Automatica 48 (2012) 1123–1131

Contents lists available at SciVerse ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Brief paper

Observer-based self sensing actuation of piezoelastic structures for robust vibration control[☆]

Thomas Rittenschober[a,1], Kurt Schlacher[b]

[a] 4020 Linz, Austria

[b] Institute of Automatic Control and Control Systems Technology, Johannes Kepler University, 4040 Linz, Austria

ARTICLE INFO

Article history:
Received 22 April 2008
Received in revised form
2 October 2011
Accepted 19 October 2011
Available online 13 April 2012

Keywords:
Smart structure
Piezoelectric material
Self sensing actuation
Vibration control
Unknown harmonic disturbance
Frequency estimator
Disturbance observer
Small gain theorem
Sylvester equation
Hamilton–Jacobi inequality
L_2 stability

ABSTRACT

This contribution is concerned with self-sensing actuation (SSA) for the adaptive vibration control of smart structures with piezoelectric actuators. The electro-mechanical model of a Kirchhoff plate equipped with two piezoelectric patches is rewritten in the form of an infinite dimensional port controlled Hamiltonian system with dissipation (PCHD) where collocation of input and output is achieved by SSA. In the case of piezoelectric actuators, self sensing requires a robust separation of electric current due to the direct piezoelectric effect from the measured electric current. Because of the unfavorable ratio of these two signals, the design of an approximate observer for the electric current due to the direct piezoelectric effect is proposed. The control design goal is the asymptotic suppression of a harmonic disturbance with unknown frequency, amplitude and phase. The control law is derived for the plant augmented by an appropriate exosystem, which models the properties of the disturbance. The novelty of this contribution is the extension of the control design methods from the finite dimensional case to the infinite dimensional one. The stability analysis for the infinite dimensional system is based on the concept of L_2-stability and the small gain theorem. Vibration attenuation around a dominant eigenfrequency is demonstrated by simulation and experiment.

1. Introduction

The notion of a smart structure refers to a mechanical structure equipped with integrated sensors and actuators. Piezoelectric materials can be used as actuators and sensors for the purpose of structural monitoring and vibration control and have gained considerable attention in the structural control community due to their high degree of integrability and capability of being also used as actuators and sensors at the same time. The latter property of piezoelectric materials is also referred to as self sensing actuation (SSA) which — from a control engineering point of view — allows us to construct a collocated actuator and sensor. The representation of such electro-mechanical systems as infinite-dimensional Port Controlled Hamiltonian System with Dissipation (PCHD) together with the special pairing of a collocated input and output facilitates controller design and corresponding proofs of stability. In the case of piezoelectric actuators, self sensing for e.g. velocities requires robust separation of the electric current due to the direct piezoelectric effect from the measured electric current. The separated signal is proportional to the strain rate integrated over the piezoelectric patch area and may subsequently be used as a control variable for vibration control. Due to the unfavorable ratio of the two signals, especially in the region of anti-resonance of the mechanical structure, the design of an approximate observer for the electric current due to the direct piezoelectric effect is proposed in this contribution. While crosstalk and impedance matching make self-sensing a challenging task in bridge circuits, see Anderson, Hagood, and Goodliffe (1992), Dosch, Inman, and Garcia (1992) and Qiu and Haraguchi (2006), the design of an approximate observer relies on accurate models of the piezoelastic structure which in our case is chosen to be a rectangular plate equipped with two piezoelectric actuators. The test rig is designed such that one piezoelectric element induces a harmonic disturbance in a controlled manner while the other piezoelectric element is part of a closed loop vibration control scheme.

☆ The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Xiaobo Tan under the direction of Editor Miroslav Krstic.

E-mail addresses: trittenschober@gmail.com (T. Rittenschober), kurt.schlacher@jku.at (K. Schlacher).

1 Tel.: +43 (0) 664 2139370; fax: +43 0 664 2139370.

0005-1098/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2012.02.038

Active vibration control of mechanical structures is an active area of research and numerous linear and nonlinear control concepts have been adapted to vibration control of beam and plate-like structures. The following references only give a brief overview of research efforts in this field and may not be considered exhaustive. Vibration control of simply supported plate structures with piezoelectric patches using H_2 and H_∞ control design is demonstrated in Reza Moheimani, Halim, and Fleming (2003), while Kugi and Schlacher (2002) demonstrates passivity-based control design applied to piezoelectric compound structures. Control schemes based on adaptive filters such as the filtered X LMS algorithm have been successfully applied to disturbance rejection in smart structure applications Kaufman, Barkana, and Sobel (1998). Adaptive disturbance rejection based on Lyapunov techniques for linear uncertain mechanical systems subject to sinusoidal disturbances with unknown amplitudes and frequencies is presented in Xian, Jalili, Dawson, and Fang (2003). A disturbance observer based tracking control algorithm is shown in Liu and Peng (2000). A self-sensing piezoelectric actuator for collocated control using a bridge circuit is presented in Anderson et al. (1992) and Dosch et al. (1992). Active vibration control of a plate using a self-sensing actuator (SSA), a bridge circuit and an adaptive control method (filtered X LMS) is proposed in Qiu and Haraguchi (2006). Collocated control of beam vibrations with piezoelectric self sensing layers is presented in Irschik, Krommer, and Pichler (2001). An observer-based SSA approach bypasses the impedance mismatching problem in bridge-based SSAs and experimental results are outlined in Dong and Sun (2006). The problem of varying capacitance of the piezoelectric element is addressed in Law, Liao, and Huang (2003) where an adaptive compensation in combination with the SSA technique is proposed.

