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OPTIMAL CONTROL TUNING IN SMART STRUCTURES WITH DELAMINATIONS

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Abstract. *An efficient strategy for calculation of delaminations in composite beams and intelligent structures is used in order to quantify structural uncertainties within a finite element model of a piezocomposite (multilayered plate theory). Furthermore the dynamical system is connected with robust and neurofuzzy control. The problem of positioning of actuators and sensors has been investigated. Model based simulations of increasing complexity illustrate some of the attractive features of the strategy in terms of accuracy as well as computational cost. This shows the possibility of using such strategies for the development of smart structural and systems.*

1 INTRODUCTION

Piezoelectric sensors and actuators are extensively employed in many practical applications such as intelligent structures due to their lightness and their capability of coupling strain and electric fields. In order to control structural vibrations, piezoelectric sensors and actuators can be easily bonded on the vibrating structure. In active vibration control, the patches are symmetrically bonded on top and bottom surfaces [1,2, 3]. An Hinfinity [4,5] controller, a fuzzy controller [20,21,26] or a hybrid neuro-fuzzy control [22,23,24,25] can be designed and optimally tuned [27, 28] to suppress the vibrations of the intelligent structure even when delamination phenomena occur [32, 33]. The position and the size of the actuators influence the response of the smart structure and determine the maximum admissible piezoelectric actuation voltage. The optimal sensor locations can be found, using genetic algorithms and multicriteria optimization [6,13]. In addition the numerical results can be compared with analytical ones obtained by the Laplace transform method [7,8]. Satisfactory vibration reduction has been observed for control cases under sinusoidal, random disturbances, confirming the reliability and validity of such algorithms. The results are very satisfactory since the vibration suppression is achieved.

2 FINITE ELEMENT FORMULATION

We base our model on the layerwise approach which takes into account the adhesive layer derived earlier in Refs [32, 33]. The structure consists of an elastic core bonded with piezoelectric sensor and actuator layers and adhesive layers between them. Delamination between the layers may appear and influences the effectiveness of active vibration control. Using a special adhesive finite element we are leading to the following equation of motion in terms of nodal variable *q*,

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

where *M* is the generalized mass matrix, *D* the viscous damping matrix, *K* the generalized stiffness matrix, f_m the external loading vector and f_e the generalized control force vector produced by electromechanical coupling effects. The exact form of these matrices are given in [32], [33].

To transform to state-space control representation, let (in the usual manner),

$$\dot{x}(t)=\begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix} \tag{2}$$

Furthermore to express $f_e(t)$ as $Bu(t)$ we write it as $f_e^* u$ where f_e^* the piezoelectric force is for a unit applied on the corresponding actuator, and u represents the voltages on the actuators. Furthermore, $d(t)=f_m(t)$ is the disturbance vector [9, 10].

Then,

$$\dot{x}(t)=\begin{bmatrix} O_{2n\times 2n} & I_{2n\times 2n} \\ -M^{-1}K & -M^{-1}D \end{bmatrix}x(t)+\begin{bmatrix} O_{2n\times 2n} \\ M^{-1}f_e^* \end{bmatrix}u(t)+\begin{bmatrix} O_{2n\times 2n} \\ M^{-1} \end{bmatrix} \tag{3}$$

$$= Ax(t) + Bu(t) + Gd(t) = Ax(t) + \begin{bmatrix} B & D \end{bmatrix} \begin{bmatrix} u(t) \\ d(t) \end{bmatrix} = Ax(t) + \tilde{B}\tilde{u}(t) \tag{5}$$

The previous description of the dynamical system will be augmented with the output equation (some displacements or velocities are measured) [10, 11, 12],

$$y(t) = \begin{bmatrix} x_1(t) & x_3(t) & \cdots & x_{n-1}(t) \end{bmatrix}^T = Cx(t) \tag{6}$$

3 ROBUST CONTROL PROBLEM

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)[12,13] 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 [14, 15]. 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 [9]

For practical applications both algorithms need several trial-and-error design iterations in order to provide appropriate control voltages, since the piezoelectric actuators can be depolled by high oscillating voltages. The effectiveness of the proposed control strategies is investigated with the help of numerical simulations [7, 9].

