Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Reduced-Order Active Control for Structural System with Nonlinear Uncertainty Based on Genetic Algorithm

LI Wen-zhang*. WU Ling-yao.**
GUO Lei***

*School of Automation, Southeast University, Nanjing, China, (e-mail: liwenzhang@ yahoo.cn).
** School of Automation, Southeast University, Nanjing, China, (e-mail:boguanban@seu.edu.cn)
*** School of Automation, Southeast University, Nanjing, China, (e-mail:l.guo@seu.edu.cn)

Abstract: This paper presents a new active control strategy based on linear matrix inequality (LMI) and genetic algorithm (GA) for the structural systems with nonlinear uncertainties and exogenous disturbances. Based on structural dynamics theory, the nonlinear uncertain structure system state-space model is established. Then, based on all-order H_∞ control and GA, the controller of minimum order is obtained by searching the object function globally. The concerning genetic algorithm adopts float coding, stochastic tournament, elitist model, linear crossover and uniform mutation. Finally, a three-degree-of-freedom building model subjected to EI Centro earthquake is considered using this method and the simulation results show that the provided controller has almost the same control effect as all-order H_∞ controller.

1. INTRODUCTION

As an effective solution to attenuate disturbances such as earthquake and wind forces, active control of structural systems has drawn considerable attention in engineering practice. Up to now, a variety of control strategies have already been proposed to attenuate the affection of structural vibration based on optimal and robust control, neural networks and fuzzy control, and nonlinear and adaptive control.

Up to now, several obstacles exist in the development of the vibration control theory and applications. One difficulty is the existence of the model uncertainties resulting from modelling errors, variations of materials, component non-linearities, and changing load environments. It has been shown that the model perturbations and exogenous disturbances can affect or even damage the stability and performances of the nonlinear systems. To this end, some feasible robust strategies have been obtained for various models containing uncertainties of different nature and levels. A robust H_2 / H_∞ active control approach for structural systems with parametric and unstructured uncertainties has been firstly developed, see (Wang *et al*., 2001). Then, a non-fragile H_∞ control strategy has been provided where the uncertainty in the mass matrix was considered directly, see(Du *et al.,*2004). However, it has been shown that complicated transformations were required there to derive the main results, which may have more conservativeness. A direct robust vibration control law has been then provided, see (Guo *et al.,* 2006), based on a uniform model and linear matrix inequality (LMI), where the robustness against the modelling and parametric perturbations, controller variations and disturbance excitations can be guaranteed simultaneously. As we know, most of the structural systems are high-order, which leads to high-order controllers. But it is quite difficult for high-order control to be implemented via hardware or software and the reliability of the system may be destroyed, whereas the simple low-order controller is easier to be adopted and understood. Therefore, it is more meaningful to research and design low-order controller for uncertain structural system, and it has already become a hotspot and difficult problem in active vibration control.

Reduced-order H_∞ controller design is a nonlinear non-convex problem, which can be described by a convex LMI and a non-convex rank restriction condition. In this paper, genetic algorithm (GA) optimization is introduced to vibration control of nonlinear and uncertain structural systems to solve the problem of reduced-order controller design. Based on GA, the problem of the rank restriction condition is changed into the problem of searching the minimum of the sum of eigenvalues of the semi-positive definite matrix. Considering the rank restriction condition as an object function of GA, the minimum order of the controller and the relevant parameters are obtained by searching the object function globally.

2. PROBLEM STATEMENT

Consider the following structural system with nonlinear uncertainties described by

$$\begin{aligned} &M\ddot{d}(t)+f_M(\ddot{d}(t))+C\dot{d}(t)+f_C(\dot{d}(t)) \\ &\quad +Kd(t)+f_K(d(t))=B_u u(t)+f_u(u(t))+B_w w(t) \end{aligned} \tag{1}$$

where $d(t)$ is the displacement, $u(t)$ is the control input, and $w(t)$ is the external disturbance or excitation. M, C, and K are the mass, damping and stiffness matrices respectively. B_u

is the input matrix and B_w is the disturbance matrix.

