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Robust reliable control in vibration suppression of sandwich circular plates

Atta Oveisi [a,*], Rezgar Shakeri [b]

[a] Ruhr-Universität Bochum, Mechanik adaptiver Systeme, Institut Computational Engineering (ICFW 03-523), Universitätsstr. 150, D-44801 Bochum, Germany
[b] Department of Railway Engineering, Iran University of Science and Technology, Iran

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ABSTRACT

The wide real life applications of circular plates under dynamic loading such as laminate saw blades and accurate slitting narrow industrial cutters require special attention to smart structural design that optimally handles the dynamic behavior of these configurations. The purpose of this paper is to investigate the vibration regulation of a sandwich circular plate using a non-fragile robust control strategy. A new dynamic modeling of the piezolaminated structure is proposed based on satisfying the Maxwell static electricity equation and on assuring the full coupling effects of the piezoelectric layers on the host structure. The Eigen functions are chosen optimally such that the boundary conditions for the piezoelectric sensor/actuator are satisfied without additional complexities. In order to reach to the desired performance in vibration attenuation, a robust controller is designed by considering the uncertainties that exist in the system matrices and controller itself. The proposed controller is obtained by solving a system of linear matrix inequalities (LMIs) that are based on the Bounded Real Lemma (BRL). Simulations show that the controller is capable of suppressing the vibration in existence of both the structured uncertainty in the system matrices and the feedback controller gain.

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1. Introduction

The turn of mechanical design entails structures to become smart and resilient with respect to environmental stimuli; so in recent years, the light weighted plates have been widely used in various engineering applications [1]. These requirements cause the structure to be sensitive with respect to undesired mechanical loading, which leads to vibration and the consequential problems such as fatigue, instability, and performance reduction. Therefore, vibration control has attracted many researchers in the fields of structural vibration analysis, damage detection, and vibration/ noise control [2–4].

Piezoelectric sensors and actuators, due to their lightness and capability of coupling structural stress with electrical charge are extensively implemented in practical applications. In order to control the structural vibrations, piezo-patches can be easily bonded on the vibrating structure [5]. Thus, the analysis of the coupled piezoelectric structures have been keenly researched. Wang and Rogers [6] developed a uniform strain model for a beam with surface bonded and embedded piezoelectric actuator patches accounting for the shear lag effects of the adhesive layer between the piezoelectric actuator and the beam. However, they assumed the distribution of electric potential in the thickness of the piezolayer to be uniform which is in contradiction with the Maxwell electricity equation. As a part of the new formulation that is proposed in this paper, the solution for the electric potential is developed so that it satisfies the Maxwell electricity equation.

In the field of structural design and vibration control, the use of active techniques for control of the dynamical behavior of the structure is the vital target especially since, for an optimal configuration, the additional masses of stiffeners or dampers should be avoided. In addition, active techniques are more effective in the cases where the system is time variant or the external disturbance is time or frequency dependent [4]. Nevertheless, most of the active methods are model-based and accordingly in the design procedure of the controller, a nominal model is required. Therefore, in terms of the optimal performance of the control system, an effective dynamic modeling is one of the key points. As a result, in recent years, extensive attention is paid for extracting the nominal open loop dynamics of the active structures for control design purposes such as finite element methods [7,8], finite difference method [9], modal analysis [10], exact mathematical modeling [11], experimental analysis [12], and system identification [13]. Conversely, in all of the mentioned modeling procedures, due to the modeling errors, variation of material properties, component

* Corresponding author.
E-mail address: atta.oveisi@rub.de (A. Oveisi).

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nonlinearities, and changing of the load environments, the system description inevitably contains uncertainties of different nature and levels [14,15]. These uncertainties can affect both the stability and performance of the control system [16]. To accommodate such possible degradation of stability and performance, methods such as robust H_∞ controllers are often used [17]. In literature [17,18], the uncertainties in the mass matrix are modeled in an additive form which is an indirect and unnatural way to describe the structural uncertainty. Moreover, such an approach may lead to uncertainties that appear in the input and disturbance matrices which will then complicate the controller design procedure and will result in conservative solutions. This issue is addressed carefully in this paper by appropriate transformation of the dynamic equation of motion in state space representation.

In all of the reviewed literature it is also assumed that the controller can be realized exactly. However, in practice, many physical limitations lead to the loss of precision in controller implementation. As an example, the effects of finite word length in any digital systems, round-off errors in numerical arithmetic, and inherent imprecision in analog devices may lead to losing the desired performance. In other words, even though a robust controller is designed, it may be sensitive to its own gain variations. Thus, special attentions have been paid to the fragility of controllers [19–25] in some abstract problems without practical realization.