The following three steps are taken in the robustness analysis [16, 17]:

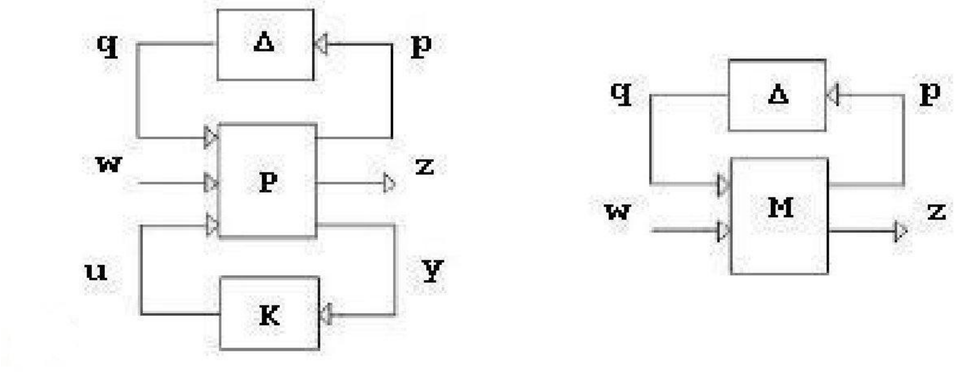

Figure 1 Uncertainty modelling

1. Expression of an *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 the 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.
Δ define the uncertainty, M define the nominal system, w are the inputs (the mechanical force and the noise of the system), z are the outputs (the state vector and the control vector). The uncertainty included in Δ satisfies $\|\Delta\|_\infty \leq 1$.

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

$$\sup_{\omega \in \mathbb{R}} \mu_\Delta(M_{11}(j\omega)) \prec 1 \tag{7}$$

The system (M, Δ) exhibits robust performance if,

$$\sup_{\omega \hat{I}_n} \mu_{\Delta_\alpha}(\mathrm{M}(j\omega)) \prec 1 \tag{8}$$

where,

$$\Delta_\alpha = \begin{bmatrix} \Delta_\rho & 0 \\ 0 & \Delta \end{bmatrix}$$

and Δ_ρ 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,

$$\begin{aligned} &\mathrm{M} = \mathrm{M}_0(\mathrm{I} + m_p \delta_{M_u}) D = D_0(I + d_p \delta_D) \\ &K = K_0(I + k_p \delta_{\mathrm{K}}) \end{aligned} \tag{9}$$

with,

$$\|\Delta\|_\infty \overset{def}{=} \left\| \begin{bmatrix} \delta_{\mathrm{M}} & & \\ & \delta_D & \\ & & \delta_{\mathrm{K}} \end{bmatrix} \right\| \prec 1 \tag{10}$$

This means that we are allowing a percentage deviation from the nominal values [6,9].
With these definitions Eq. (1) becomes,

$$\Rightarrow \mathrm{M}_0 \ddot{q}(t) + D_0 \dot{q}(t) + K_0 q(t) = \tilde{D} q_u(t) + f_m(t) + f_e(t) \tag{11}$$

Where,

$$q_u(t) \overset{def}{=} \begin{bmatrix} \ddot{q}(t) \\ \dot{q}(t) \\ q(t) \end{bmatrix}$$

$$\tilde{D} = -\begin{bmatrix} M_0 m_p & D_0 d_p & K_0 k_p \end{bmatrix} \begin{bmatrix} I_{2n\times 2n}\delta_{\mathrm{M}} & & \\ & I_{2n\times 2n}\delta_\Delta & \\ & & I_{2n\times 2n}\delta_{\mathrm{K}} \end{bmatrix} \tag{12}$$

Writing [5]in state space form, gives,

$$\dot{x}(t) = \begin{bmatrix} O_{2n\times 2n} & I_{2n\times 2n} \\ -M^{-1}K & -M^{-1}D \end{bmatrix} x(t) + \begin{bmatrix} O_{2n\times 2n} \\ M^{-1} f_e^* \end{bmatrix} u(t) + \begin{bmatrix} O_{2n\times 2n} \\ M^{-1} \end{bmatrix} d(t) + \begin{bmatrix} O_{2n\times 6n} \\ M^{-1} D \end{bmatrix} q_u(t)$$

$$\dot{x}(t) = Ax(t) + Bu(t) + Gd(t) + G_u q_u(t) \tag{13}$$

In this way we treat uncertainty in the original matrices as an extra uncertainty term.