Stability investigations of complex distributed parameter systems usually involves the spatial discretization of the mathematical model by use of Ritz–Galerkin methods, finite element methods or finite difference approximations. The resulting system can eventually be analyzed using stability tests from finite dimensional systems theory. In general, we may not infer the stability of the distributed parameter system from its finite dimensional approximation. Research, however, has made considerable progress in the stability analysis of distributed parameter systems, see Komornik (1994), Lagnese (1989) and Luo, Guo, and Morgul (1999).

In the scope of this contribution, the control design goal is the asymptotic suppression of harmonic disturbances unknown with respect to frequency, amplitude and phase. The control law is derived for the plant augmented by an appropriate exosystem, which models the properties of the disturbance Isidori, Marconi, and Serrani (2003). Since we have to respect that the electric current due to the direct piezoelectric effect, the state and the frequency of the exosystem are not available by measurement, we propose to reconstruct a finite-dimensional approximation of the state based on a finite-dimensional approximation of the plant. An estimate of the unknown frequency is generated by an update law which will be derived from a Lyapunov stability argument Krstic, Kanellakopoulos, and Kokotovic (1995) and Kaufman et al. (1998). The major novelty of this contribution lies in the rigorous extension of control design methods from the finite dimensional case to the infinite dimensional one with special attention to the piezoelastic structure under investigation.

Now, this contribution is organized as follows. Section 2 presents the mathematical model of the piezoelastic structure under investigation. In Section 3, we present the proposed control concept. Section 4 highlights the performance of the control algorithm. Vibration control around a dominant eigenfrequency is demonstrated and corresponding sensor and control signals are depicted along with actual plate vibrations.

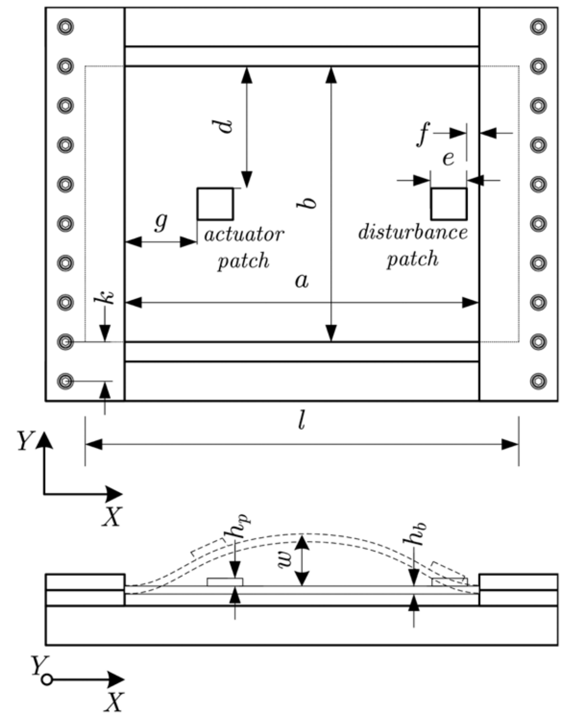

Fig. 1. Geometric configuration of the piezoelastic structure.

2. The mathematical model

The plate structure under investigation along with its geometric properties is depicted in Fig. 1, see Section 4 for actual numerical values of geometric parameters and material properties.

The piezoelectric patches are placed on the central nodal line along the X axis in order to avoid the excitation of certain modes and thus, keep the modal density at an acceptable level. This approach will not constitute any limitations on the proposed control concept. But we shall remark that an external disturbance such as the one from fluid–structure interaction may excite unobservable and uncontrollable modes. This situation which is not in the scope of this contribution, leads to the problem of optimal actuator placement such that the modes of interest can be observed and controlled by the controller. An interesting scenario already occurs for double modes of simply supported quadratic plates, where the natural frequencies coincide, i.e. $\omega_{ij} = \omega_{ji}$. In such a case, multivariable control is necessary in order to prevent singularities in the corresponding controllability and observability Gramians Preumont (2002).

Under the assumption of linearized piezoelasticity and the linearized Kirchhoff strain displacement relations, the PCHD (Port Controlled Hamiltonian with Dissipation) representation, see e.g. Schlacher (2008), of a rectangular plate equipped with a piezoelectric patch actuator in self sensing mode is derived from the linearized partial differential equation, see Ennsbrunner and Schlacher (2006) and Fuller, Elliott, and Nelson (1993),

$$\left(\mu \frac{\partial^2}{\partial t^2} + \bar{D}\left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2}\right)^2\right) w\,(t, X, Y) = cu\,(t)\left(\frac{\partial^2}{\partial X^2} + \frac{\partial^2}{\partial Y^2}\right)\lambda\,(X, Y)\,, \tag{1}$$

together with appropriate boundary and initial conditions. Local mass loading and added structural stiffness due to bonding the piezoelectric patch onto the plate as well as the longitudinal dynamics of the plate will be neglected here.