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Multi-mode passive piezoelectric shunt damping by means of matrix inequalities

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ABSTRACT

This paper deals with the use of matrix inequalities for the aim of multi-modal piezoelectric shunt damping. The paper shows that the shunt impedance can be seen as a controller in a state space model of the electro-mechanical system; this makes it possible to use the mentioned approach to find the layout of the impedance for different kinds of control problems. The particular focus is on passive multi-mode vibration control with the aim of finding the optimal shunt impedance among the passive and realizable candidates. The proposed method overcomes most of the problems related to the development of the optimal shunt electrical network, which arise when using the most common shunt design strategies for multi-mode control. The results were validated experimentally and compared to well-established methods for multi-mode shunt damping. The proposed method proved to be effective, and the results demonstrate the capability of the matrix inequality approach to provide attenuation levels that are usually higher than those from the reference methods.

1. Introduction

The use of piezoelectric actuators shunted to electric impedances as vibration controllers is a well-established topic [1]. According to the kind of impedance used, it is possible to provide a vibrating structure with a control action focused on just one mode or on several modes together. In the former case, the impedances commonly used are a simple resistance [1,2] and the parallel or series connection of a resistance and an inductance [1–5].

There are several possibilities to build the shunt impedance for multi-mode control:

1. the use of a negative capacitance (NC) [6–10] coupled to a resistance. Indeed, the coupling between an NC (which is an active component made from an operational amplifier [11–13]) and a simple resistance can provide a broadband damping action and thus control different modes together [6,9,14]. However, the use of an NC makes the control semi-active and thus poses some problems related to system instability;
2. the use of non-linear shunt impedances based on switches (e.g. [15,16]). Such methods offer good control performance. This approach can sometimes require a complex controller structure when the switches in the shunt impedance have to be driven by digital systems. Nevertheless, Lallart et al. [17] demonstrated that this complexity can be reduced by using self-powered circuits that can remove the need for digital controllers;

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3. the use of passive impedances (i.e. made from resistances, inductances, and capacitances) that are properly designed to tune the control action on the modes considered. This approach does not suffer from any possible problem related to instability thanks to the passive nature of the shunt impedance, and it does not require any digital system or feedback sensor.

The third approach plays an important role due to its passivity, lack of instability, and lack of additional devices, especially in the industrial and aerospace fields. There are different methods of designing a proper shunt impedance for a given control problem. The methods can be divided in to those that work with either one or more piezoelectric actuators, and those based on several piezoelectric actuators together, which often exploit the advantages of periodic structures.

For the first type, Hollkamp was the first to propose an impedance design method using a single piezoelectric patch working on different modes at the same time [18]. The proposed network design is made from as many branches connected in parallel as the number of modes to be damped. The main problems related to this method are the cross-talk between the branches of the circuit, which requires perfectly decoupled modes, and the complexity of the procedure to fix the values of all the electric components.

Wu [19] and Behrens et al. [20] respectively proposed the current blocking (CB) and current flowing (CF) methods, where the shunt impedance is again made from as many branches as the number of modes to control. All the branches are again connected in parallel. In CB [19], there are N_i elements in each branch connected in series (where N_i is the number of modes to be damped). The first of these elements is a parallel connection of a resistance and an inductance, while the other elements are parallel connections of a capacitance and an inductance. Although a method was proposed to simplify the design of the shunt impedance somewhat, the complexity of the circuit is evident, especially when the number of modes to control increases. Another problem with the CB method is that there are some degrees of freedom in the tuning of the network. Indeed, the values of some electric components must be fixed arbitrarily without any guidelines, which results in non-optimal control actions.

In the CF technique [20], each branch is made from three elements: a resistance, a capacitance, and an inductance. The values of the resistances in the shunt impedance must be fixed by numerical minimisation [21]. Furthermore, there are some degrees of freedom that lead to a non-optimal solution in this case as well, although Cigada et al. [22] proposed some guidelines to overcome this problem. There are also cross-talk effects that are not accounted for in the tuning procedure and can be solved just by using numerical minimisations [22].

Fleming et al. [23] introduced a smart method that can be seen as a mix of CB and CF. The shunt network is a combination of cells connected in series and parallel (i.e. series-parallel approach). Like in other approaches [19,20], the main drawback of the method is that there are some degrees of freedom in the tuning of the network with arbitrarily fixed component values. The same paper also shows that adding a capacitor to the shunt circuit decreases the global coupling coefficient and thus the damping performance. This effect is related to all multi-mode shunts working with a single patch because of the unavoidable addition of capacitors in the shunt circuit [24]. This problem could be mitigated by using multiple piezoelectric actuators.

Several techniques have also been proposed to tune the shunt impedances using more than one piezoelectric actuator together. Moheimani et al. [25] proposed a multi-mode control approach with more than one piezoelectric actuator shunted by a multi-input impedance, which relies on the representation of the shunt damping as a feedback controller. They presented only tests carried out with a synthetic controller. The method provides good performance, but there are again some degrees of freedom that must be fixed by the user without any guidelines. Moreover, Fleming and Moheimani [26] presented an approach to design shunt impedances for multi-mode control based on well-established methods such as linear quadratic Gaussian (LQG) control, H_2 control, and H_∞ control. This approach works with one or more piezoelectric actuators. The three control methods were compared, showing that shunts can provide good attenuation performance. However, the main issue is that LQG and H_∞ controllers required active components in the shunt impedance (e.g. negative reactive components).

Maurini et al. [27] studied electric vibration absorbers made of distributed piezoelectric devices for the control of beam vibrations. The absorbers were obtained by interconnecting an array of piezoelectric transducers uniformly distributed on a beam with different modular electric networks. The electrical network is expected to show resonances at specific target frequencies. Batra et al. [28] showed that this is possible by interconnecting passive branches comprising inductances and capacitances. Giorgio et al. [29] proposed a method to control N_i modes of undamped systems with N_i interconnected actuators. The approach does not guarantee the realisation of the network with passive elements, even if further complication of the method could allow this constraint to be satisfied. Andreaus et al. [30] proposed a method for controlling the flexural vibrations of beams with more than one actuator by finding an electrical circuit analogue to a Timoshenko beam through a Lagrangian method. The main limit of this approach is related to the lumped nature of the piezoelectric devices used and the electric circuit, which link the lowest controllable wavelength to the size of the piezoelectric patch (i.e. the lowest controllable wavelength is approximately equal to the size of the actuators). However, the problem can be limited by using enough elements per wavelength. Moreover, given the electrical network, the values of the capacitive and inductive elements are fixed to match the mechanical resonances of the beam. As for the resistances, the tuning procedure is not straightforward. Although some approaches to tune additional resistances are given to provide the appropriate damping to the electric impedance, no criteria are available to fulfil a given control problem (e.g. H_∞). Bisegna et al. [31] proposed a multi-modal vibration damping method for an elastic beam equipped with multiple piezoelectric actuators connected to an