4 FUZZY AND NEURO-FUZZY CONTROL

A fuzzy inference system can be developed within MALAB using the fuzzy toolbox. The control scheme usually consists of a Mamdani [20,21] or a Sugeno-type controller [22,23,24]. This system can be used for the study of smart structures such as smart beams [21,24,25], plates [26,27], etc.The controllers usually consist of two inputs and one output. As for inputs, the controller can take displacement and velocity or the electric potential and current and returns the control force. The membership functions have triangular, trapezoidal, Gaussian or sigmoid both for inputs and output. An example of triangular and trapezoidal functions is shown in Fig. 2. The inference system involves membership functions combined with use of logical operations. Namely, the decision is based on a set of if-then rules, thus the recurring system is a rule-based system. A set of rules as this one shown in Table 1, can be considered. The graphic representation of rules is given by the fuzzy surface shown in Fig. 2.

1. Displacement / 2. Velocity	3. Far up	4. Close up	5. Equilibrium	6. Close down	7. Far down
8. Up	9. Max	10. Med+	11. Low+	12. Null	13. Low-
14. Null	15. Med+	16. Low+	17. Null	18. Low-	19. Med-
20. Down	21. High+	22. Null	23. Low+	24. Med-	25. Min

Table 1. Fuzzy inference rules

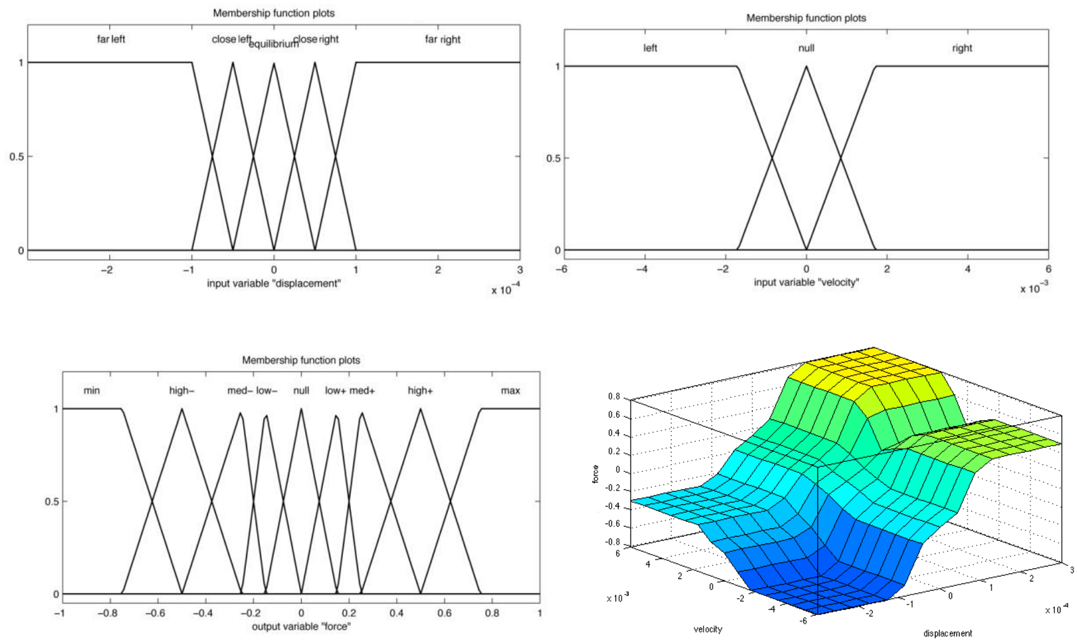

Figure 2: Membership functions prior optimization and fuzzy surface

5. OPTIMIZATION OF CONTROL

The results given solely by fuzzy control in previous investigations of our team [21, 24, 26], were very satisfactory in terms of displacement. However, the results regarding the velocity and the acceleration were not acceptable.