$f_M(\ddot{d}(t)), f_C(\dot{d}(t)), f_K(d(t))$, and $f_u(u(t))$ can represent the corresponding perturbations, which are supposed to satisfy

$$\| f_M(\ddot{d}(t)) \| \le \| V_M M\ddot{d}(t) \|, \| f_M(\dot{d}(t)) \| \le \| V_C C\dot{d}(t) \|, \\ \| f_M(d(t)) \| \le \| V_K K d(t) \|, \| f_u(u(t)) \| \le \| V_u u(t) \|. \tag{2}$$

where, V_M , V_C , V_K ,and V_u are known matrices to represent the bounds. $w(t)$ is supposed to have the bounded L_2 norm, which can also represent the un-modelled dynamics. It is shown that the above nonlinear uncertainties can be generalized to most models studied in the literature with both the parametric uncertainties and the un-modelling dynamics. Especially, introduction of $f_u(u(t))$ can be also used to describe the variations of the controller.

By using $x(t) = \begin{bmatrix} d^T(t) & \dot{d}^T(t) \end{bmatrix}^T$, (1) can be formulated as

$$\dot{x} + Ee(\dot{x},t) = Ax + F_1 f_1(x,t) + B_1 w + B_2 u + G_1 f_2(u(t)) \tag{3}$$

where

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ M^{-1}B_w \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ M^{-1}B_u \end{bmatrix},$$
$$E = \begin{bmatrix} I & 0 \\ 0 & M^{-1} \end{bmatrix}, F_1 = \begin{bmatrix} 0 & 0 \\ -M^{-1} & -M^{-1} \end{bmatrix}, G_1 = \begin{bmatrix} 0 \\ -M^{-1} \end{bmatrix},$$

and

$$e(\dot{x},t) = \begin{bmatrix} 0 \\ f_M(\ddot{d}(t)) \end{bmatrix}, f_1(x,t) = \begin{bmatrix} f_K(d(t)) \\ f_C(\dot{d}(t)) \end{bmatrix}, f_2(u(t)) = f_u(u(t))$$

Correspondingly to the practical situation in structural systems, based on (2) the following condition can be verified.

$$\|e(\dot{x},t)\| \le \|W_0 \dot{x}\|, \|f_1(x,t)\| \le \|W_1 x\|, \|f_2(u,t)\| \le \|W_2 u\|. \tag{4}$$

where

$$W_0 = \begin{bmatrix} 0 & 0 \\ 0 & V_M M \end{bmatrix}, W_1 = \begin{bmatrix} V_K K & 0 \\ 0 & V_C C \end{bmatrix}, W_2 = V_u.$$

In the following, it is shown that $\|M^{-1}V_M\| < 1$ is required as a necessary condition for impulse-free solutions. It is shown that the existence of non-impulsive solutions for the above systems with nonlinearity and disturbances can be guaranteed under the assumption.

In the following, the reference output is set to be

$$z(t) = C_1 x(t) + D_{11} w(t) + D_{12} u(t) \tag{5}$$

where C_1 and D_{11} are two weighting matrices to adjust the system performance. Also, tuning of D_{12} can confine the controller gain within the scope of the physical permission. In the following, the arguments in all of the nonlinear functions may be omitted for brevity in case of no confusion. The problem considered in this work is stated as follows: to design state feedback controllers for (3) such that the closed-loop system is stable and satisfies $\|z(t)\|_2 \le \gamma \|w(t)\|_2$.

3. OUTPUT FEEDBACK CONTROLLER

From Section 2, we can get the following description of uncertain structural system

$$\dot{x} = Ax + B_1 w + B_2 u + F_1 f_1(x,t) + G_1 f_2(u(t)) - Ee(\dot{x},t) \\ z = C_1 x + D_{11} w + D_{12} u \\ y = C_2 x + D_{21} w + D_{22} u \tag{6}$$

Suppose there exist a strict proper output feedback controller of order n_k as follows:

$$\dot{\hat{x}} = A_k \hat{x} + B_k y \\ u = C_k \hat{x} \tag{7}$$

The closed-looped system resulting from combing (6) and (7) is

$$\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}_1 w + \bar{F}_1 \bar{f}_1 - \bar{E}e(\dot{x},t) \\ z = \bar{C}_1 \bar{x} + \bar{D} w \tag{8}$$

where

$$\bar{x} = \begin{bmatrix} x \\ \hat{x} \end{bmatrix}, \bar{A} = \begin{bmatrix} A & B_2 C_k \\ B_k C_2 & A_k \end{bmatrix}, \bar{B}_1 = \begin{bmatrix} B_1 \\ B_k D_{21} \end{bmatrix},$$

$$\bar{F}_1 = \begin{bmatrix} F_1 & G_1 \\ 0 & 0 \end{bmatrix}, \bar{f}_1 = \begin{bmatrix} f_1(x,t) \\ f_2(C_k \hat{x},t) \end{bmatrix}, \bar{E} = \begin{bmatrix} E \\ 0 \end{bmatrix},$$

$$\bar{C}_1 = \begin{bmatrix} C_1 & D_{12} C_k \end{bmatrix}, \bar{D} = D_{11}.$$

