180 & 3.1853 \end{bmatrix} \frac{Ns}{m} \tag{36}$$

Based on the location of the actuators in Fig. 3, the control force location matrix is

$$B = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{37}$$

The excitation location vector E in Eq. (1) is calculated as

$$10^3 \times [-215.2 \ -209.2 \ -207 \ -204.8 \ -266.1]^T \tag{38}$$

For considering the uncertainty, the Norm-Bounded uncertainties are taken as $\Delta M = +10\% M.\ \Delta K = +10\% K \ and \ \Delta C = -10\% C.$ It is evidence that by creation of changes in the mass matrix, the uncertainties are applied to the E_w, too. By considering Eq. (17) and $\|\Delta D_{Bk}\| \leq 0.2222\ \|B_{u2}^{-1} D_k\| = 2.0937 \times 10^8 = \delta_{ma1}.\ \|\Delta D_{Bc}\| \leq 0.2222 \|B_{u2}^{-1} D_c\| = 5.2694 \times 10^5 = \delta_{ma2}.$ and$\delta_{ma} = 2.0937 \times 10^8$. Also, from Eq. (16), we have ΔB_{Bu} that it is assumed $\Delta B_{Bu} \leq 0.1.$ The uncertainties percent that are represented above, create the smallest $D_c + \Delta D_c$, by considering $\Delta C = -0.1C$ and $\Delta M = 0.1M$ and the largest $D_k + \Delta D_k$ from $\Delta K = 0.1K$ and $\Delta M = 0.1M$. Hence, from $D_k = M^{-1}K$, we will have $D_{k2} = (1.1)^{-1} M^{-1} (1.1) K = M^{-1}K$, therefore, $\Delta D_k = 0$. Similar to previous computations, $\Delta \mathrm{D_c} = 0.1819 \mathrm{D_c}$ and $\Delta \mathrm{B_u} = -0.1$ are computed. Now, system matrices A and $\mathrm{B_u}$ take the following form

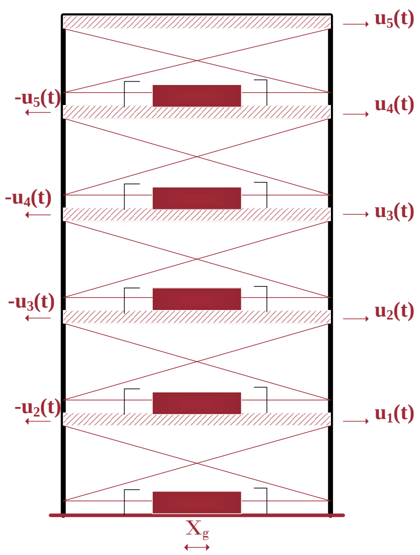


Fig. 3 Shear Modeling of the five-story structure with active tendon system

$$\begin{aligned} \mathrm{A} &= \begin{bmatrix} 0_{5\times5} & \mathrm{I}_{5\times5} \\ -(\mathrm{D_k} + \Delta \mathrm{D_k}) & -(\mathrm{D_c} + \Delta \mathrm{D_c}) \end{bmatrix} \\ &= \begin{bmatrix} 0_{5\times5} & \mathrm{I}_{5\times5} \\ -\mathrm{D_k} & -0.8181 \mathrm{D_c} \end{bmatrix} \\ \mathrm{B_u} &= \begin{bmatrix} 0 \\ 0.9 \mathrm{B_u} \end{bmatrix} \end{aligned} \tag{39}$$

4.1.1 Perturbed centralized static-output feedback controllers

By supposing above perturbed system matrices and solving the LMI optimization problem in Eq. (27) with normal symmetric configuration for Q_s, Q_R and general configuration for Y_R matrix, the optimum values for η and LMI variables, $Y_R . Q_R$, are calculated. Then by considering $k = Y_R Q_R^{-1}$ and $kC_y = G$, that in former sections is displayed, velocity state gain matrix, C_{uc} for the perturbed centralized case is obtained as follows

$$10^6 \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -3.3472 & 0.4567 & 0.3003 & 0.1221 & 0.0918 \\ 0 & 0 & 0 & 0 & 0 & 0.5125 & -3.1368 & -0.0084 & 0.2168 & 0.0681 \\ 0 & 0 & 0 & 0 & 0 & 0.3743 & 0.0678 & -2.9287 & 0.1117 & 0.1597 \\ 0 & 0 & 0 & 0 & 0 & 0.1983 & 0.2810 & 0.1341 & -3.1065 & 0.0746 \\ 0 & 0 & 0 & 0 & 0 & 0.1233 & 0.1168 & 0.1824 & 0.0814 & -3.2552 \end{bmatrix} \tag{40}$$

Based on the minimization of the H_∞ transform function in the centralized case, the optimization value of the δ gets as, $\delta_o = 0.7115$.

