Robust control in smart systems and their management

Amalia Moutsopoulou

Phd candidate, Department of Production Engineering and Management, Technical University of Crete, GR-73100 Chania, Greece, email: amalia@dpem.tuc.gr

Anastasios Pouliezos

Professor, Department of Production Engineering and Management, Technical University of Crete, GR-73100 Chania, Greece, email: tasos@dpem.tuc.gr

Georgios E. Stavroulakis

Professor, Department of Production Engineering and Management, Technical University of Crete, GR-73100 Chania, Greece, email: gestavr@dpem.tuc.gr

Abstract

A "smart" structure is one that monitors itself and its environment in order to respond to changes in its conditions. Smart infrastructure systems are a combination of smart structures and the management systems that operate them.

In this paper a "smart" system is considered with embedded piezoelectric sensors and actuators. External disturbances are rejected by using controllers, which in practice are based on applied voltages on the actuators. This means that the controllers are the elements that feed forward the signal from the sensor, after suitable modification, to a corresponding actuating signal (controlled release of energy) for carrying out required repair work. Using the theory of production systems and mainly the active vibration control, a composite beam with embedded sensors and actuators is simulated. The control problem is to keep the beam in equilibrium, to face the external disturbances like wind and noise, and to model inaccuracies using the available measurements and controls.

After the analysis of the system we check the robust stability and system performance. The introduction of uncertainty permits us to keep the structure in service up to given limits of uncertainty. After that point repair or maintenance actions must be considered. Therefore the management of the system must be considered together with the robust analysis of it. Numerical simulations show the effectiveness and the good quality of the proposed method.

Keywords

smart structure, smart system, infrastructure, smart management system, production systems, robust control, uncertainty, disturbance rejection.

1. INTRODUCTION

A "smart" structure is one that monitors itself and its environment in order to respond to changes in its conditions (Tamer (2002)). The smart structure is made of four basic physical elements: 1) a host structure, 2) an array of sensors 3) one or more actuators, embedded or attached/installed on it, and 4) Controllers. In civil infrastructure, a host structure may be a bridge, a highway, or a dam that has to be monitored and controlled for safe performance of its intended use. This paper presents a model 'smart' structural system for controlling and rejecting oscillations from external disturbances, such as the wind power. The main types of controlling and supervising constructions are the following: the simple surface control, which is similar to the accelerated optical one, the instrument control, and finally the control, which is based on 'smart' systems. The efficient deployment of smart structures requires the employment of equally smart management systems to operate them. Smart infrastructure system refers to the combination of smart structures.

2. MODES OF SMART SYSTEM

Three modes (or levels) of Smart Systems (SS) deployment can be proposed: *Moderately Smart System:*A moderately smart system (MSS), having either an array of sensors or array of actuators but not both, is being proposed for organization that could not isolate the human interface from the management loop. Thus moderate level of smartness can be achieved by using either sensor technology for monitoring the facility or actuators to initiate the rehabilitation (Tamer (2002)). *Highly Smart System:* In highly smart system (HSS) both sensors and actuators are used in an integrated fashion where data from sensors are tied to decision-making software and mechanism and then flow back to actuators. Moreover, the highly smart system entails wide application of sensor technology all over the organization's projects. Macro decisions are done at the top management level, while day-to-day decision about data handling and host structure actuation is mainly automated with human involvement limited to verifying system operation and data flow(Tamer (2002), (Levvit (1997)). Data from different geographically located sensors is received and processed under the internal decision support systems (DSS) and according to certain codes. The HSS is therefore a complete system within its own environment. (Tamer (2002)). *Ultra Smart System:* The difference between HSS and the ultra smart system (USS) is that the latter collects data not only from different HSS and MSS but also from other data generating organizations. The interface of USS is such that a user can access information from any geographical location including data from vendors, contractors and regulatory bodies. For example, sensors specifications are accessed automatically through the web during the design of new systems through connectivity between the organization and the vendor (Tamer (2002)), (University of Salford (2001)).

3. A HIGHLY SMART SYSTEM

The highly 'smart' structure control system that we present automatically recognizes environmental changes and responds to them accordingly. The apparent system comprises embedded piezoelectric sensor, actuator which are capable of monitoring the behavior of the construction. Smart materials are embedded in constructions and are used as efficient actuators and sensors. To put forward a model of smart structures a girder cantilever beam with embedded piezoelectric effects that react as sensors, as well as actuators, needs to be projected.