By denoting $\bar{W}_1 = \begin{bmatrix} W_1 & 0 \\ 0 & W_2 C_k \end{bmatrix}, \bar{W}_0 = \begin{bmatrix} W_0 & 0 \end{bmatrix}$, (4) can be rewritten as

$$\|\bar{f}\|^2 = \|f_1\|^2 + \|f_2(C_k \hat{x})\|^2 \le \|W_1 x\|^2 + \|W_2 C_k \hat{x}\|^2 = \|\bar{W}_1 \bar{x}\|,$$

$$\|e(\dot{x},t)\| \le \|W_0 \dot{x}\| = \|\bar{W}_0 \dot{\bar{x}}\|.$$

The following results provide a solvability condition for the closed loop systems described by (8).

Theorem 1 *For some parameters λ_1 and λ_2, suppose that there exist the Lyapunov matrix $P > 0$ and controller parameter matrices A_k, B_k, C_k satisfying*

$$\begin{bmatrix} \Phi_{11} & \Phi_{12} \\ \Phi_{12}^T & \Phi_{22} \end{bmatrix} < 0 \tag{9}$$

where

$$\Phi_{11}=\begin{bmatrix}\Phi_{111} & P\bar{F}_1+\lambda_2^2\bar{A}^T\bar{W}_0^T\bar{W}_0\bar{F}_1 & -P\bar{E}-\lambda_2^2\bar{A}^T\bar{W}_0^T\bar{W}_0\bar{E}\\ * & -\lambda_1^2 I+\lambda_2^2\bar{F}_1^T\bar{W}_0^T\bar{W}_0\bar{F}_1 & -\lambda_2^2\bar{F}_1^T\bar{W}_0^T\bar{W}_0\bar{E}\\ * & * & \lambda_2^2(\bar{E}^T\bar{W}_0^T\bar{W}_0\bar{E}-I)\end{bmatrix},$$

$$\Phi_{12}=\begin{bmatrix}P\bar{B}_1+\lambda_2^2\bar{A}^T\bar{W}_0^T\bar{W}_0\bar{B}+\bar{C}\bar{D}_{11}\\ \lambda_2^2\bar{F}_1^T\bar{W}_0^T\bar{W}_0\bar{B}_1\\ -\lambda_2^2\bar{E}^T\bar{W}_0^T\bar{W}_0\bar{B}_1\end{bmatrix},$$

$$\Phi_{22}=\bar{D}_{11}^T\bar{D}_{11}+\lambda_2^2\bar{B}_1\bar{W}_0^T\bar{W}_0\bar{B}_1-\gamma^2 I,$$
$$\Phi_{111}=P\bar{A}+\bar{A}^TP+\lambda_1^2\bar{W}_1^T\bar{W}_1+\lambda_2^2\bar{A}^T\bar{W}_0^T\bar{W}_0\bar{A}+\bar{C}_1^T\bar{C}_1.$$

then the closed loop system (8) is stable and satisfies $\|z(t)\|_2<\gamma\|w(t)\|_2$.

It is noted that $\begin{bmatrix}X_{11} & X_{12}\\ X_{12}^T & X_{22}\end{bmatrix}<0$ holds if and only if $X_{11}-X_{12}X_{22}^{-1}X_{12}^T<0$ and $X_{22}<0$, which is well known as the Schur complement formula. Multiple applications of the Schur complement on (9), we can get the corollary 1.