4.1.2 Perturbed decentralized static-output feedback controllers

4.1.2.2 Fully decentralized controller

For the fully decentralized control system, the gain matrix has a diagonal form. Based on the matrices form in Eq. (31), since $kQ_R = Y_R$, we will have $k = Y_R Q_R^{-1}$, hence for getting the desired form of the gain matrix, defining diagonal form for Y_R and Q_R matrices is necessary. Similar to the former section the perturbed state velocity gain matrix, $\mathrm{G_{udf}}$ in this case is computed as follows

$$10^6 \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -3.8206 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -2.4182 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.8441 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.5084 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.3473 \end{bmatrix} \tag{41}$$

4.1.2.3 Perturbed partial decentralized controller (uncoupled)

In the uncoupled form, subsystems do not have any overlapping with each other. Then, the perturbed gain matrix and its construction matrices get matrix forms in Eqs. (31) and (32) respectively. The perturbed state gain matrix calculation process is similar to before sections. In this example a five story building structure is divided in to two substructures. First substructure is constructed of first and second stories and second substructure is included with third, fourth and fifth stories.

$$10^6 \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -3.8206 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -2.4182 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.8441 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.5084 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.3473 \end{bmatrix} \tag{42}$$

4.1.2.4 Perturbed partial decentralized controller (coupled)

In this case, based on the output gain matrix form in Eq. (33), we have the following matrix for G_{udc}.

$$10^7\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -3.8947 & 2.8771 & 0.1485 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.6626 & -5.8266 & 2.6145 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2273 & 2.9300 & -5.6907 & 2.7357 & -0.0818 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.9630 & -5.4345 & 2.6178 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0398 & 2.5964 & -4.4558 \end{bmatrix} \quad (43)$$

Unlike the uncoupled case, in the coupled case the control force in the overlapping story between substructures is calculated based on the state variables from that story and neighboring stories. In this case similar to uncoupled case, there are two substructures but the first substructure consists of first, second and third stories and second substructure contains of third, fourth and fifth stories. In the coupled case third story is overlapping story.

4.1.3 Results

Full-scale North-South Kobe 1995 seismic record with an absolute acceleration peak of 8.18 $\frac{m}{s^2}$ is used as the ground excitation for example model. The record acceleration and velocity are shown in Figs. 4 and 5 respectively.

As indicated, in each story of the structure, one actuator to produce active control force and importing it in to the story is deployed. It is supposed that the actuators don't have any time delay and have unlimited capacity to generate the control force. For taking into account the uncertainty, the structure is modeled under uncertain conditions as shown in the previous section. The fifth story perturbed displacement and velocity time histories in five-story building structure are shown in Figs. 6 and 7. As shown in figures, applying the control algorithms, make the notable decrease in the displacement and velocity amounts of the fifth floor.

The maximum displacement in the uncontrolled case gets 48.67 cm value, this value decreases in centralized, fully decentralized, partial decentralized (uncoupled) and partial decentralized (coupled) cases to the following values respectively: 7.45, 9.53, 8.52 and 7.53 cm. The maximum velocity is 308.91 cm/s, but similar to the displacement, this parameter in the centralized, fully decentralized, partial decentralized in uncoupled and coupled cases gets the following values: 77.05, 86.41, 82.44 and 77.63 cm/s. according to the above results among the control cases after the centralized controller, decentralized controller in coupled case gets best values. Also based on the results, despite the perturbation, the decrease in displacement and velocity responses is notable.

Comparing the results of the perturbed model containing uncertainty in its dynamical properties with the model without uncertainty can show the amount of the robustness of the control method. The results of the maximum inter story drifts for the perturbed and unperturbed models are plotted in Fig. 8. As shown in Fig. 8, all four controlled cases of control strategies are achieved a great reduction at inter story drifts in both perturbed and unperturbed models. In the four top stories, the biggest reduction in results has occurred in the decentralized case with uncoupled configuration, and the smallest reduction is related to fully decentralized case, but there are not considerable differences among the controlled cases.

It can be derived that partial decentralized cases are taken better performance and fully decentralized is showed worst performance. Fig. 8(b) includes the comparison results of the inter story drifts for the perturbed model with uncertainty. Results are similar to the unperturbed model (Fig. 8(a)) with a little increase in responses. Again, the best performance is resulted in partial decentralized case. The time history of control forces applied in the fifth floor for both the perturbed and unperturbed models are shown in Fig. 9.