3.1 Theoretical Formulation

The dynamical description of the system is given by,

$$M\,\ddot{q}(t) + D\,\dot{q}(t) + K\;q(t) = f_m(t) + f_e(t) \tag{1}$$

where M is the generalized mass matrix, D the viscous damping matrix, K the generalised stiffness matrix, f_m the external loading vector and f_e the generalised control force vector produced by electromechanical coupling effects. The independent variable $q(t)$ is composed of transversal deflections w_i and rotations ψ_i, [2]. To transform to state-space control representation, let (in the usual manner),

$$\dot{x}(t) = \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix}$$

Furthermore to express $f_e(t)$ as $Bu(t)$ we write it as $f_e^{*}u$, where f_e^{*} is the piezoelectric force for a unit applied on the corresponding actuator, and u represents the voltages on the actuators (Miara, Stavroulakis and Valente (2007)). Lastly $d(t)=f_m(t)$ is the disturbance vector. Then,

$$\dot{x}(t) = \begin{bmatrix} 0_{2n\times 2n} & I_{2n\times 2n} \\ \text{-}M^{-1}K & \text{-}M^{-1}D \end{bmatrix} x(t) + \begin{bmatrix} 0_{2n\times n} \\ M^{-1} f_e^{*} \end{bmatrix} u(t) + \begin{bmatrix} 0_{2n\times 2n} \\ M^{-1} \end{bmatrix} d(t)$$

$$= Ax(t) + \tilde{B}\tilde{u}(t) \quad (2)$$

We can augment this with the output equation (*displacements* only measured),

$$y(t) = [x_1(t)\ x_3(t)\ \ldots\ x_{n-1}(t)]^{\mathrm{T}} = Cx(t) \quad (3)$$

4. STATEMENT OF THE ROBUST CONTROL PROBLEM

The optimal control problem is initially studied for the nominal system, i.e., the beam with known elastic, piezoelectric and viscous properties. A more realistic question concerning the robustness of the control in the presence of defects is also addressed. The fact that the system is influenced by disturbances, such as the wind power, as well as the noise of measurements, is taken into account. The mathematical pattern being used in the designing is an approximation of the real one. Further, two control laws for the composite beam are designed in order to suppress the vibrations. Because of its linearity and easy implementation, the linear quadratic regulator (LQR) is presented first. The response of the controlled nominal and damaged beams is investigated. In order to take into account the incompleteness of the information about the eventual damages and external additional influences a robust H_∞ controller is designed. A system analysis is made on condition that the system is not accurate but includes uncertainty that may be related to some kind of damage (Foutsitzi and Stavroulakis (2003)).

Robustness Analysis The following three steps are taken in the robustness analysis:

1. Expression of *uncertainty set* by a mathematical model.
2. *Robust stability* (RS): check if the system remains stable for all plants within the uncertainty set.
3. *Robust performance* (RP): if system is robustly stable, check whether performance specifications are met for all plants within the uncertainty set.

To perform the robustness analysis, the interconnection of Figure 1 will be used.

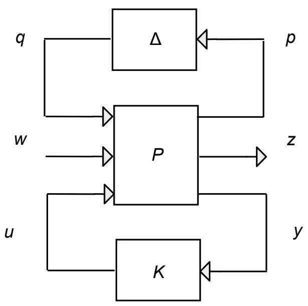

Fig. 1 Uncertainty modeling

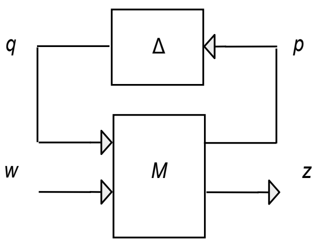

Fig.2 Uncertainty modeling

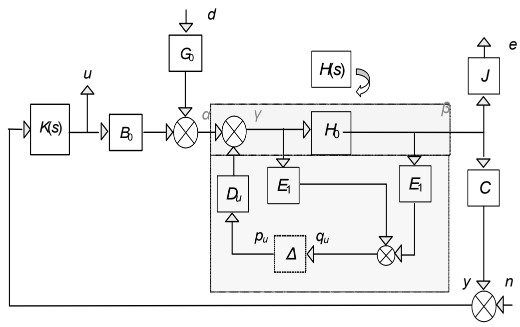

Fig.3 Elaborate illustration of the system

Here *P* is the nominal plant defined by figure 1 which includes the uncertainty modelling and *K* is the calculated H_∞ controller. The uncertainty included in Δ satisfies $\|\Delta\|_\infty \leq 1$.