Corollary 1 *For some parameters* λ_1 *and* λ_2*, suppose that there exist the Lyapunov matrix* $P>0$ *and controller parameters matrices* A_k, B_k, C_k *satisfying*

$$\begin{bmatrix}P\bar{A}+\bar{A}^TP & P\bar{F}_1 & -P\bar{E} & P\bar{B}_1 & \lambda_1\bar{W}_1^T & \lambda_2\bar{A}^T\bar{W}_0^T & \bar{C}_1^T\\ * & -\lambda_1^2 I & 0 & 0 & 0 & \lambda_2\bar{F}_1^T\bar{W}_0^T & 0\\ * & * & -\lambda_2^2 I & 0 & 0 & -\lambda_2\bar{E}^T W_0^T & 0\\ * & * & * & -\gamma^2 I & 0 & \lambda_2\bar{B}_1^T W_0^T & \bar{D}_{11}^T\\ * & * & * & * & -I & 0 & 0\\ * & * & * & * & * & -I & 0\\ * & * & * & * & * & * & -I\end{bmatrix}<0 \quad (10)$$

then the closed loop system (8) is stable and satisfies $\|z(t)\|_2<\gamma\|w(t)\|_2$.

It is noted that in (10), P and A_k, B_k, C_k (being included implicitly in the coefficient matrices of the closed loop systems) are coupled in a bilinear matrix. To separate the Lyapunov matrix and the controller coefficient matrices, and to provide an LMI-based design procedure, the following result can be obtained.

Theorem 2 *For some parameters* λ_1 *and* λ_2*, system (8) exist a output feedback controller if and only if there exist positive definite matrices* X and Y *satisfying the following matrix inequalities*

$$N_{P1}^T T_1 N_{P1}<0 \quad (11)$$

$$N_{Q1}^T H_1 N_{Q1}<0 \quad (12)$$

$$\begin{bmatrix}X & I\\ I & Y\end{bmatrix}\geq 0 \quad (13)$$

and rank restriction condition

$$Rank\begin{bmatrix}X & I\\ I & Y\end{bmatrix}\leq n_k+n \quad (14)$$

where

$$T_1=\begin{bmatrix}AY+YA^T & F & G_1 & -E & B_1 & \lambda_1 YW_1^T & \lambda_2 YA^TW_0^T & C_1^T\\ * & -\lambda_1^2 I & 0 & 0 & 0 & 0 & \lambda_2F_1^TW_0^T & 0\\ * & * & -\lambda_1^2 I & 0 & 0 & 0 & \lambda_2G_1^TW_0^T & 0\\ * & * & * & -\lambda_2^2 I & 0 & 0 & -\lambda_2E^TW_0^T & 0\\ * & * & * & * & -\gamma^2 I & 0 & \lambda_2B_1^TW_0^T & D_{11}^T\\ * & * & * & * & * & -I & 0 & 0\\ * & * & * & * & * & * & -I & 0\\ * & * & * & * & * & * & * & -I\end{bmatrix},$$

and

$$H_1=\begin{bmatrix}A^TX+XA & XF_1 & XG_1 & -XE & XB_1 & \lambda_1 W_1^T & \lambda_2 A^TW_0^T & C_1^T\\ * & -\lambda_1^2 I & 0 & 0 & 0 & 0 & \lambda_2F_1^TW_0^T & 0\\ * & * & -\lambda_1^2 I & 0 & 0 & 0 & \lambda_2G_1^TW_0^T & 0\\ * & * & * & -\lambda_2^2 I & 0 & 0 & -\lambda_2E^TW_0^T & 0\\ * & * & * & * & -\gamma^2 I & 0 & \lambda_2B_1^TW_0^T & D_{11}^T\\ * & * & * & * & * & -I & 0 & 0\\ * & * & * & * & * & * & -I & 0\\ * & * & * & * & * & * & * & -I\end{bmatrix},$$

N_{P1} is a random combination of column base vectors of
$$\ker\left(\begin{bmatrix}0 & I & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ B_2^T & 0 & 0 & 0 & 0 & 0 & \lambda_2W_2^T & \lambda_2B_2^TW_0^T & D_{12}^T\end{bmatrix}\right),$$

N_{Q1} is a random combination of column base vectors of

$$\ker\left(\begin{bmatrix} 0 & C_2^T & 0 & 0 & 0 & 0 & 0 & 0 \\ I & 0 & 0 & D_{21} & 0 & 0 & 0 & 0 \end{bmatrix}\right).$$