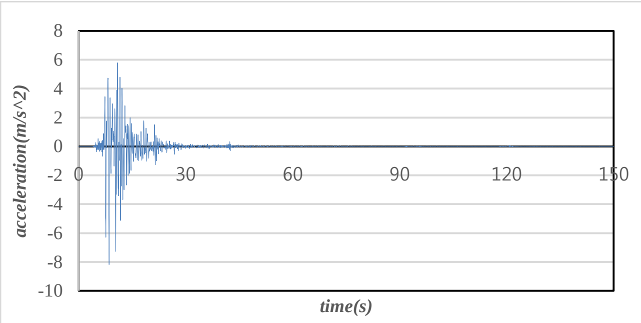


Fig. 4 The full-scale North-South Kobe 1995 seismic record acceleration

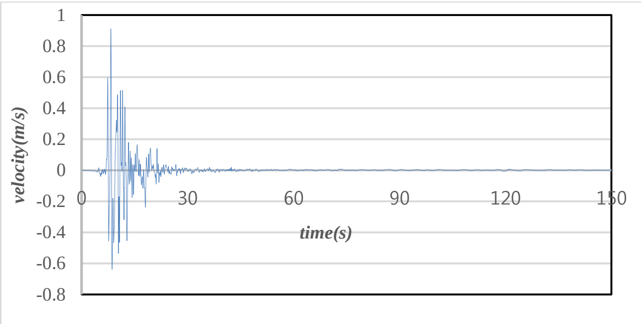


Fig. 5 The full-scale North-South Kobe 1995 seismic record velocity

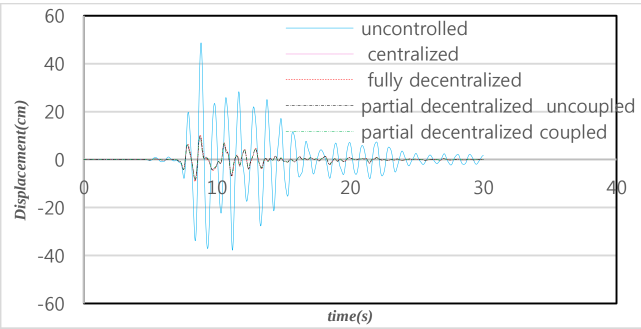


Fig. 6 The time history of the perturbed displacement response of the example model in the fifth floor under earthquake excitation and applying several control strategies

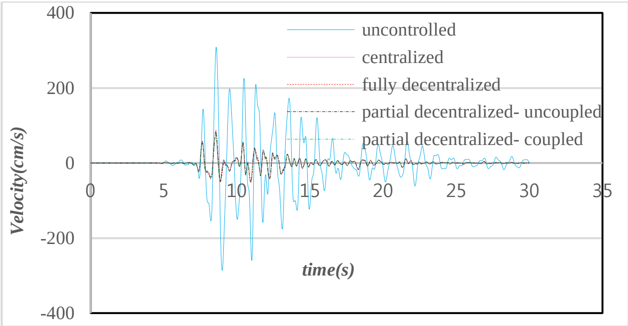
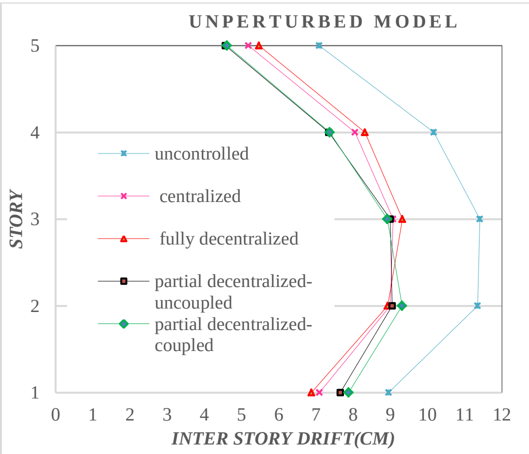
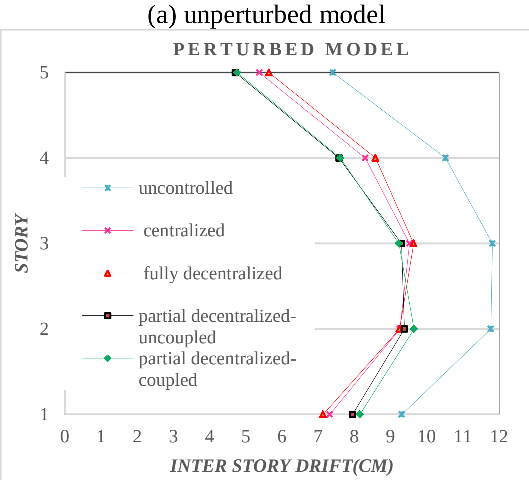


Fig. 7 The time history of the perturbed velocity response of the example model in the fifth floor under earthquake excitation and applying several control strategies