This paper is mainly concerned with forced vibration analysis of a simply supported piezo-elastic circular plate. A new consistent formulation that satisfies the Maxwell static electricity equation is presented so that the effect of the piezoelectric layer on the dynamic characteristics of the coupled circular plate can be estimated and the boundary conditions for the piezoelectric sensor and actuator are satisfied. The presented modeling technique makes it possible to establish numerical models for fast assessment of disturbance rejection control (DRC). Two aspects of the vibration control are considered; One is the robust H_∞ DRC for structural system with parametric uncertainties and second is the robustness of the closed-loop system with respect to controller gain variations due to the implementation and numerical imperfections. The non-fragile H_∞ state feedback controller is considered to deal with additive controller gain variations with an optimal selection of the admissible uncertainties. The results for controller design that are developed in this paper are given in terms of the feasibility of some LMIs which can be solved using standard numerical software such as MATLAB/Scilab. The rest of the paper is organized as follows: Section 2 formulates the dynamic equation of motion for the piezolaminated circular plate in order to reach to a state space model of the smart structure with associated uncertain terms. Then, the robust non-fragile control design procedure is presented in Section 3. The detailed numerical implementation and performance investigation of the designed controller on the smart system together with validation/verification of the mathematical model are carried out in Section 4. Finally, the conclusion and final remarks are made.

2. Formulation

The geometry of the circular plate with two piezoelectric layers mounted on its surfaces is shown in Fig. 1. For wave propagation in the structures with ratio of radius to the thickness more than ten, the displacement field can be written as [26]

$$u_z = u_z(r,\theta,t) = w(r,\theta,t),$$
$$u_r = u_r(r,\theta,t) = -z\frac{\partial w}{\partial r},\qquad(1)$$
$$u_\theta = u_\theta(r,\theta,t) = -\frac{z}{r}\frac{\partial w}{\partial \theta},$$

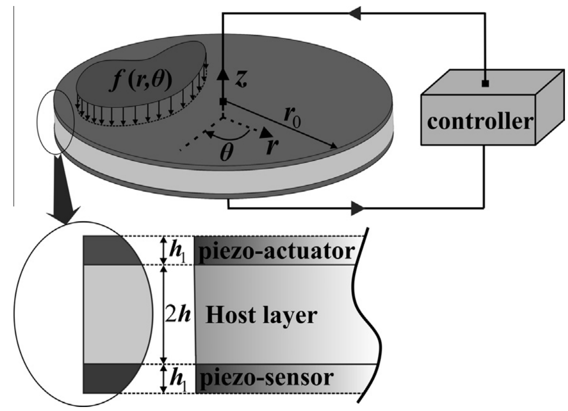

Fig. 1. Geometry of the problem.

where u_z, u_r, and u_θ are the displacements in the transverse z-direction, radial r-direction, and tangential θ-direction of the plate, respectively.

The poling direction of the piezoelectric material is assumed to be in transverse direction. The strain tensor (ε) in the host and piezoelectric layers in r- and θ-directions can be calculated in a similar manner as Wang et al. [26] with respect to the shear components. Then, following the stress–strain relations of isotropic host domain with E and v being the Young's modulus and the planar Poissons's ratio of the host material, the relation between displacement and stress fields is obtained. Similarly, the stress components in the piezoelectric medium can be written as

$$\begin{aligned}\sigma^2_{rr} &= \overline{C}^E_{11}\varepsilon_{rr} + \overline{C}^E_{12}\varepsilon_{\theta\theta} - \bar{e}_{31}E_z,\\ \sigma^2_{\theta\theta} &= \overline{C}^E_{12}\varepsilon_{rr} + \overline{C}^E_{11}\varepsilon_{\theta\theta} - \bar{e}_{31}E_z,\\ \tau^2_{r\theta} &= \left(\overline{C}^E_{11} - \overline{C}^E_{12}\right)\varepsilon_{r\theta}.\end{aligned}\qquad(2)$$

In Eq. (2), the superscripts 1 and 2 denote the variables in the elastic and the piezoelectric layers, respectively. $\overline{C}^E_{11}$, $\overline{C}^E_{12}$, and $\bar{e}_{31}$ are the transformed reduced material constants of the piezoelectric layer (Appendix A), and are given as

$$\overline{C}^E_{11} = C^E_{11} - \frac{\left(C^E_{13}\right)^2}{C^E_{33}},\quad \overline{C}^E_{12} = C^E_{12} - \frac{\left(C^E_{13}\right)^2}{C^E_{33}},\quad \bar{e}^E_{31} = e_{31} - \frac{C^E_{13}e_{33}}{C^E_{33}},\qquad(3)$$

where $C^E_{ij},\ i,j = 1,2,3$ are the elastic modulus of the piezoelectric material which are measured at constant electric field and e_{31} is the piezoelectric constant. The sensor and actuator layers are electroded on both sides to activate the electromechanical coupling. When an external voltage $V(r,\theta,t)$ is applied, the electric potential distribution on the surface of the electrode remains constant. The electric potential Φ on the mid-surface of the piezoelectric layers is written as

$$\Phi(r,\theta,z,t) = \frac{1}{h_1^3}(z-h-h_1)\left(z^2-h^2\right)\varphi(r,\theta,t) + \frac{1}{h_1^3}(z+h+h_1)\left(z^2-h^2\right)V(r,\theta,t).\qquad(4)$$

The electrical potential in the z-direction (Eq. (4)) is selected such that, the electric boundary conditions for the piezoelectric actuator and sensor layers are satisfied with respect to the conditions presented by Ray et al. [27] without additional modeling complexity. In this equation z is measured from the mid-plane of the plate in the global z-direction and h_1 is the thickness of the piezoelectric

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