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Short communication

Decentralized stabilization of semi-active vibrating structures

Dominik Pisarski

Institute of Fundamental Technological Research, Polish Academy of Sciences, Pawińskiego 5b, 02-106 Warsaw, Poland

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ABSTRACT

A novel method of decentralized structural vibration control is presented. The control is assumed to be realized by a semi-active device. The objective is to stabilize a vibrating system with the optimal rates of decrease of the energy. The controller relies on an easily implemented decentralized switched state-feedback control law. It uses a set of communication channels to exchange the state information between the neighboring subcontrollers. The performance of the designed method is validated by means of numerical experiments performed for a double cantilever system equipped with a set of elastomers with controlled viscoelastic properties. In terms of the assumed objectives, the proposed control strategy significantly outperforms the passive damping cases and is competitive with a standard centralized control. The presented methodology can be applied to a class of bilinear control systems concerned with smart structural elements.

1. Introduction

Over the last decade, decentralization has emerged as one of the major trends in the field of control systems. The growing interest in this control concept derives from the functionality of modern devices, which can be perceived as compact modules since they are fully equipped with sensors, actuators, and computing units. Furthermore, decentralization is a natural response to the demand that systems be robust and able to adapt to various tasks. In many applications, the design of a traditional centralized control system is not only problematic but sometimes also unfeasible. In particular, centralized systems fail in large-scale vibrating structures where, due to the complexity of the feedback systems, the computational burden and the amount of instrumentation employed exceed reasonable limits.

Since the roots of decentralized control can be traced to the field of distributed computing, the emergence of the consensus algorithms in the 1960s and 1970s [1] significantly boosted its popularity. In networks of dynamical systems, "consensus" refers to an agreement regarding a certain quantity of interest that depends on the state of the system's members [2]. Recently, the consensus algorithms have been rediscovered by the control and robotics communities for cooperative coordination of multi-agent systems [3], in particular, in the so-called rendezvous problem [4]. Decentralized control algorithms have found numerous applications to urban [5] and air [6] traffic, as well as to cooperative vehicle systems [7]. By employing parallel computing procedures [8], decentralized controllers can provide the benefit of an efficient and robust realization of optimal processes, including the control of large-scale traffic [9] and power [10] networks.

The use of decentralized methods in structural vibration control has not been extensively studied so far. In order to derive an efficient stabilizing or optimal control law in a decentralized form, it is desirable that the dynamics of the system be weakly interconnected. Unfortunately, this is not the case for the majority of mechanical systems, which are governed by a fully interconnected set of dynamical equations. The decentralized control of such systems requires novel design

E-mail address: dpisar@ippt.pan.pl

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methodologies. In the existing literature, we can find [11,12], which examine a decentralized linear-quadratic-Gaussian controller in stabilizing a large-scale civil structure. They suggested partitioning the structure into a set of subsystems controlled by independent subcontrollers. The interaction between the subsystems was treated as an external disturbance. An analogous system partitioning was adopted in designing a decentralized controller to stabilize the motion of a robot manipulator [13]. In [14] it was demonstrated that a decentralized controller can be effectively employed to stabilize the trajectory of a load traveling over a carrying structure. The decentralized system that was designed supervised a set of magneto-rheological dampers controlled by means of the average measures of the structure's state, computed by using a distributed averaging protocol. It was validated experimentally that the designed decentralized controller exhibits a performance comparable to that of a centralized optimal control method.

In the present paper, we will present a novel method of decentralized stabilizing control of semi-active vibrating structures. The controller will be validated for a double-cantilever system equipped with elastomer blocks. The proposed method is, however, generalized to a class of systems described by bilinear differential equations, which includes a variety of smart structures equipped with materials of controlled viscoelastic properties, e.g., granular materials, thermoresponsive polymers, or commonly used electrorheological and magnetorheological fluids, foams, and gels. Firstly, on the basis of a typical state-feedback design used in structural vibration control, we will define the concept of a decentralized controller. Then, we will briefly present a method of designing robust and optimal decentralized controllers with an emphasis on their benefits and limitations. The remainder of that section will be devoted to the design of a switched controller that finds a compromise between optimality and practical simplicity. A set of numerical tests have been performed to determine the performance of different architectures of a decentralized controller in stabilizing both the primary and the higher vibration modes. The results will be compared to those obtained with the use of a centralized controller and the best passive damping strategy.

2. The architecture of a decentralized controller

Before we present the method for designing a decentralized stabilizing control, let us first introduce the notion of the architecture of a decentralized control system. Consider a vibrating structure equipped with state sensors $i = 1, 2, \ldots, n$ and local controllers/actuators $j = 1, 2, \ldots, m$ (see Fig. 1). We assume that the structure's state is uniquely characterized by the vector $x = [x_1, x_2, \ldots, x_n]^T$, where x_i is permanently accessible to the sensor i. With the use of communication channels, denoted by red arrows, the state information is transmitted to the local controllers/actuators that make control decisions $u_1, u_2, \ldots, u_m$ and actuate the structure.

Now we will characterize the topology of the communication channels between the sensors and the local controllers. Let each $g_{ij},\ i = 1, 2, \ldots, n,\ j = 1, 2, \ldots, m$ be a Boolean parameter, where $g_{ij} = 1$ if the sensor i sends the state information to the controller j and $g_{ij} = 0$ otherwise. The state information accessible to the local controller u_j can be then described by the set $\mathcal{G}_j = \{i : g_{ij} = 1\}$. Depending on the structures of the sets $\mathcal{G}_j,\ j = 1, 2, \ldots, m$, we can distinguish between two types of control system architectures. We say that a control system is based on *a centralized architecture* if each local controller receives the full state information, i.e.,

$$\mathcal{G}_j = \{1, 2, \ldots, n\}, \quad j = 1, 2, \ldots, m. \tag{1}$$

Otherwise, the control system is said to be *decentralized*. In particular, we can consider *a completely decentralized* system, where each local controller is provided only with its adjacent state. Assuming equal numbers of sensors and controllers $n = m$, a completely decentralized system is defined by

$$\mathcal{G}_j = \{j\}, \quad j = 1, 2, \ldots, m. \tag{2}$$

In this paper, we will also be interested in decentralized architectures where the local controllers receive the information of their adjacent and neighboring states:

$$\begin{aligned} &\mathcal{G}_1 = \{1, 2\}, \mathcal{G}_m = \{m-1, m\}, \\ &\mathcal{G}_j = \{j-1, j, j+1\}, \quad j = 2, 3, \ldots, m-1. \end{aligned} \tag{3}$$

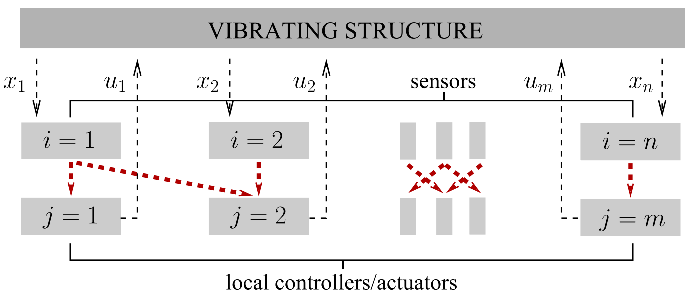

Fig. 1. Vibrating structure actuated by employing a decentralized state-feedback controller.