(a) unperturbed model

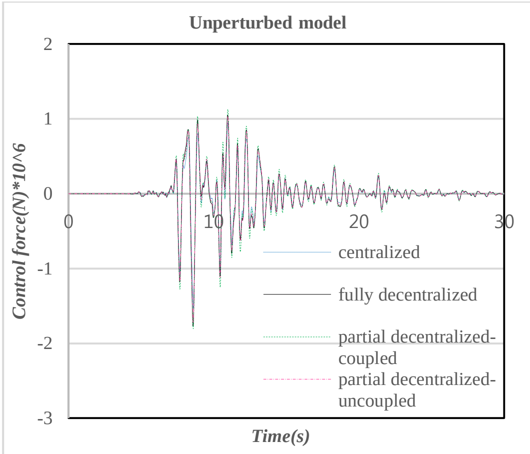


(b) perturbed model

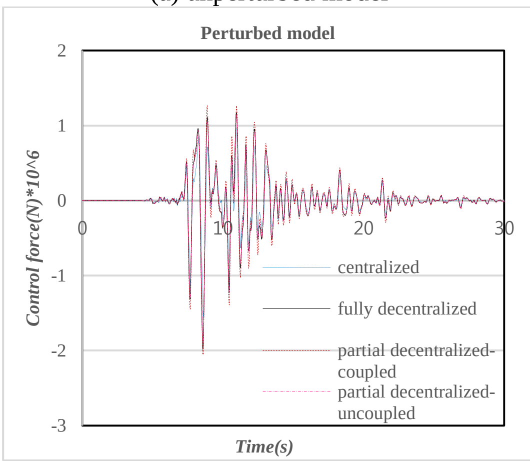
Fig. 8 Inter story drifts for five story building structure

The control forces in the perturbed and unperturbed models for three cases of decentralized control (fully decentralized, partial decentralized coupled and uncoupled), with a little difference, adapt with the centralized controller.

Fig. 10 comprises an unperturbed model and a perturbed model for centralized and fully decentralized cases in displacement responses at supposed 8.94th second. It can be shown that the used algorithm has very good robustness against the uncertainty of the parameter.



(a) unperturbed model



(b) perturbed model

Fig. 9 The time history of maximum control force in the fifth floor for five story building

There happens a little increase in the value of displacement in the perturbed model compared to the unperturbed model. In the centralized case the difference is 14 mm moderately, and this value for the fully decentralized case is 8 mm.

The requirement of maximum control forces in the centralized, fully decentralized, partial decentralized (coupled and uncoupled) cases in the unperturbed model and perturbed model are compared in the Table 1. Intermediately there happens 0.15 N difference in the value of the maximum control force between the nominal model and perturbed model. This negligible difference indicates that the used control algorithm has notable robustness against the uncertainties. Also based on the results it can be seen that partial decentralized controller in uncoupled case gives the closest results to the centralized controller. Among four controlled cases, the largest peak control force value belongs to the partial decentralized coupled control case.

To investigate the performance of the used control method, the maximum singular values of the closed loop pulse transfer function with different arrangement of gain matrices and the open loop pulse transfer function in the unperturbed and perturbed models are presented in Figs. 11(a) and 11(b), respectively. It can be clearly seen the structure resonant frequencies that in the uncontrolled system happen at the 1.03, 2.84, 4.51,5.81 and 6.76 Hz, with singular values 0.9276, 0.5228, 0.2656, 0.1509 and 0.1063 are decreased considerably with H_{∞} output-feedback controller in four cases.

Fig.11(a) shows that all of the controlled cases that have an important role to mitigate the structural response in the resonant frequencies, but fully decentralized and centralized controllers have the largest decreasing in the building vibrational responses and partial decentralized controllers specially in frequencies larger than 3.5 Hz, have a little distance with them. These investigations are performed for the perturbed model. The results, in this case, are presented in Fig. 11(b). The graphic shows the building resonant frequencies are located at 1.01, 2.82, 4.49, 5.79 and 6.76 Hz and the singular values corresponding to these frequencies are 1.1335, 0.6381, 0.3232, 0.1813 and 0.1261. By comparing the unperturbed model and perturbed model, it can be seen that natural singular values have increased about 0.2 in the uncontrolled structure by entering uncertainties to the building model. The different control cases have shown a considerable reduction in resonant frequency responses in the perturbed model. There is a little increment in singular values at resonant frequencies about 0.09 are occurring in the perturbed model.

Fig. 12 shows the time history of inter-story drift responses in the fifth floor in the perturbed and nominal models for centralized and fully decentralized cases. It can be seen that in both of the centralized and fully decentralized cases, responses have notable reduction in comparison with uncontrolled case, also, nominal and perturbed models get very similar results, that can be said they are coincident.

By comparing four cases in Fig. 13, in the uncontrolled form there is the large value of H_{∞}-norm that means the transfer function of excitation input w_2 to control output z has a maximum value that is the worst-case.