Since *K* is known, figure 1 can be simplified to figure 2.

Given this structure it is known that,

I. The system (*M*, Δ) is *robustly stable* if,

$$\sup_{\omega \in \mathbb{R}} \mu_{\Delta}\left(M_{11}(j\omega)\right) < 1 \qquad (4)$$

where, $$\frac{1}{\mu_{B}(M)} = \left\{ \inf_{\Delta \in B_{\Delta}, \det(I - M\Delta) = 0} \bar{\sigma}(\Delta) \right.$$

is the *structured singular value* of *M* given the structured uncertainty set B_{Δ}.

II. The system (*M*, Δ) exhibits *robust performance* if,

$$\sup_{\omega \in \mathbb{R}} \mu_{\Delta_a}\left(M(j\omega)\right) < 1, \text{ where,}$$

$$\Delta_a = \begin{bmatrix} \Delta_p & 0 \\ 0 & \Delta \end{bmatrix}$$

and Δ_p has the same structure as Δ but dimensions corresponding to (*w*, *z*).

Unfortunately, only bounds on μ can be estimated.

To proceed let us assume uncertainty in the *M*, *D* and *K* matrices of the form,

$$M = M_0(\mathrm{I} + m_p \delta_M) D = D_0(\mathrm{I} + d_p \delta_D)$$
$$K = K_0(\mathrm{I} + k_p \delta_K)$$

$$\text{with, } \|\Delta\|_{\infty} \overset{def}{=} \left\| \begin{bmatrix} \delta_M & & \\ & \delta_D & \\ & & \delta_K \end{bmatrix} \right\|_{\infty} < 1$$

This means we are allowing a percentage deviation from the nominal values.

With these definitions Eq. (1) becomes,

$$\Rightarrow M_0\, \ddot{q}(t) + D_0\, \dot{q}(t) + K_0 q(t) = \tilde{D} q_u(t) + f_m(t) + f_e(t) \qquad (5)$$

where, $$q_u(t) \overset{def}{=} \begin{bmatrix} \ddot{q}(t) \\ \dot{q}(t) \\ q(t) \end{bmatrix}, \quad \tilde{D} = -\begin{bmatrix} M_0 m_p & D_0 d_p & K_0 k_p \end{bmatrix} \begin{bmatrix} I_{2n\times 2n}\delta_M & & \\ & I_{2n\times 2n}\delta_D & \\ & & I_{2n\times 2n}\delta_K \end{bmatrix}$$

Writing (5) in state space form, gives,

$$\dot{x}(t) = \begin{bmatrix} 0_{2n\times 2n} & I_{2n\times 2n} \\ -M^{-1}K & -M^{-1}D \end{bmatrix} x(t) + \begin{bmatrix} 0_{2n\times n} \\ M^{-1} f_e^{*} \end{bmatrix} u(t) + \begin{bmatrix} 0_{2n\times 2n} \\ M^{-1} \end{bmatrix} d(t) + \begin{bmatrix} 0_{2n\times 6n} \\ M^{-1}\tilde{D} \end{bmatrix} q_u(t)$$
$$= \mathrm{A}x(t) + \mathrm{B}u(t) + Gd(t) + G_u q_u(t)$$

In this way we treat uncertainty in the original matrices as an extra uncertainty term.To express our system in the form of figure 2, consider Figure 3

5. Results

For the numerical simulations a cantilevered composite beam with viscous and piezoelectric layers bonded on its top and bottom and discredited with four finite elements, is used. A finer finite element discretization, which certainly is required for the approximation of higher frequencies, does not change the trend of the results. The parameters of the beam are similar to that used in (Liao and Wang (1997)). Our aim is to study the response of the composite beam in the presence of defects and damages. Three kinds of dynamic loading are used as disturbances:

- Transient force 4*N* distributed in the free end of the beam.
- Periodic sinusoidal loading pressure acting on every node on one side of the structure simulating a strong wind (Figure 4).