Thus, the need of optimization some of the parameters of the fuzzy controller arose. This fine tuning is a really exacting process, thus a simple, effective and well known procedure has to be chosen.

For example, a genetic algorithm can be used due to its simplicity and smooth behavior in such problems [27]. The algorithm was used in order to optimize the membership functions of the variables (inputs/outputs) or other characteristics of the fuzzy controller. In this case, a population of different solutions try to reach total optima via a stochastic iterative process.

Another method that may be useful for the fine tuning of the parameters of a controller, used for vibration suppression of smart structures, is the particle swarm optimization method [28, 29, 30] and the differential evolution [31]. These methods are similar to the genetic approach, however they can provide more accurate results.

6. DELAMINATION MODELING

For the simulation of delamination, a non-linear delamination law can be considered to the structural model investigated, as shown in Fig. 3:

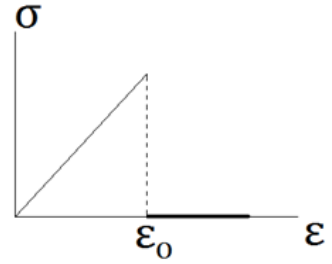

Figure 3: Stress-strain behavior in the adhesive

The above law leads to appropriate modification of the existing stiffness matrix of the structure in order to take into account the differences in the behavior before and after the delamination [32].

For each finite element, the element average strain ε_{zz}can be calculated as follows:

$$\varepsilon_{zz}^{(a_i)} = \frac{w^{(i+1)} - w^{(i)}}{h^{(a_i)}} \qquad (14)$$

where w is the vertical displacement of layers, whose behavior in delamination is investigated, and h(a) is the thickness of the adhesive layer. If the strain is less than ε_o, no delamination appears in the element. Otherwise, delamination takes place. In this case, the delamination can occur between the lower-middle and the middle-upper plate layer.

For the implementation of the non-linear delamination law, the Newton-Raphson incremental-iterative procedure has been used, as follows [33]:

Incremental step
Load enforcement
Start iterations
-Loop to the whole of elements
-Calculate the mean strain of each element
-Compare with ε_o

-Appropriate estimation of the tangential stiffness matrix

-Estimation of the internal force vector

-Solving equilibrium equs and finding incremental

and global displacements

-Error control and continuation iteration

orcontinue the incrementalstep

7. RESULTS AND DISCUSSION

For the numerical simulations a cantilever composite beam with piezoelectric layers bonded on its top and bottom and discretized with finite elements, is used. Periodic sinusoidal loading pressure acting on the side of the structure simulating a strong wind. A sinusoidal load with an amplitude of 15N and frequency of 6.5 *rad/sec*, has been considered. Fig 4 shows the dynamical response for the displacements of the uncontrolled and controlled beam with LQR control [12] and H_∞ control [18], for the four nodes of the beam. Fig 5shows the dynamical response for the rotations of the uncontrolled and controlled beam with LQR control and H_∞ control strategy, for the four nodes of the beam. The beam with H_∞ control keeps in equilibrium and we have zero ddisplacements, complete vibration reduction is achieved. The comparison of the open and closed loop frequency response of the system are shown in Figure 6, as shown in figure, there is a significant improvement in the effect of disturbance on error up to the frequency of 1000 Hz. Figure 7 shows the control voltages for the four nodes of the beam. The control voltages for the disturbance rejections of the beam are less than 500 volt.
Results are very good, and the beam remains in equilibrium. Reduction of vibrations is observed, while piezoelectric add-ons produce voltage within their tolerance limits (±500volt).