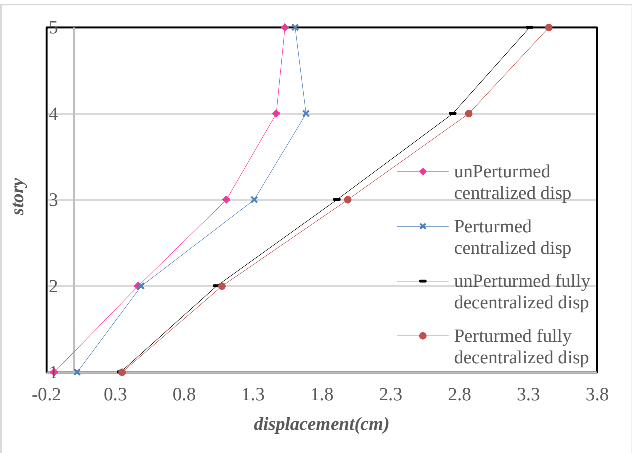
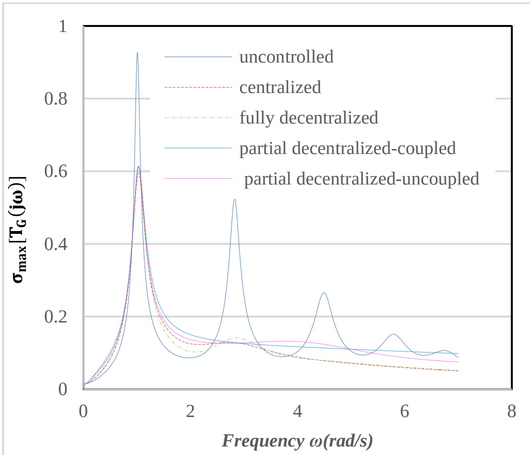


Fig. 10 Comparison of displacements for the unperturbed model and perturbed model in the centralized and fully decentralized cases at 8.94th second

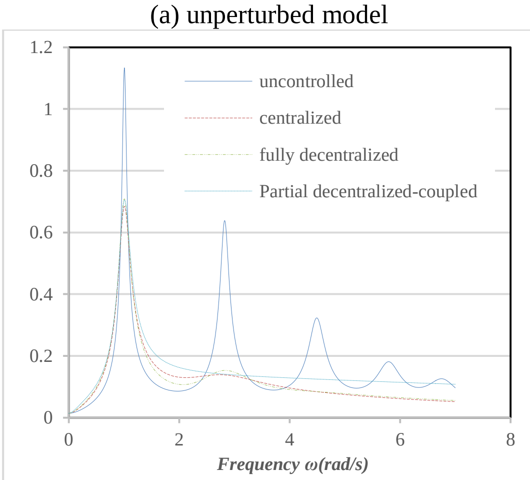
Table 1 Comparison of maximum requirement control force in four control cases for nominal and perturbed model in the fifth story

$\times 10^6 N$	Cen[1]	F.D[2]	P.D[3] coupled	P.D uncoupled
unperturbed	1.5246	1.7674	1.8056	1.715
Perturbed	1.5444	1.9832	2.0554	1.8992

Cen[1]: Centralized; F.D[2]: Fully Decentralized; P.D[3]: Partial Decentralized



(a) unperturbed model



(b) perturbed model

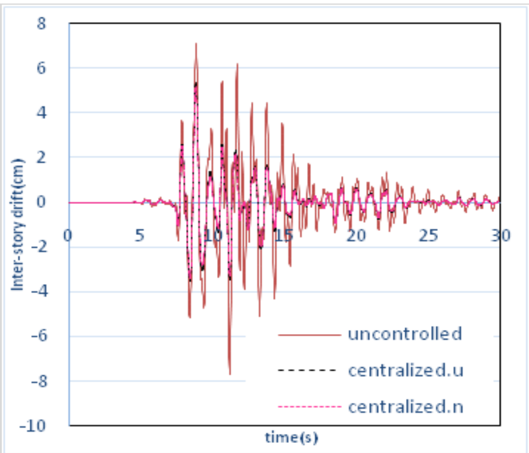
Fig. 11 Maximum singular values for five story building structure

Among the four controlled cases, the centralized control takes the minimum value of H_{∞} norm, because in this case all state variables are available to calculate the gain matrix and control decisions. The centralized control method has the best performance among the other control cases, and it needs all information about structural responses.