The restriction conditions (11), (12), and (13) in Theorem 2 are LMIs, when design of all-order controller the condition (14) is satisfied automatically. But when concerned with reduced-order controller design, the condition (14) will be a nonconvex problem. Based on LMI, the problem of reduced-order H_∞ controller design can be described as

$$\underset{R,S>0}{Minimize}\ Rank\begin{bmatrix} X & I \\ I & Y \end{bmatrix} \quad (15)$$
$$Subject\ to\ LMIs\ (11), (12), (13).$$

This problem is generally called Rank Minimization Problem. It is equivalent to the problem of reducing the minimum $n-n_k$ eigenvalues of matrix $\begin{bmatrix} X & I \\ I & Y \end{bmatrix}$ to zero. So the problem can be turned into

$$\underset{R,S>0}{Minimize}\ \psi(X,Y)=\sum_{i=1}^{n-n_k}\lambda_i\begin{bmatrix} X & I \\ I & Y \end{bmatrix} \quad (16)$$
$$Subject\ to\ LMIs\ (11), (12), (13).$$

where, $\lambda_1 \le \cdots \le \lambda_{n-n_k}$ represent the minimum $n-n_k$ eigenvalues of matrix $\begin{bmatrix} X & I \\ I & Y \end{bmatrix}$. Then the problem of reduced-order H_∞ controller design has been changed into searching the minimum of $\psi(X,Y)$ when the relevant paired parameter (X,Y) satisfy the LMIs (11), (12), and (13). Therefore, the existence of reduced-order H_∞ controller equals to the existence of the global minimum zero of $\psi(X,Y)$.

4. REDUCED-ORDER CONTROLLER

Synthesizing the above results and standard GA, this paper presents an improved GA to search the optimal solution described by (16). The feasible design steps are as follows:

Step1 Parameter Coding

We use float coding due to its high quality on precision and searching space. The symmetric elements in matrices X and Y will be coded once to save memory space. Therefore, we only need to code the elements above the diagonal and then get the individual

$$P_j=[x_{11},x_{12},\cdots,y_{11},y_{12},\cdots,\gamma],\ P_j(j=1,2,\cdots,N).$$

Step2 Population Initialization

Through solving LMIs (11), (12), and (13), we can get initial population containing N individuals. N represents the population size.

Step3 Fitness Determination

we define the fitness function as $f=1/[\psi(X,Y)+\zeta_{\min}]$, where $\zeta_{\min}$ is a tiny positive scalar. A fitness value is generated for each solution in the population to drive the "selection" process. Each solution in the population has a chance of surviving to the next generation proportionate to its "fitness" level. Selection of fitness function is very important in the design process of GA. It can directly affect the performance of GA.

Step4 Selection

Selection also called copy is a probabilistic procedure, based on the fitness values of each individual in the population, used to select the individuals that will move on to the next generation (Chatfield *et al*.,2005). We utilize stochastic tournament selection with generational replacement. Simple elitism is also employed, which automatically passes one unaltered copy of the best feasible individual in a population to the next generation. Set 2 as tournament size.

Step5 Crossover Strategy

Crossover operation decides how many individuals participate in the recombination process, and it is in proportion to the forming of new schema and the survival of parental ones. Crossover operation plays an important part in GA and is the main process to generate new individuals. In order to ensure that individuals after crossover still satisfy restriction LMIs (11), (12), and (13), linear crossover mechanism is applied to the chromosomes used in this study.

$$children = parent_2 + ratio_1 * (parent_1 - parent_2) \quad (17)$$

where $ratio_1$ is a random number chosen from [0, 1].

Step6 Mutation

Uniform mutation strategy is used in this study

$$children = parent + ratio_2 * \Delta \quad (18)$$

where Δ represents the increase value of individual and $ratio_2$ is a random number chosen from [-1, 1]. In order to ensure that individuals after mutation still satisfy restriction LMIs (11), (12), and (13), the closed-loop controller need to be constructed to confirm the stability of the system. If not stable, the existence probability of the new individual must be decreased through a punishment function.

Based on above steps, search for the parameter (X,Y), satisfying $\psi(X,Y)\le\zeta_{\min}$ starts from $n_k=n-1$. If we can find the appropriate solution, then try $n_k=n-2$, otherwise we can't find any solution after evolutions of G generation, and then the search stops.