• Random white noise with zero mean acting along the transverse direction (Fig.4). Let us first investigate the response of the free and LQR-controlled composite beam with piezoelectric and viscous layers for various parameters of the glue layer. A vertical impulsive load is applied at the free-end of the beam. Figure 5a shows the response of the beam's free end to a constant external force of 4N applied to the free end.

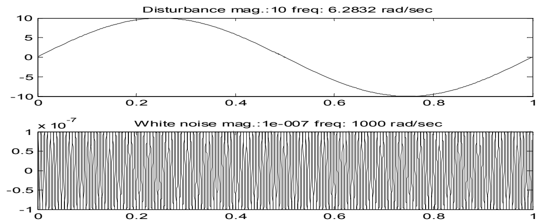

Fig. 4 Periodic sinusoidal loading and random white noise

The control effort is shown in Figure 5c, where it is seen that both controllers use comparable voltage and are well within the 500V limit of piezoelectric actuators. With finer tuning (perhaps by adding a D term also), the speed of response and other transient characteristics (overshoot) can of course be improved.

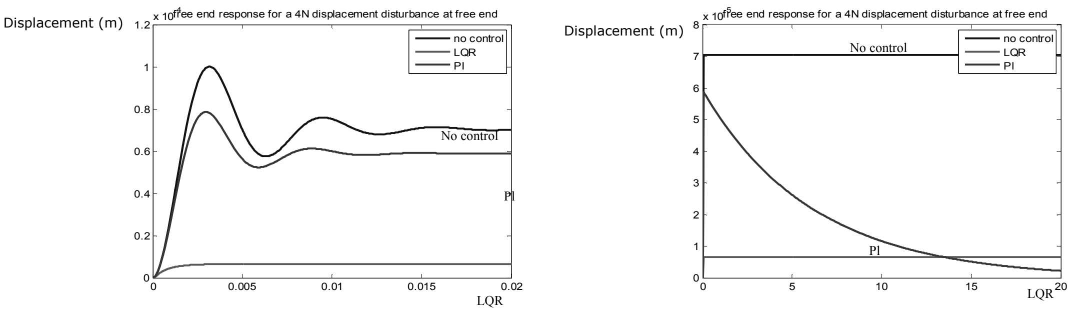

Fig 5 a.b. Response of the free vibrating beam with and without control

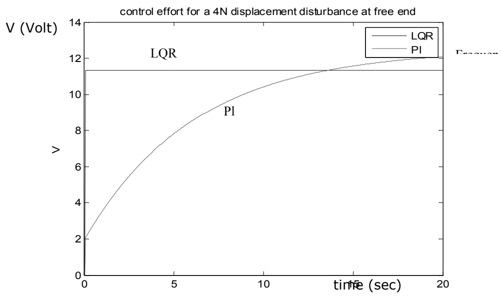

Fig 5 c. Control Voltages

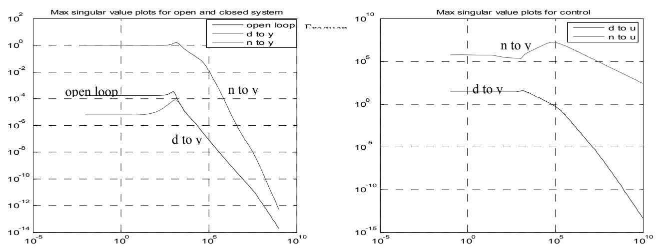

Fig. 6 Singular value

Figure 7 shows the response of the uncontrolled beam and controlled beam using H_∞ control strategy. The nominal performance is depicted in Figures. 6-8