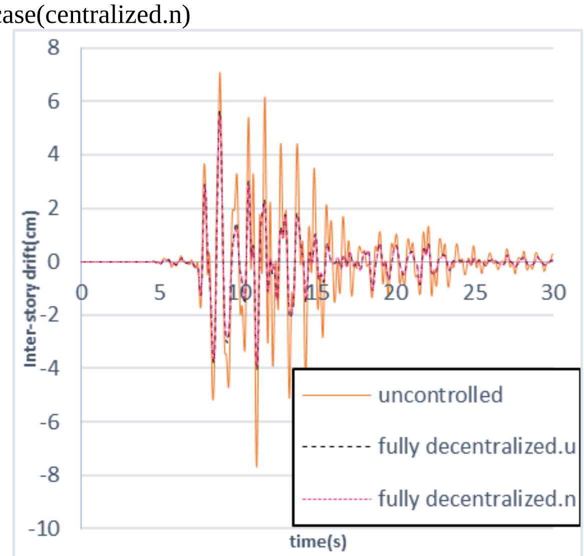
Second class among the controlled cases is decentralized case that is divided in to three groups. From this class, the fully decentralized case has the largest H_{∞} norm among the controllers. This result is reasonable because the least accessibility to information about the structure for each control device occurs in this case. In the decentralized class, there are coupled and uncoupled cases that coupled case has the lowest H_∞ norm among the decentralized cases. Because, existence stories in every substructure have relation with the stories from the other substructures, hence, that takes more information about the structure comparing the other decentralized cases. Other part of Fig. 13 is appertained to perturbed model of the structure. It can be easily shown the increase of norms compared rather than the nominal case. This is because of the existence of the uncertainty in the structural parameters.

4.2 The 20-story benchmark building with uncertainty

To investigate the operation of H_∞ control and its robustness against uncertainties in large-scale structures, a 20 story benchmark building structure is simulated. The building is modeled as a lumped-mass shear structure that actuators are located between the neighboring stories.



(a) centralized model in perturbed case with uncertainty(centralized.u) and in nominal case(centralized.n)



(b) fully decentralized model in perturbed case with uncertainty (fully decentralized.u) and in nominal case(fully decentralized.n)

Fig. 12 The time history of inter story drifts in the fifth floor for five story building

The mass and stiffness parameters of building for every story have the following values

$$m_1 = 1.126 \times 10^6 kg.m_2 - m_{19} = 1.1 \times 10^6 kg.m_{20} = 1.17 \times 10^6 kg.k_1 - k_5 = 862.07 \times \frac{10^6 N}{m}.k_6 - k_{11} = 554.17 \times \frac{10^6 N}{m}.k_{12} - k_{14} = 453.51 \times \frac{10^6 N}{m}.k_{15} - k_{17} = 291.23 \times \frac{10^6 N}{m}.k_{18} - k_{19} = 256.46 \times \frac{10^6 N}{m}.k_{20} = 171.7 \times \frac{10^6 N}{m}$$

the damping ratio is %5. A Kobe 1994 full scale earthquake is applied to the base of the building. The H_∞ controller is designed in centralized and decentralized cases. Also, the decentralized controller is implemented in four cases that are shown in Fig. 14.

Each case in Fig. 14 has some substructures that include a limited number of stories and there is one controller for each substructure. A substructure's controller is allowed to access the sensor data within that substructure.

Centralized controller has one substructure that covers 20 stories, fully decentralized case has 20-substructures that each substructure covers one story, the partial decentralized controller in the uncoupled case has five substructures covering four stories in every substructure.