5. SIMULATION

In the following, we consider the active control problem for the steady state motion of an uncertain three-degree-of-freedom building model. The building model is shown in Fig.1, see(Ou Jing-ping, 2003). The dynamic equation of the system is given as in (1) with system matrices given by

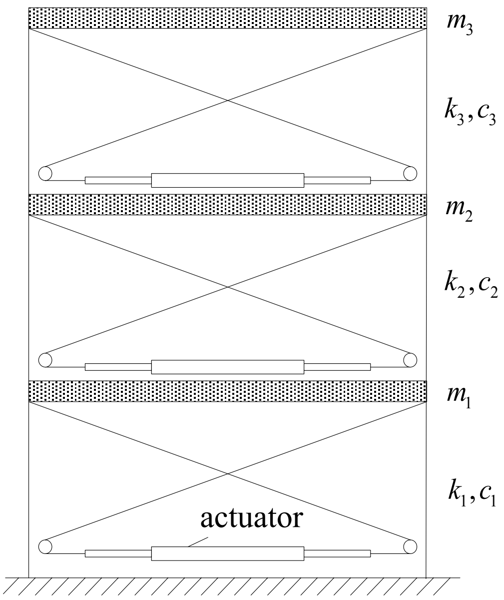

Fig.1 3-d.o.f building model

$$M=\begin{bmatrix}4&0&0\\0&4&0\\0&0&4\end{bmatrix}\times10^{5}\,(kg)\,,\;K=\begin{bmatrix}4&-2&0\\-2&4&-2\\0&-2&2\end{bmatrix}\times10^{8}\,(N/m),$$

$$C=\begin{bmatrix}1.3506&-0.5286&0\\-0.5286&1.3506&-0.5286\\0&-0.5286&0.8220\end{bmatrix}\times10^{6}(N\cdot s/m).$$

It is assumed that each storey of the building model has a controller and $B_u = I$, $B_\omega = -[m_1\ m_2\ m_3]^T$. we suppose the nonlinear uncertainties are described through $V_M = 0.01$, $V_K = V_C = 0.1$ 和 $V_u = 0.1$.

A time history of acceleration from the 1940 EI Centro (California) earthquake is applied to the base of the structure. Its peak value is $\ddot{x}_g(t)_{\max} = 0.34g$,and sample time is $0.02s$,and duration is $30s$. According to Theorem 2, we can get an all-order optimal H_∞ controller and performance index $\gamma_{opt} = 0.7065$ .Outputs of simulation with 6-order controller for the uncontrolled and controlled displacement of each storey are shown in Fig.2.

In the following, we utilize above provided method based on GA to design a reduced-order controller for the structural system model. It is supposed that initial population size $N = 15$, maximum evolution generation $G = 200$, crossover factor $ratio_1 = 0.5$ in (17), mutation factor $ratio_2 = 0.004$ in (18), and stop limit $\zeta_{\min} = 10^{-8}$. First we set $n_k = 5$, after 30 generations of evolution, optimal object value can be reduced to 2.6×10^{-10} . But when $n_k = 4$, after 140 generations of evolution, optimal object value can only be reduced to 0.0698. So, the minimum order controller for the system is 4. According to the current value of (X,Y) , we finally get the 4-order controller and performance index $\gamma_{opt} = 0.9365$. Under the time history of acceleration from the 1940 EI Centro (California) earthquake, outputs of simulation with 4-order controller for the uncontrolled and controlled displacement of each storey are shown in Fig.3.

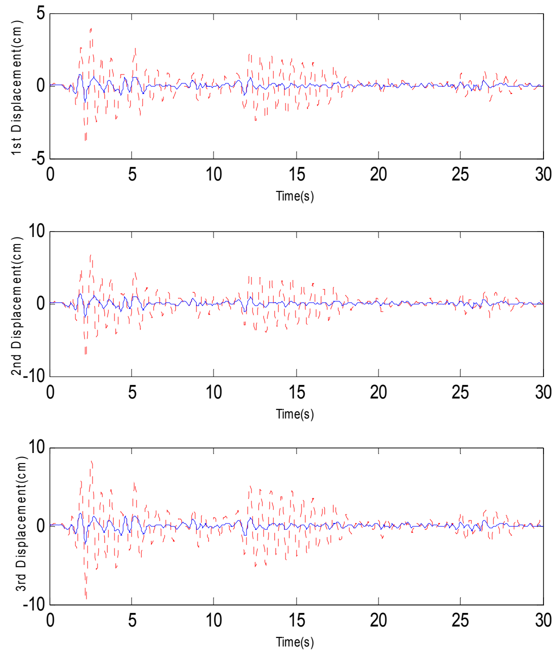

Fig.2 Responses of the uncertain system under the earthquake excitation with the full-order H_∞ controller.