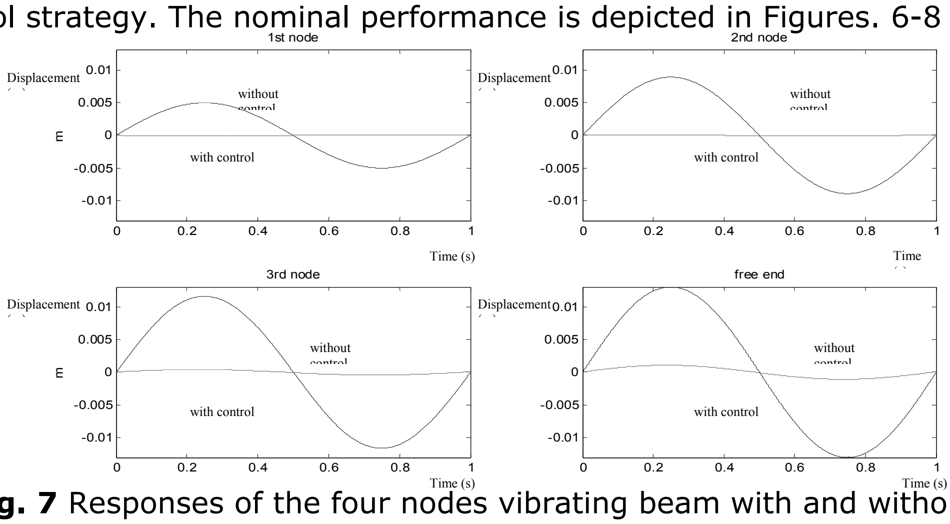

Fig. 7 Responses of the four nodes vibrating beam with and without control

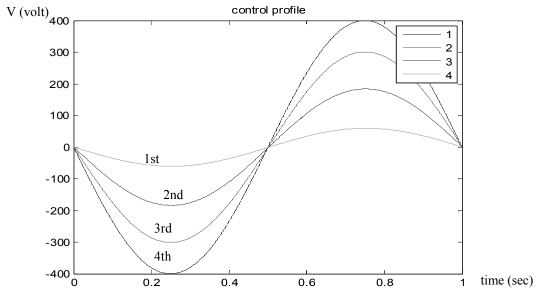

Fig. 8 Control profile for the four nodes

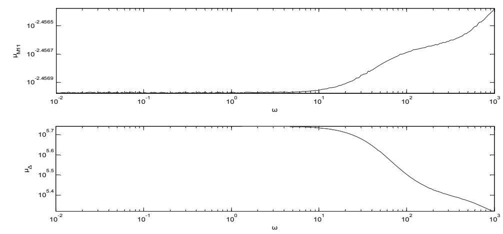

Fig. 9 Robust performance

As seen, nominal performance is very satisfactory with controls within limits. Robust performance is pictured in Figure 9.

6. CONCLUSIONS

The theoretical formulation of a highly smart beam is presented in this paper using LQR and H_∞ control theory for the nominal and damaged sandwich beam. After the analysis of the system we check the robust stability and system performance. The introduction of uncertainty permits us to keep the structure in service up to given limits of uncertainty. After that point repair or maintenance actions must be considered. Therefore the management of the system must be considered together with the robust analysis of it.

REFERENCES

Tamer, El-Tiraby and Khan Falahudin Kashif (2002), "Modes of application of smart structures and system in construction", First international conference on Construction in the 21st Century, 25-26 April, Miami, Florida, USA.

Miara, B., Stavroulakis, G., Valente, V.(Eds.) (2007), "Topics on mathematics for smart systems". Proceedings of the European Conference, Rome, Italy, 26-28 October 2006, World Scientific Publishers, Singapore, International.

Levvit, R.E., Yan, J., Gaye, O., John, K. and Tore, C. (1993), "Computational Enterprise Models" Towards Analysis Tools for Designing Organizations, in Coordination Theory and Collaboration Technology., New Jersey, USA.

Liao, W.H. and Wang, K.W. (1997), "On the analysis of viscoelastic materials for active constrained layer damping treatment", J. Sound and Vibration 207, pp. 319-334.

Foutsitzi, G., Marinova, D., Hadjigeorgiou, E. and Stavroulakis, G. (2003), "Robust H-2 vibration control of beams with piezoelectric sensors and actuators", Proceedings of Physics and Control Conference (PhyCon03), St. Petersburg, Russia, 20-22 August, Vol. I, pp. 158-163.

University of Salford (2001), United Kingdom. Process Protocol II-An Overview, http://pp2.dct.salford.ac.uk/mainpege.htm