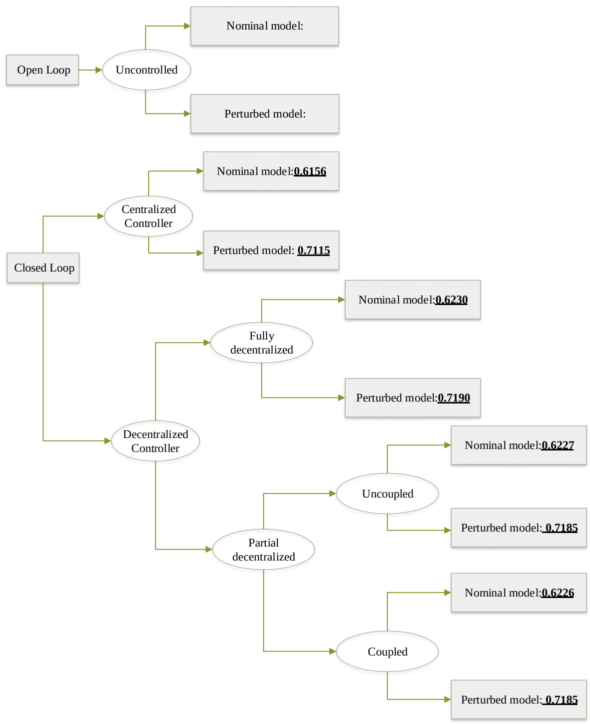
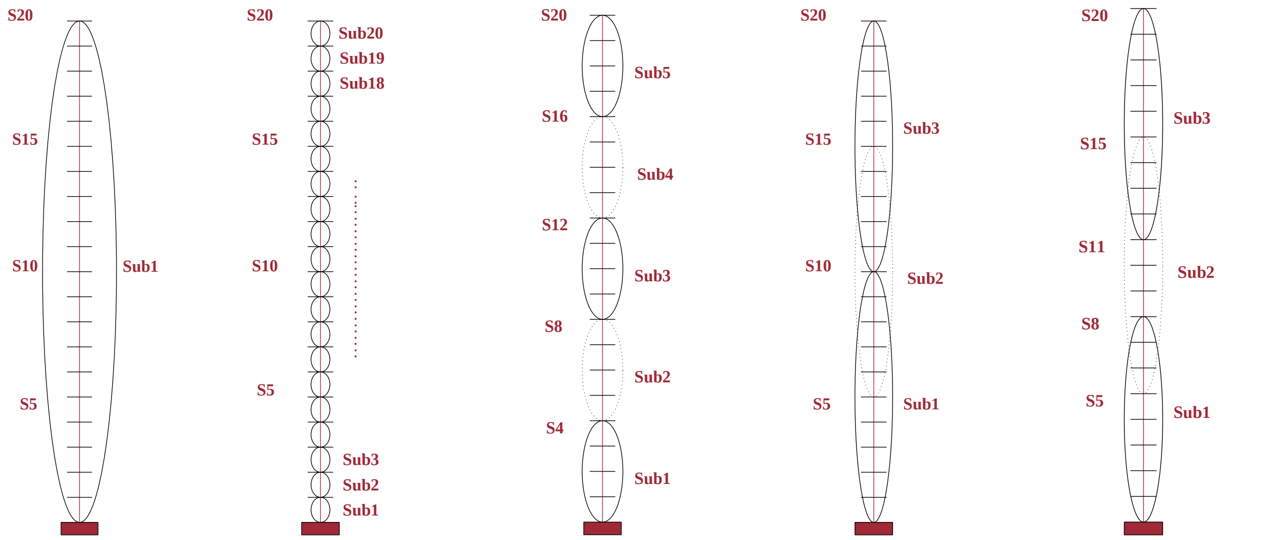
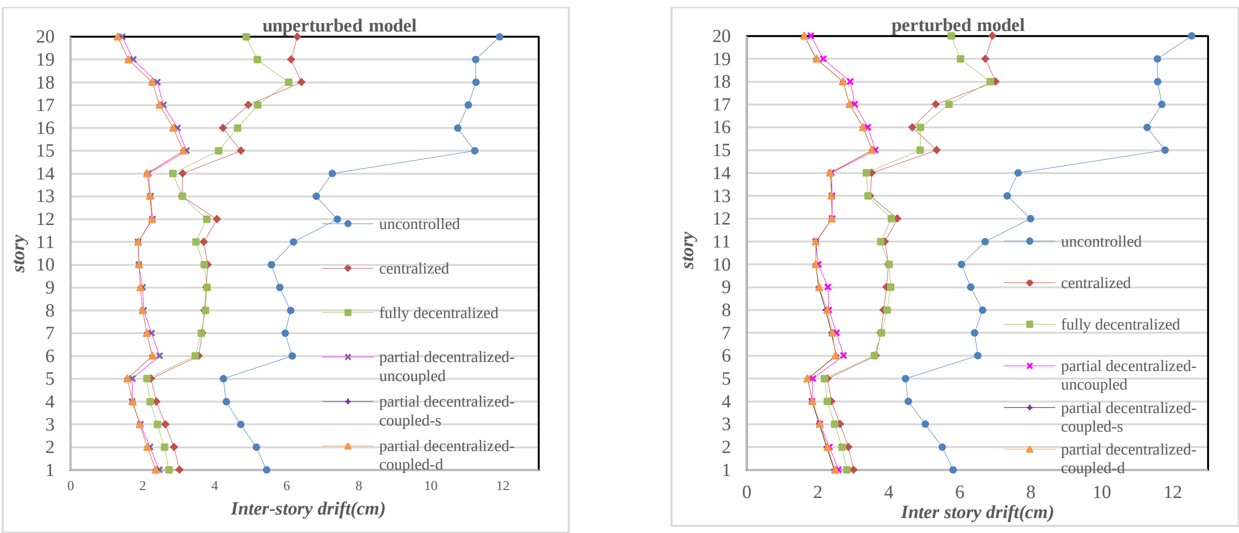


Fig. 13 H_∞ norms of the open loop transfer function H_{zw} and the closed loop transfer function H_{zw} in different degrees of centralization



(a) Centralized controller
(b) fully decentralized controller
(c) partial decentralized controller (uncoupled)
(d) partial decentralized controller (coupled) equal stories
(e) partial decentralized controller (coupled) different stories

Fig. 14 Different controller algorithms for the 20 story benchmark building



(a) (b)

Fig. 15 Inter story drifts for 20 story building in the six cases in the (a) Unperturbed model and (b) Perturbed model

Also, the partial decentralized controller in coupled case has two formats, first with three substructures covering equal story numbers in each substructure and second with three substructures covering different story numbers in each substructure. In the coupled case, there are overlaps between substructures. For stories that there exist in overlapping substructures, controllers should have access to data from all the overlapping substructures. Simulations are performed for above cases in the nominal model and perturbed model. Fig. 15 shows maximum-inter story drifts in six cases for nominal and perturbed models, respectively.