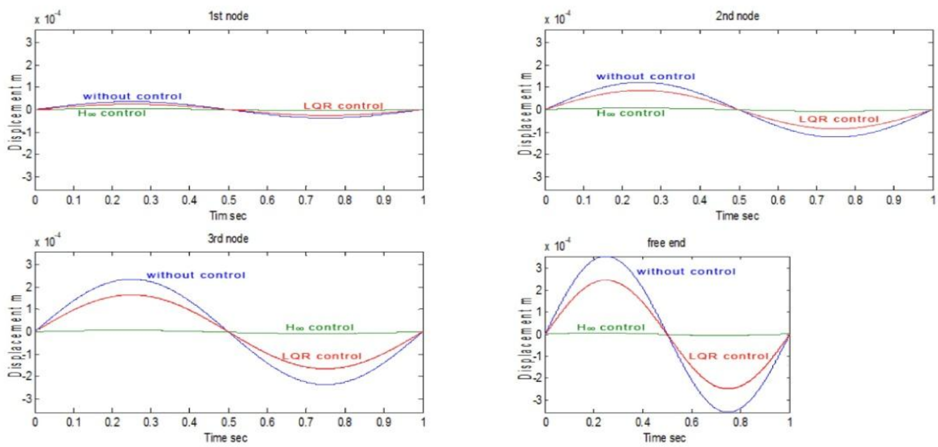

Figure 4: Response of the four nodes for the displacement with LQR and H_∞ control and response without control.

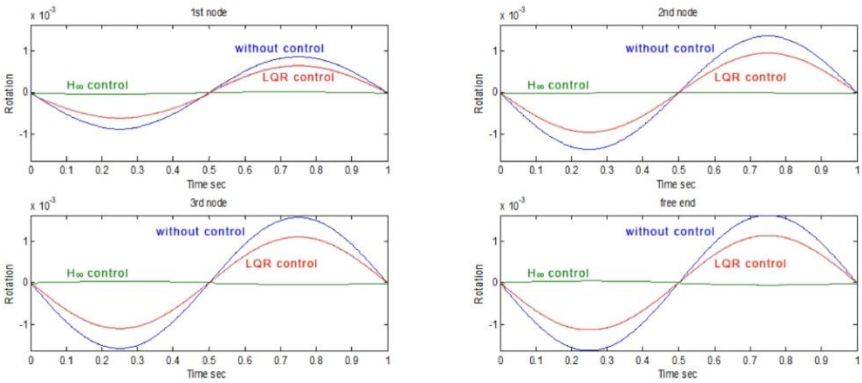

Figure 5: Response of the four nodes on the vibrating beam for the rotation with LQR and H_∞ control and without control.

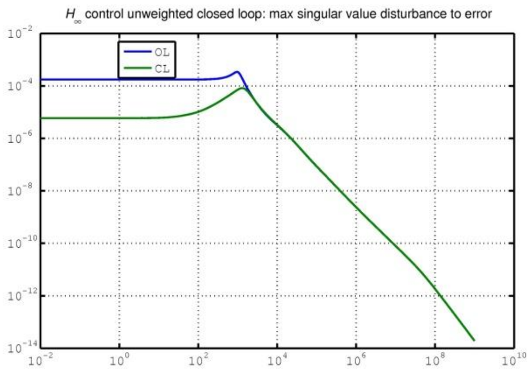

Figure 7: Singular Value for H_∞ control strategy.

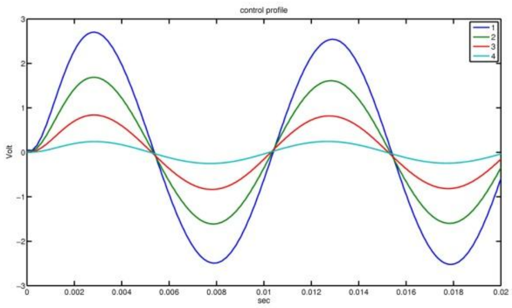

Figure 8: Response of the four nodes for the displacement with LQR and control and response without control.

As a conclusion one can say that structural uncertainty in smart piezocomposites can be quantified by using techniques of computational mechanics. This gives rise to more accurate design and optimal tuning of robust controllers, either following classical or soft computing techniques. Further investigation includes the optimal positioning of sensors and actuators and the incorporation of other uncertainties (crack initiation and propagation, fatigue).

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