a

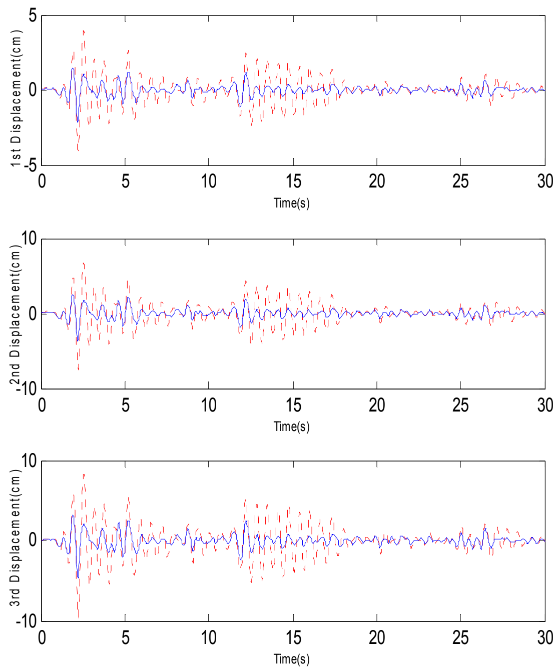

Fig.3 Responses of the uncertain system under the earthquake excitation with the reduced-order H_∞ controller.

6. CONCLUSIONS

This paper presents a new approach to design reduced-order H_∞ controller based on GA optimization for structural systems with nonlinear perturbations in the mass matrix, damper matrix and input matrix. The simulation results show that the proposed controller has almost the same control effect as all-order H_∞ controllers, although the vibration amplitude is a little higher. The designed reduced-order H_∞ controller can be easily put to engineering practice at a low cost. In this paper, the control delays of reduced-order controller are not considered, but they are very important in practice, we also leave this issue for future work.

REFERENCES

Rabin Alkhaticb and M. F Goinaraghi (2004). Active Structural Vibration Control: A Review. *The Shock and Vibration Digest*, **35(5)**, 367-383.

S. G. Wang, H. Y. Yen, and P. N. Roschke (2001). Robust Control for Structural Systems with Parametric and Unstructured Uncertainties. *Journal of Vibration and Control*, **7**, 753-772.

H.Du, J. Lam, and K. Y. Sze (2004). Non-fragile H_∞ Vibration Control for Uncertain Structural Systems. *Journal of Sound and Vibration*, **273**, 1031-1045.

L. Guo, L. Wu, W. Li, *et al* (2006). Active Control for Structural Systems with Nonlinear Perturbations and Exogenous Disturbances, *Proceedings of International Conference on Innovative Computing, Information and Control*, **IS21-009**, Beijing.

Pan Wei, Jing Yuan-wei (2004). Reduced-Order H_∞ Controllers Based on Genetic Algorithm. *Journal of Northeasten University*, **25(6)**, 520-522.

L. Guo and M. Malabre (2003). Robust H-infinity Control for Descriptor Systems with Non-linear Uncertainties. *International Journal of Control*, **76**, 1254-1262.

Izumi. M, Yoshiyuki. K, Atsumi. O, *et al* (1997). H_∞ Control for Descriptor System: A Matrix Inequalities Approach. *Automatica*, **33(4)**, 669－673.

Dean C. Chatfield (2005). The Economic Lot Scheduling Problem: A Pure Genetic Search Approach. *Computer and Operations Research.,* **34(2007)**, 2865-2881.

Ou Jin-ping (2003). *Vibration Control for Structural System----Active , Semi-active and Intelligent Control,* 80-97. Science Press, Beijing.

Esfahani S.H. and Petersen I.R (2000). An LMI Approach to Output-Feedback-Guaranteed Cost Control for Uncertain Time-delay Systems. *International Journal of Robust and Nonlinear Control*, **10(2)**, 157-172.