As shown in Fig. 15, in all control schemes, the maximum inter-story drifts are reduced compared to the uncontrolled case. The partial decentralized controller results similar values for the maximum inter story drifts in all stories in coupled case with different numbers of stories in each substructure (partial decentralized-coupled-d), coupled case with the same numbers of stories in each substructure (partial decentralized-coupled-s) and uncoupled case. Also, it achieves larger mitigation of drifts at all stories compared to the fully decentralized and centralized controllers.

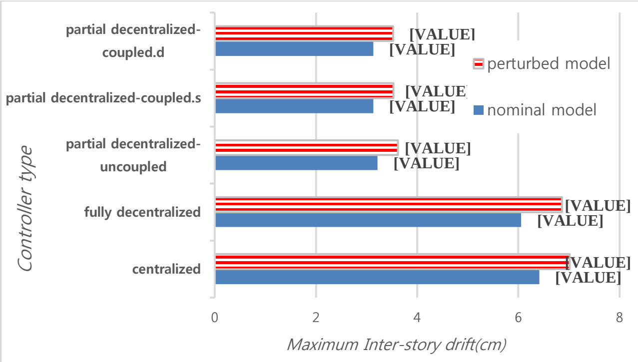


Fig. 16 Comparison of the maximum inter story drifts among all stories between nominal model and perturbed model

There happens 89% reduction in drift response in the 20th story compared to an uncontrolled case in the partial decentralized control case. This reduction is 59% and 47% for the fully decentralized controller and centralized controller, respectively. The comparison between the fully decentralized controller and the centralized controller shows that these two cases have similar results in most of the stories, just in the two top stories centralized controller results inter story drifts larger than the fully decentralized controller. Fig. 15(b) includes the maximum inter story drifts for six cases in perturbed model. But, it should be considered that is similar to the nominal model. Partial decentralized controllers give the largest reduction in responses. The partial decentralized-coupled-d and the partial decentralized-coupled-s are almost coincident, but unlike the nominal model, the uncoupled case has a little distance with them. The fully decentralized controller and centralized controller have results close to each other alone in the 19th and 20th story. The fully decentralized controller has responses less than the centralized controller and this difference is 0.7 and 1.16 cm, respectively. In the perturbed model, responses are increased, but this increment is not notable. Fig. 16 shows the comparison between inter story drift responses in the two nominal and perturbed models.

As shown in Fig. 16, the biggest growth in inter story drift responses in the perturbed model occurs in the fully decentralized case that it's about 8 mm. This is not significant change and it can be said that the used control method is robust against the uncertainties in large scale building structures.

5. Conclusions

In this work, a static-output feedback control with centralized and decentralized approach to reduce the building structure's responses by considering the uncertainties has been presented. For this purpose, a robust H_∞ controller is used to mitigate the complications of the robust controller. Moreover, the linear matrix inequalities are applied to the controller formulations. This approach is developed to consider the various forms of decentralization, including the fully decentralized controller, the partial coupled decentralized controller and the partial uncoupled decentralized controller with a change in the number of stories in substructures like substructures with the same number of stories and substructures with different number of stories and the effect of them on the structural responses. Also, the effect of uncertainties is investigated on the structural responses and the ability of the proposed control method for resistance against the uncertainties.

Numerical examples including a five-story and a 20-story shear building structures to illustrate the applicability, effectiveness and robustness of the implemented control method are used. In the proposed control method, a series of controllers with different degrees of centralization are considered that all of them are static-output feedback controllers. A centralized controller, a fully decentralized controller, partially coupled and uncoupled decentralized controllers, considering the uncertainties and without them lied in this series. The H_∞-norms of the controllers with different degrees of centralization are compared. The inter story drifts, displacements, velocities and control forces responses of building structures using the full scale North South Kobe 1995 records for the different control configurations and two type models including the nominal and perturbed models are shown. The inter story drift response for fully decentralized and centralized controllers is compared and the needed control force in controllers with different structures is computed. To demonstrate the performance of the proposed controllers, the frequency response from them is investigated. Results show that the decentralized controllers considerably mitigate the structure responses. The fully decentralized controller in the both of the five-story and 20-story buildings takes the results similar to the centralized controller and among all of the controllers partial decentralized controllers have the best performances. Changing the number of stories in every substructure does not affect the results and coupled and uncoupled controllers get similar results. By entering the uncertainties to the computations, the responses are a little increased, but this is not notable and is negligible. Then, the used control method despite the uncertainties in different decentralized configurations shows very good robustness that is very important. Also it should be considered that despite the uncertainties, the increase in the number of stories doesn't have any negative effect on the operation of the used method and this method shows good robustness in tall structures too.

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