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Vibration suppression of distributed parameter flexible structures by Integral Consensus Control

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ABSTRACT

Integral Consensus Control (ICC) is proposed and implemented in this paper for the first time, as a novel approach for vibration control in distributed parameter flexible structures. The ICC consists of multiple parallel first-order lossy integrators, with the goal of targeting all major participating resonant modes in the oscillation of the structure. The vibration control design is taken to a different level, by integrating the concept of consensus control design into the new dynamics. Each control patch on the flexible structure is considered as a node of a network, and a communication topology with consensus control terms are augmented in the controller design dynamics. The result is an effective vibration controller, which is also robust to failures and inconsistencies in the control system. A cantilever is used as a sample flexible structure to investigate the control method. Multi-agent representation of the system, state estimator dynamics and the ICC model are designed for the structure. Extensive numerical simulations have been conducted to show the suppression performance of the ICC under different input disturbances. A comparative study is presented to show the advantage of the decentralized design over the conventional centralized approach. The new consensus control design provides new possibilities to vibration control problems, where an effective, robust and synchronized suppression is needed.

1. Introduction

Active vibration control using smart materials has been applied to suppress unwanted vibrations in different structures for decades. The need for reducing ambient induced oscillations in various systems has resulted in developing new approaches. To have an effective suppression, certain factors have to be considered for each specific problem such as specifications of the structure under vibrations (e.g., its dimensions, shape and material), the type of the induced ambient disturbances, required level of suppression, and so on. Although physics of the system plays an important role in these problems, proper control elements selection and innovative control algorithm design are two other salient factors that can significantly change the vibration attenuation result. Piezoelectric materials have been frequently used for vibration control, in either form of actuators or sensors. They can be easily attached to thin-walled structures that are prone to be oscillated with large amplitudes, while they do not increase the weight of the structure significantly. As actuators, they can apply the required actuation power in real-time to make active approaches superior to other passive vibration reduction methods.

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When used as sensors, they eliminate the need for additional bulky devices, while they are relatively cheap, do not require calibrations and they are ready to use once installed. Some example studies on piezoelectrically controlled distributed parameter structures are vibration reduction in damped sandwich beams [1], optimal actuator/sensor placement [2] and a comparison between classical and optimal feedback control strategies [3].

The control algorithm, as the other important factor in effective suppression, has been the focus of different research studies, as the methodologies have been developed from simple direct output-feedback methods to more complicated configurations. It has been shown in various studies that how proper controller design can positively affect the result of the suppression task; some examples are Hybrid Positive Feedback (HPF) control design [4], non-collocated Positive Position Feedback (PPF) for a sandwich plate [5], minimum actuation power based controller [6], nonlinear controller designed for a nonlinear vibrating system in [7], a Lyapunov function based [8], and a pole-placement–integral resonant control approach [9]. Although vibration amplitudes in a small-sized structure can be successfully reduced using only one piezoelectric actuator (see examples in [10,11]), more actuation patches are required in larger structures, depending on the size. Five piezoelectric actuators were used for vibration control of a plate [12], multiple layers in large deformable composites [13], and in a shell structure [14]. Broadband vibration control of wall of a water tank [15], and piezoelectric reinforcement of a wind turbine blade [16] are two other studies on vibration control of large scale structures. When the problem of vibration control with multiple control patches is considered, it is essential to ensure that all actuators are working in perfect synchronization with one another. If one actuator falls out of phase with others, control performance will be defected, and the closed-loop system may even become unstable. These kinds of malfunction could be caused by failure in a sensor, connection issues or errors in the centralized processing unit. Also in some cases, sudden changes or shocks, or local disturbances on one control patch may result in performance inconsistency in the control system.

The problems due to the size of the control system and the need for a synchronized performance had not been considered in vibration controller problems, until the idea of consensus PPF control was proposed in [17]. In consensus design in general, elements of a relatively large-scale control system (i.e., agents or nodes) are connected to one another under a graph with a certain topology. These elements can be moving vehicles or aircraft with the goal of reaching to a common heading angle/velocity [18] or to a certain formation [19]; robots with the purpose of position synchronization [20] or rendezvous [21]; and satellites that require attitude alignment [22]. In the new setting for the consensus control in distributed parameter structures, the attached control patches to the structure are considered as the control agents. Then, the consensus control law is applied to force the performance disagreement between the agents to zero.

In this paper, a new Integral Consensus Controller (ICC) is developed for the first time and implemented for vibration control of flexible structures enhanced by multiple piezoelectric control patches. The ICC consists of N individual controllers for N control patches on the structure, which are connected to one another under a certain directed communication graph. The compensator at each of these controllers consists of a linear combination of n lossy integrators, to targets the first n modes of the structure. Implementation of this first-order set of compensators increases the damping of the system targeting the resonant frequencies, and results in higher suppression ability against various disturbances. The consensus is enforced between the ICC agents using controller states, which are ultimately used to calculate the controller output of each agent. The consensus term removes the disagreements between the control agents that may occur for any reason, and makes the controller resilient to failure in some control system components. To the purpose of controller development, the multi-agent representation of the multi-actuator/sensor enhanced flexible structure for a cantilever is developed, then the optimal observer dynamics are studied. The configuration of ICC is described later and the consensus condition and optimality are discussed. The controller is numerically evaluated in the end and responses of the system to different disturbances and a failure scenario in controller input provision is investigated.

2. Distributed system modeling and observer design

As the first step of the analysis, a multi-agent dynamic model of the flexible vibrating structure with multiple actuation/sensing patches has to be derived. The considered clamped-free boundary conditions for the sample structure is frequently used in different systems and structures of various scales. Some examples can be mentioned as a flexible robot arm [23], a wind turbine tower [24], wings of an airplane [25], solar panels of a satellite [26,27], flexible marine riser [28,29]; or even in smaller scale as a micro-cantilever beam in a scanning probe microscope [30]. The free end of a cantilever makes it more susceptible to high-amplitude vibrations, in addition to the fact that cantilever beams have higher number of modes in lower frequency region compared to other boundary conditions [31]; which results in a higher chance of being excited at a resonant frequency. Hence, vibration control in cantilevers is more frequently studied and applied in practice.

2.1. Dynamic multi-agent model derivation

Partial differential equation (PDE) of the system under clamped-free boundary conditions is considered using the principle of Euler–Bernoulli theory according to reference [32], and the method of separation of variables is applied later to